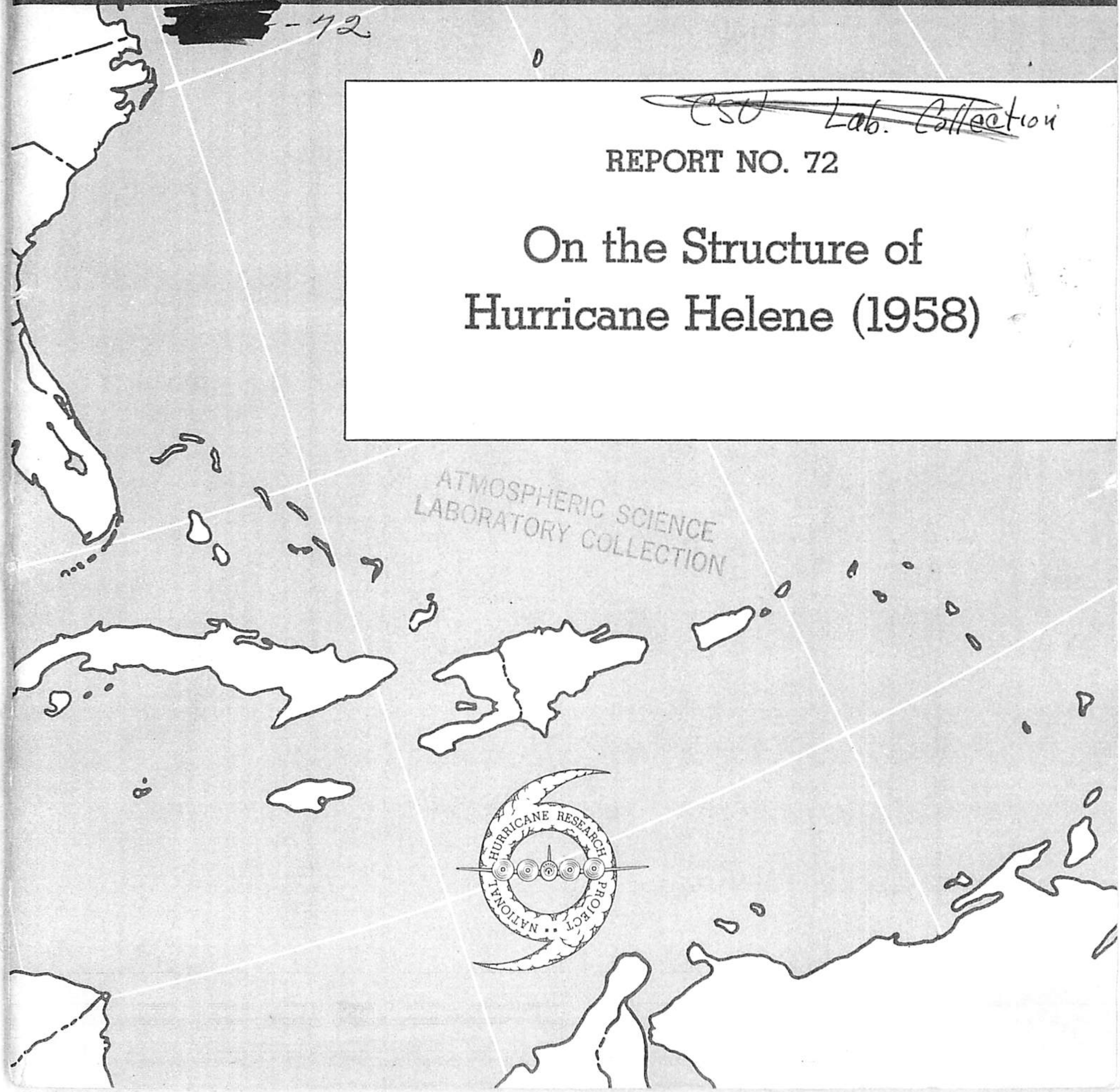
NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 72

On the Structure of Hurricane Helene (1958)



U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, Secretary
WEATHER BUREAU
Robert M. White, Chief

NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 72

On the Structure of
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by

José A. Colón

ane Research Laboratory, Miami, Fla.

Washington, D. C.
December 1964

NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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ON THE STRUCTURE OF HURRICANE HELENE (1958)

José A. Colón

National Hurricane Research Project, U. S. Weather Bureau, Miami, Florida

ABSTRACT

An investigation into the core of hurricane Helene was carried out by the U. S. Weather Bureau research aircraft from September 24 to 26, 1958. A discussion of the structure of this hurricane is presented.

The major part of the data collected inside the circulation is illustrated in the form of radial profiles and selected horizontal charts. These data give an excellent view of the properties of a mature hurricane and of the changes that accompanied the process of intensification.

Initially, hurricane Helene was a well defined vortex circulation, but with a highly disorganized velocity distribution and a rather large eye. With time, in a period of 48 hours, the system intensified considerably. The central pressure was reduced by about 60 mb. The circulation evolved into a much better organized vortex, with a smaller eye, an extremely warm core of air confined to the center, large thermal gradients across the eye wall, and a more typical wind distribution around it. All these features are illustrated and discussed in this report.

1. INTRODUCTION

During the period September 24 to September 26, 1958, the research aircraft of the U. S. Weather Bureau carried out a rather extensive investigation of hurricane Helene. At the time, this hurricane was moving on a northwestward track in the region east of the Bahama Islands (fig. 1). A total of five separate missions was carried out over the 3-day period at altitudes ranging from 3000 to 35,000 ft.; three of these missions were carried out almost simultaneously at low, middle, and high altitudes on September 26 and gave a good view of the three-dimensional properties of the hurricane near the time of maximum intensity. Parts of the data gathered have already been analyzed and studied by Miller [12], Colón [1], Krishnamurti [10], Gentry [4], and others. These reports deal with selected portions of the Helene data, which were used to discuss or illustrate specific topics of hurricane dynamics and kinematics. In the present report we shall attempt a more complete presentation of the data and discussion of this hurricane. The format of the discussion and illustrations follow closely the work done in connection with hurricane Daisy (1958) (Colón, [1]). The four principal parameters measured by the research aircraft, wind, temperature, pressure, and humidity, are illustrated in the form of radial profiles. Available cloud and radar data are also included in the profiles.

A rather complete discussion on the operation of the research aircraft in hurricanes, of the characteristics of the data gathered, and of the postflight processing of these data was presented in a previous report by Hawkins et al. [5]. Information on analysis methods and on accuracy and shortcomings of the various parameters measured was also included in the aforementioned Daisy report. None of these aspects of the data will be discussed here, except as necessary or pertinent to a better understanding of the present discussion.

2. DEVELOPMENT AND MOTION OF HURRICANE HELENE

Hurricane Helene developed slowly in an easterly wave that could be traced back to the region of the Cape Verde islands on September 16, 1958 (Staff WBO, Miami, [16]). At the time the wave was located near longitude 50°W., pressure falls and abnormal weather reported by ships in the area gave indications of potential intensification. On September 21 military reconnaissance aircraft located a weak perturbation near 19°N., 54°W, with maximum winds of 35 to 40 kt. in squalls. During September 22 the system continued in a west-northwestward direction at a fast speed of 20 m.p.h., with some intensification. The picture at the surface at 1200 GMT, September 22, is shown in figure 2. On the morning of September 23 (fig. 3) reconnaissance aircraft located the center near 23°N, 68°W. with maximum winds of around 50 kt. and central pressure of 1005 mb. The forward speed had then decreased to around 12 m.p.h. The first advisory on hurricane Helene was issued at 1600 GMT on September 23.

The Weather Bureau research aircraft penetrated the storm circulation for the first time near noon on September 24. The storm was then located in the region east of the Bahama Islands (fig. 4). Maximum winds of about 60 kt. were measured at an altitude of 13,000 ft. Hurricane Helene continued in a west-northwestward to northwestward track with more rapid intensification (fig. 5). A one-plane mission at 6400 ft. altitude on September 25 revealed a circulation with maximum winds of 80 kt. and central pressure of around 980 mb. A three-plane mission was carried out on September 26; at that time the central pressure was near 940 mb. and the maximum winds were close to 120 kt. Hurricane Helene reached a minimum central pressure of around 935 mb. early on September 27, at about the time it started recurving northward.

Hurricane Helene turned out to be one of the most destructive of the 1958 season over the continental United States even though the center never crossed the coastline. For a period of about 18 hr. and while the center moved parallel to and a short distance away from the Carolinas coast destructive winds on the left side of the circulation battered the coastal areas causing considerable property damage. There was one particular property of the Helene circulation, to be discussed later in this report, which was important in causing the heavy damage.

3. HURRICANE STRUCTURE, SEPTEMBER 24

Only one flight mission, lasting about seven hours, was carried out on September 24. Helene was then just reaching hurricane intensity and starting on the period of rapid intensification (fig. 5). The aircraft approached the center from a west-southwest direction at an altitude of 9800 ft. (700 mb.). It circled in the eye for about one hour, first descending from 9800

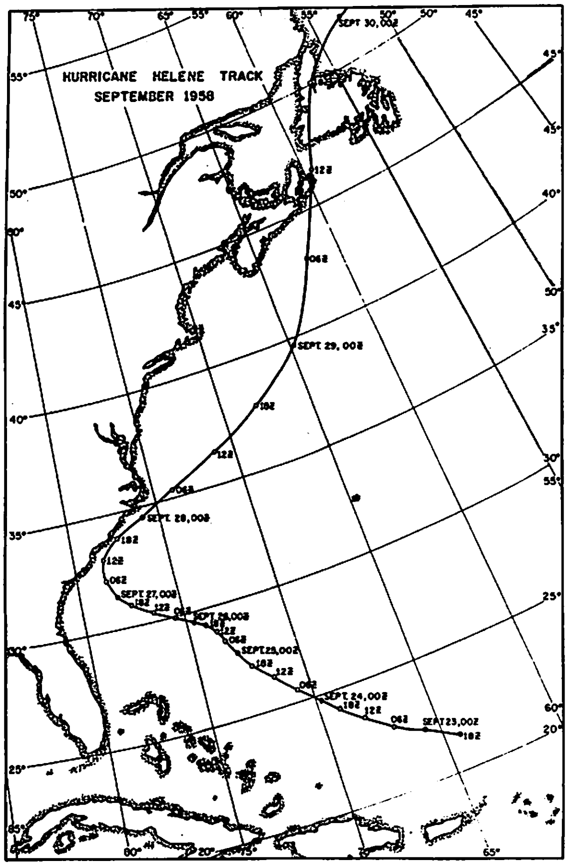

Figure 1. - Track of hurricane Helene, September 29, 1958.

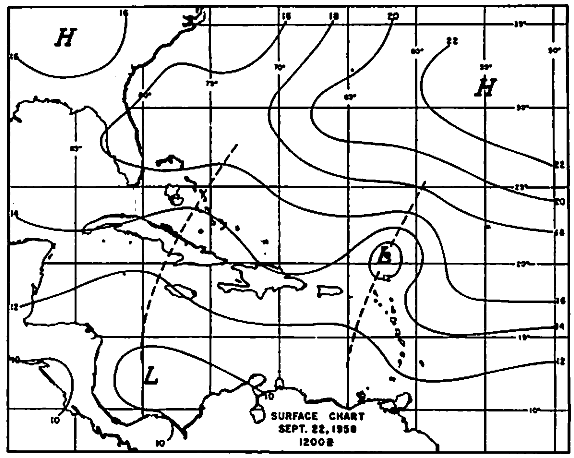

Figure 2. - Surface chart, September 22, 1958.

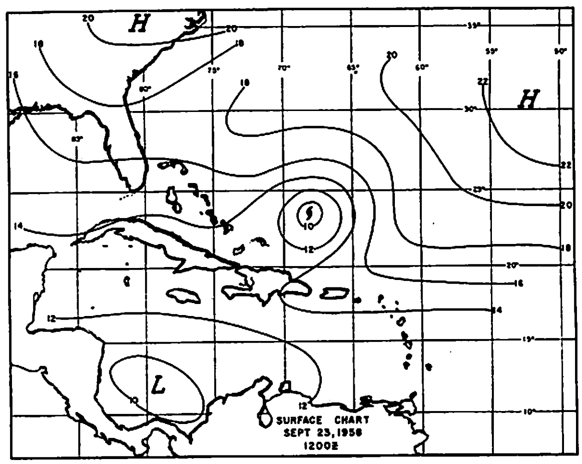

Figure 3. - Surface chart, September 23, 1958.

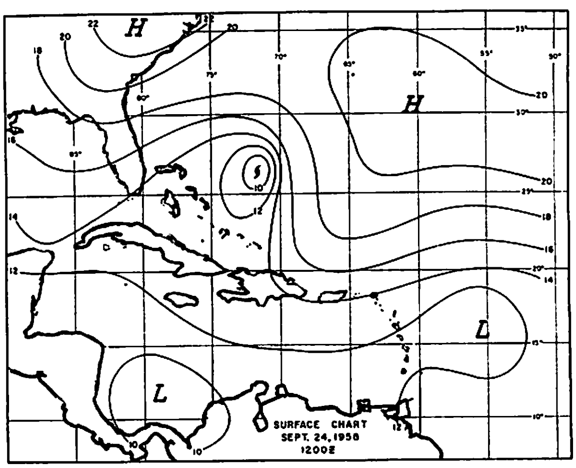

Figure 4. - Surface chart, September 24, 1958.

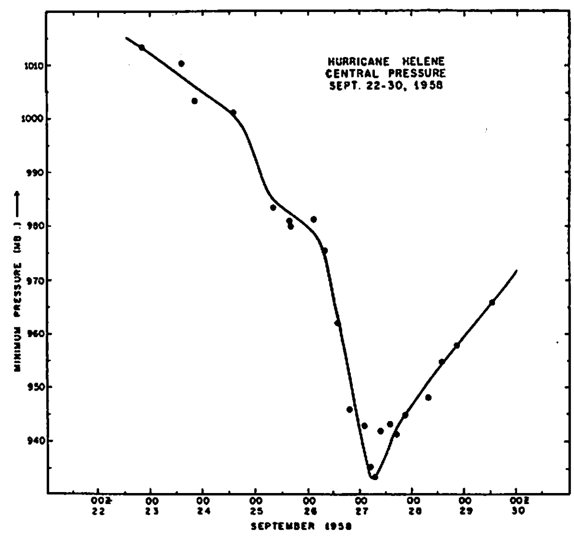

Figure 5. - Time changes in the minimum central pressure in hurricane Helene.

to 3000 ft. and then ascending to an altitude of 13,000 ft. A thorough investigation of the circulation at 13,000 ft. up to a radius of 60 mi. was then carried out in a track illustrated in figure 15.

A. Radar Field

An indication of the degree of organization and development existing in a given tropical cyclonic system can be obtained from the distribution of radar bands associated with it. Careful study of the radar bands crossed by the aircraft is also necessary for a better interpretation and understanding of the data, since it has been found that the horizontal variations in the parameters measured depend very much on the cloud systems encountered at flight level. The profiles illustrated in this report contain available information on the character of the cloud field at flight level and on the precipitation bands detected by the radar set aboard the same plane. In trying to prepare a radar composite for Helene on September 24 it was found that significant time variations in the shape, intensity, and distribution of echoes, particularly in the vicinity of the center, were observed during the period of the mission. It was, therefore, difficult to harmonize all the data and arrive at a picture representative of the entire period of the flight. As an alternative the composites for three different periods, centered on three different penetrations into the eye, are illustrated in figures 6 to 8. The effective range of the radar was about 50 mi.

In the preparation of these space composites, as well as of others introduced later in this report, certain approximations were made in compromising conflicting information resulting from time variations in the behavior of echoes during the period of the composite and from limitations on the accuracy of the measurements. Therefore, exact consistency between the data in the horizontal charts and the radar markings shown in the profiles should not be expected. The composites are meant to give a representative general view of the horizontal distribution of echoes over the composited period, while the data in the profiles give a more precise picture of the extent and timing of the bands actually traversed by the aircraft.

The distribution of bands around the eye at about 1839 GMT observed during the north-to-south pass (fig. 6), showed a series of isolated echoes very poorly organized in a quasi-circular shape. Very few extensive bands were detected; the more prominent ones were located on the north, west, and south sectors. There was a striking void outside the 40-mi. radius to the east of the center. There was also difficulty in establishing good continuity for bands spiralling inward to the center.

The configuration of the eye at about 1924 GMT (fig. 7) showed some change from the previous penetration. The main bands around the eye, located 15 to 20 mi. from the center, were better organized, and with a more complete circular shape. A large well-defined band was observed at about 35 mi. in the west quadrant. Outside, there were some scattered isolated echoes with poor band definition.

In the final penetration into the eye, at about 2008 GMT (fig. 8), a very prominent hooked band, forming a three-quarter circle and open to the northwest, was observed. The changes from figure 6 to figure 8 give evidence

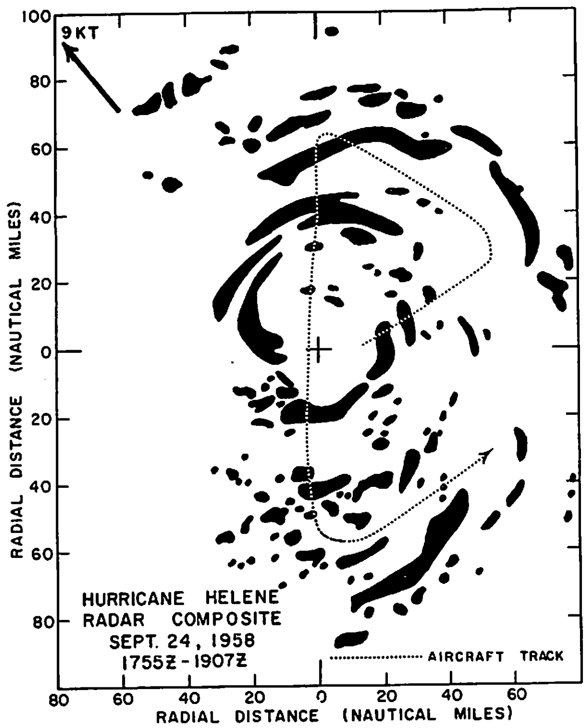

Figure 6. - Composite distribution of radar echoes observed by APS-23 radar aboard aircraft, 1755-1907 GMT, September 24, 1958. Storm motion shown by heavy arrow. (In this and other similar charts shown in this report the top of the figure is north.)

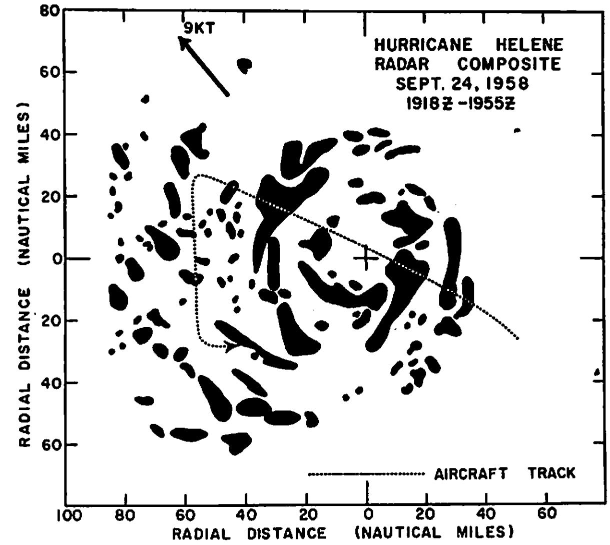

Figure 7. - Composite distribution of radar echoes observed by APS-23 radar aboard aircraft, 1918-1955 GMT, September 24, 1958.

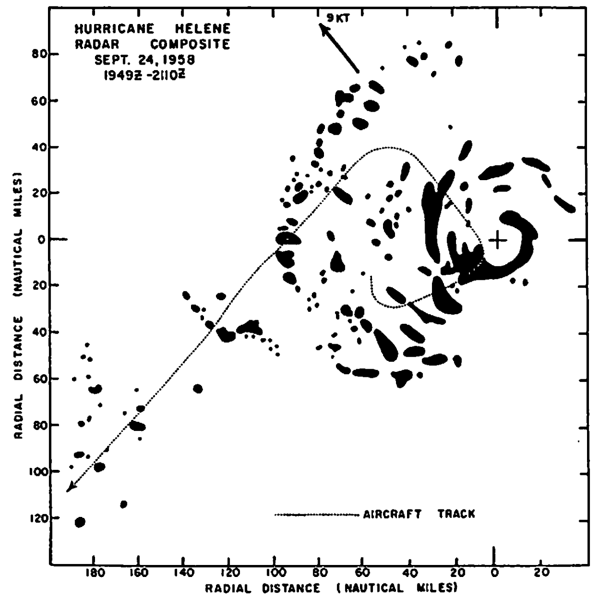

Figure 8. - Composite distribution of radar echoes observed by APS-23 radar aboard aircraft, 1949-2110 GMT, September 24, 1958.

of the trend in organization of the eye system. The pronounced band in the west was still present 30 to 35 mi. from the center. There were some concentrations of echoes at the 50 mi-radius, at the 90 mi. radius, and to the southwest at the 120 and 190 mi. radii.

B. Circulation at the 700-mb. Level

On approaching the hurricane from the west side at an altitude of 9800 ft. (700 mb.) the aircraft was in the clear at flight level during most of the route. Above flight level, clear conditions prevailed outside the 200-mi. radius; at that point the cirrus shield was encountered. From there into the center there were no breaks in the overcast above, with solid layers of either cirrus and/or altostratus. Below flight level, cloudless conditions persisted outside the 200-mi. radius, except for a sector with broken cumulus between the 370 and 290-mi. radii. In this sector some isolated cloud tops extended up across the aircraft's path. Inside the 200-mi. radius, the cloudiness also increased at low levels; a few cloudless sectors were encountered below flight level, but they were of short extent There was one between the 186 and 169-mi. radii; others inside the 140-mi. radius are indicated in figure 9. Extensive cloud layers at flight level were not encountered until the 45-mi. radius.

Important radar bands were encountered inward from the 70-mi. radius Outside, there were only isolated echoes. The most important band was crossed near the 40-mi. radius (fig. 9). Other important bands visible in the radar scope during this penetration were located south of the center There were no radar echoes visible in the western, southwestern, and eastern sectors of the storm.

The wind speed, temperature, humidity, and pressure data recorded in this penetration appear in figure 9. Wind speeds of 20 to 25 kt with little radial variation were observed outside the 80-mi. radius. From the 80-mi. radius inward there was a slow increase in speed. A wide belt with winds of about 35 kt. was recorded from the 50 to 20-mi. radii; then the wind decreased in the eye. The maximum winds recorded were only about 36 kt., and there was no typical concentration in the eye wall.

The temperature field showed fairly constant temperatures outside the 70-mi. radius with values between 8.5° and 10°C.; the average was close to 9°C. (just about normal for the month of September (Jordan, [8]). At the 70-mi. radius, where the first important radar echoes were encountered, there was a sharp drop in temperature. Between the 70 and 30 mi. radii the temperature averaged about 8°C., 1° below normal. From there into the eye there was a steady increase to a maximum of close to 11°C , 2° above normal.

The dew point-temperature curve indicated generally dry air on the periphery and fairly moist conditions, with relative humidities of the order of 90 percent, from the 60 to the 20-mi. radii. Saturated conditions were observed in the radar band near the 40-mi. radius. Drier conditions were observed inside the 20-mi. radius; the relative humidity in the eye was about 80 percent.

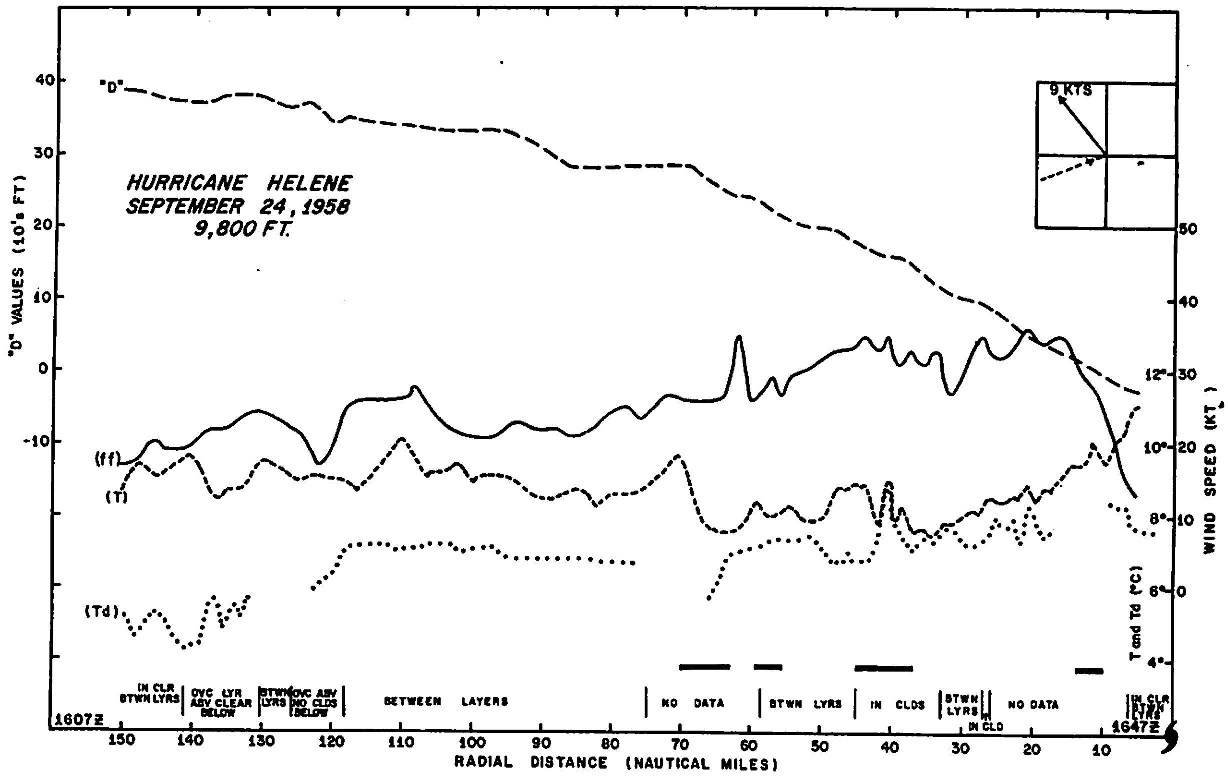

Figure 9. - Distribution with radius of actual wind speed, temperature, dew point, and "D" values. Data at the 9800-ft. level (pressure altitude, U. S. Standard Atmosphere), 700 mb. Small insert is a horizontal diagram showing the approximate path of the aircraft and the storm motion. Radar bands observed by the same aircraft are shown in dark horizontal segments; brief remarks on the cloud distribution apply to the sectors between the vertical lines. The same format is followed in all other data profiles illustrated in this report.

The profile of D-values showed very little radial pressure gradient outside the 70-mi. radius, and a steady decrease inward from that radius. The minimum D-values in the eye were +80 ft., which, with use of the extrapolation graphs introduced by Jordan [9], indicate a central pressure of about 995 mb.

Taken as a whole these data revealed a fairly well organized, but weak, wind vortex. The most significant radial variations were recorded inside the 70-mi. radius, where most of the convective bands were located. The variability of wind, temperature, and humidity was generally larger in the area of pronounced convection. The region as a whole (eye-core not included) was colder than its surroundings, but there were instances, as at the 40-mi. radius (fig. 9), when the temperature increased significantly inside a radar band. Similar features were observed throughout the whole Helene data, as well as in previous hurricanes studied (Colón, [1]). Gentry [4] made a detailed study of the variations of properties across and along rain bands and detected considerably larger variations in bands than outside. These variations are generally due to convective scale circulations within the bands.

C. Hurricane Circulation at 13,000 ft.

After climbing to this level inside the eye the aircraft departed toward the northeast and followed a track that described a three-leaf clover through all quadrants of the storm. The data recorded along the radial directions are illustrated in figures 10 and 14, while the horizontal distribution of winds and temperature are shown in figures 15 and 16.

(1) Wind field: The wind data in the passes through the northeastern and southern quadrants (figs. 10, 11) show lack of the typical concentration of wind speed. Instead, a wide zone of winds at nearly constant speed extended from about the 20-mi. to the 60-mi. radii. The maximum winds were invariably recorded in the vicinity of the 40 to 50-mi. radii. The path illustrated in figure 12 crossed the center from the rear to the forward side in a direction almost parallel to the motion. In the rear, outside the eye, the wind speed was around 40 to 50 kt. and quite variable. In the forward side, however, there was a distinct wind concentration with maximum winds of 60 kt. at about the 45-mi. radius. A final penetration into the center yielded two more profiles through the southwestern and northwestern quadrants (figs. 13, 14). Both revealed a larger degree of organization than had been observed in the earlier passes, but the maximum winds were not as concentrated as in figure 12. The data shown in figure 14 were obtained in about the same azimuth direction as those shown on the right side of figure 12, and only 45 minutes later. Both showed similar variations and maximum flow in about the same radial position, but the minor irregularities in the wind profile were quite different.

There were very significant differences between the profiles in the eastern semicircle obtained in the early part of the mission and those obtained in the western sector. The data on the western or left semicircle showed stronger and better organized flow than that of the right semicircle, contrary to what is normally expected. This may have been due to variations in either space or time and it is difficult to determine which of the two were more important. Significant asymmetries of this nature, particularly in formative storms, have been observed by hurricane workers in numerous other instances.

In the composite horizontal wind chart, obtained from a combined analysis of the various individual profiles plus other peripheral data (fig. 15), many of the minor-scale oscillations in the profiles were smoothed out so as to depict the salient features of the general field. Time differences that may have existed are ignored and it is implied that the unified picture gives a realistic and representative view of the existing distribution. The typical field of nearly circular and slightly converging streamlines was observed. The isotachs showed a main zone of over 50 kt. in the northwestern quadrant and other minor ones scattered over the northeastern quadrant. Outside the 80-mi. radius in the western sector, there was little radial variation in wind speed; winds of 20-30 kt. were observed over a large radial segment, similar to the observations at 9800 ft. (see fig. 9).

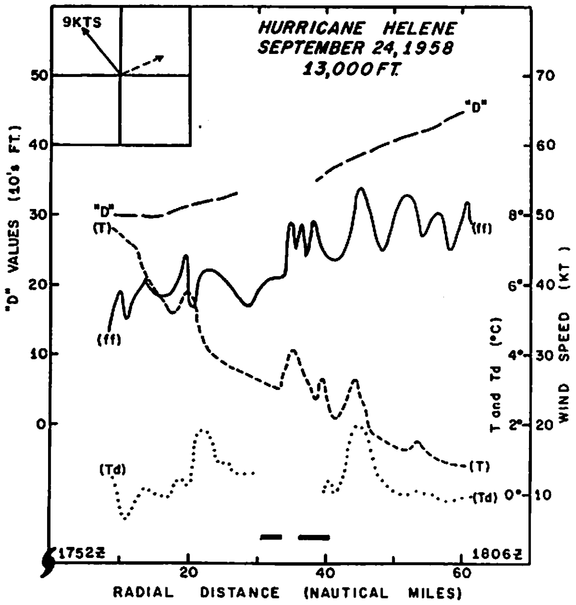

Figure 10. - Data profile at 13,000 ft. (620 mb.), September 24, 1958.

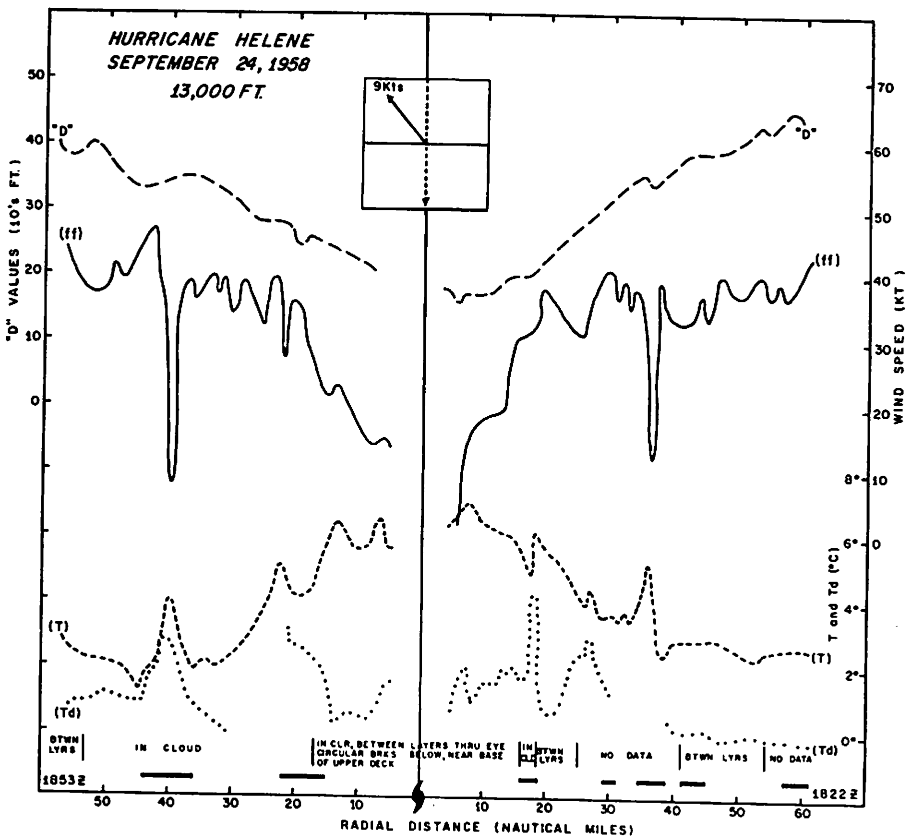

Figure 11. - Data profile at 13,000 ft. (620 mb.), September 24, 1958.

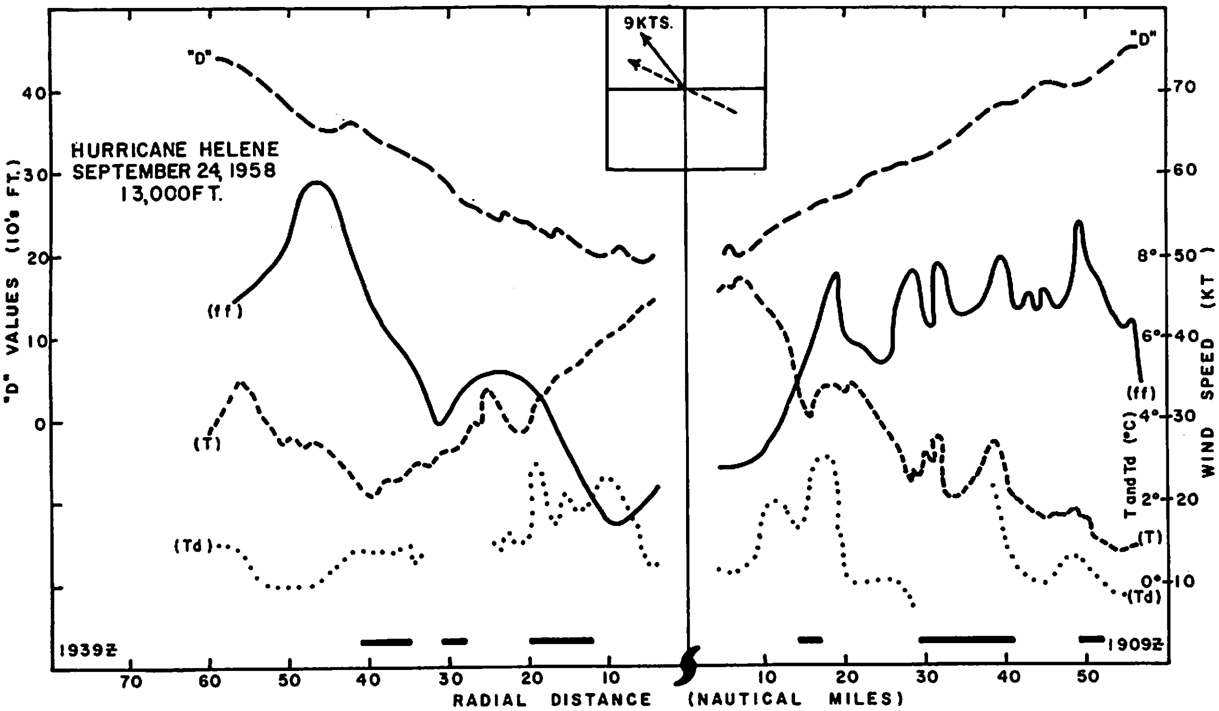

Figure 12. - Data profile at 13,000 ft. (620 mb.), September 24, 1958.

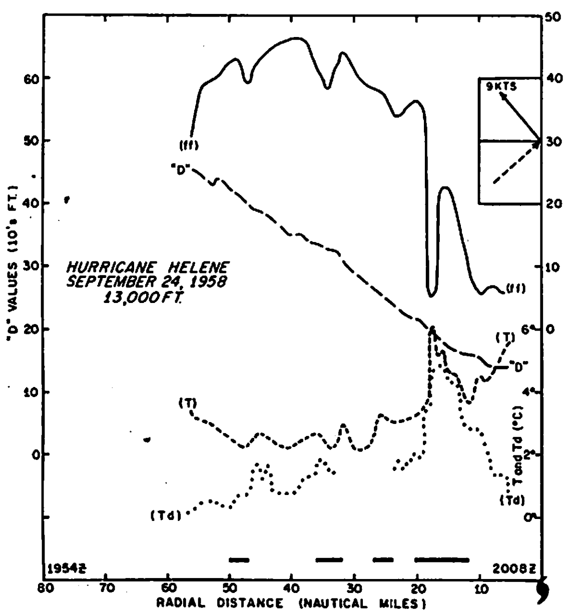

Figure 13. - Data profile at 13,000 ft. (620 mb.), September 24, 1958

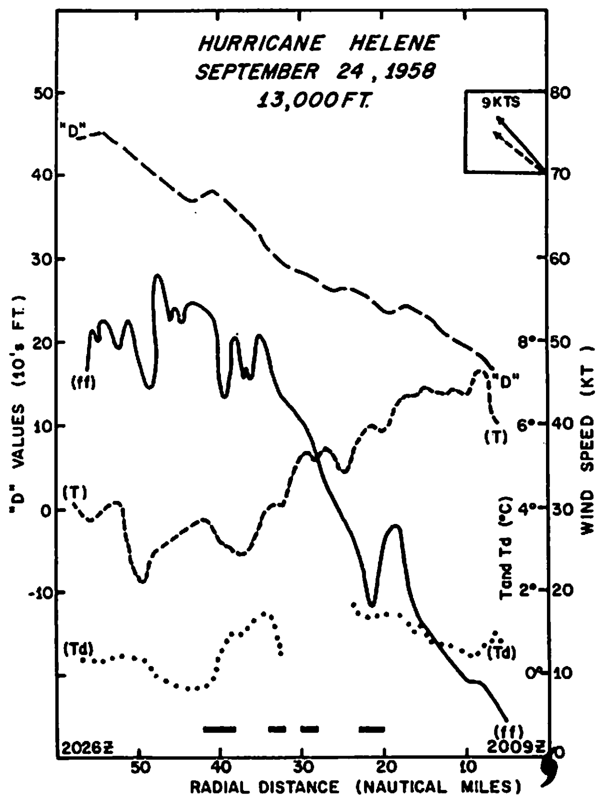

Figure 14. - Data profile at 13,000 ft. (620 mb.), September 24, 1958

In figure 15 the circulation center appears displaced to the southwest of the indicated center. A comment might be made on this point. As has been explained in previous NHRP hurricane reports (Staff NHRP, [15]; Colón, [1]; Hawkins et al., [5]), the so-called radar center of the storm, that is, the geometric center of the inner eye-wall band, was generally used as a first choice for centering of data. Other centering aids used are the position of the maximum winds and the center of the relative wind field. In the case of Helene on September 24 there was not a very clear definition of the eye-wall bands, except perhaps toward the end of the mission, so that centering on the radar eye introduced large uncertainties. Also, with changes in radar configuration such as indicated in figures 6 to 8 it was not certain that the geometric center of the radar field was a conservative point. Therefore, a larger margin of error than is normally the case must be allowed in the centering of the data for September 24. Furthermore, there was in this case a wide zone of the order of 20 to 30 mi. in diameter of variable weak flow. Therefore, the circulation center would not necessarily have to coincide with the radar center and one could also find small eddies with more than one circulation center.

On occasions the changes in wind speed were quite large, to the extent that there was a question as to the accuracy and representativeness of the data. Such examples appear at the 36-mi. radius on the right side, and at the 40-mi. radius on the left side of figure 11. Others are noted in figures 12-14. The ones mentioned in figure 11 and also the one observed at the 17-mi. radius in figure 13 were accompanied by a pronounced warming of about 2°C. They occurred in radar bands and, judging by the temperature variation, were probably associated with vigorous, buoyant, convective cells. A reduction in horizontal wind speed in areas of strong vertical motion would not be unreasonable, but the magnitude of the reduction shown in figures 11 and 13 seems to be too high. The uncertainty is increased by the fact that the experience to date points to numerous instances of malfunction in the Doppler navigation system in areas of heavy precipitation leading to spurious reductions in wind speed. These arise when the Doppler signal transmitted from the aircraft bounces off a heavy precipitation shield below the aircraft, instead of off the surface, as it is supposed to. Under these conditions the ground speed computation is spuriously reduced leading to drastic and unrealistic reductions in wind speed. This effect does not occur all the time, and, unfortunately, its presence can not be easily verified.

In spite of possible inaccuracies arising from this effect, the writer's experience in dealing with data from several hurricanes leads to the belief that the wind oscillations are in general realistic and result from the complex and highly transitory microscale circulations associated with the convective cells embedded in the cloud system of the hurricane. The fact that oscillations tend to be larger and more numerous at middle levels (10,000 to 20,000 ft.) was noted also in the Daisy data (Colón, [1]) and in the study by Gentry [4]. They are probably reflections of stronger vertical motions in the convective cells at those levels.

A thorough investigation of possible errors in the data is not attempted here. Our main purpose in this part of the discussion is to point out the complexity and variability of observations inside the hurricane system,

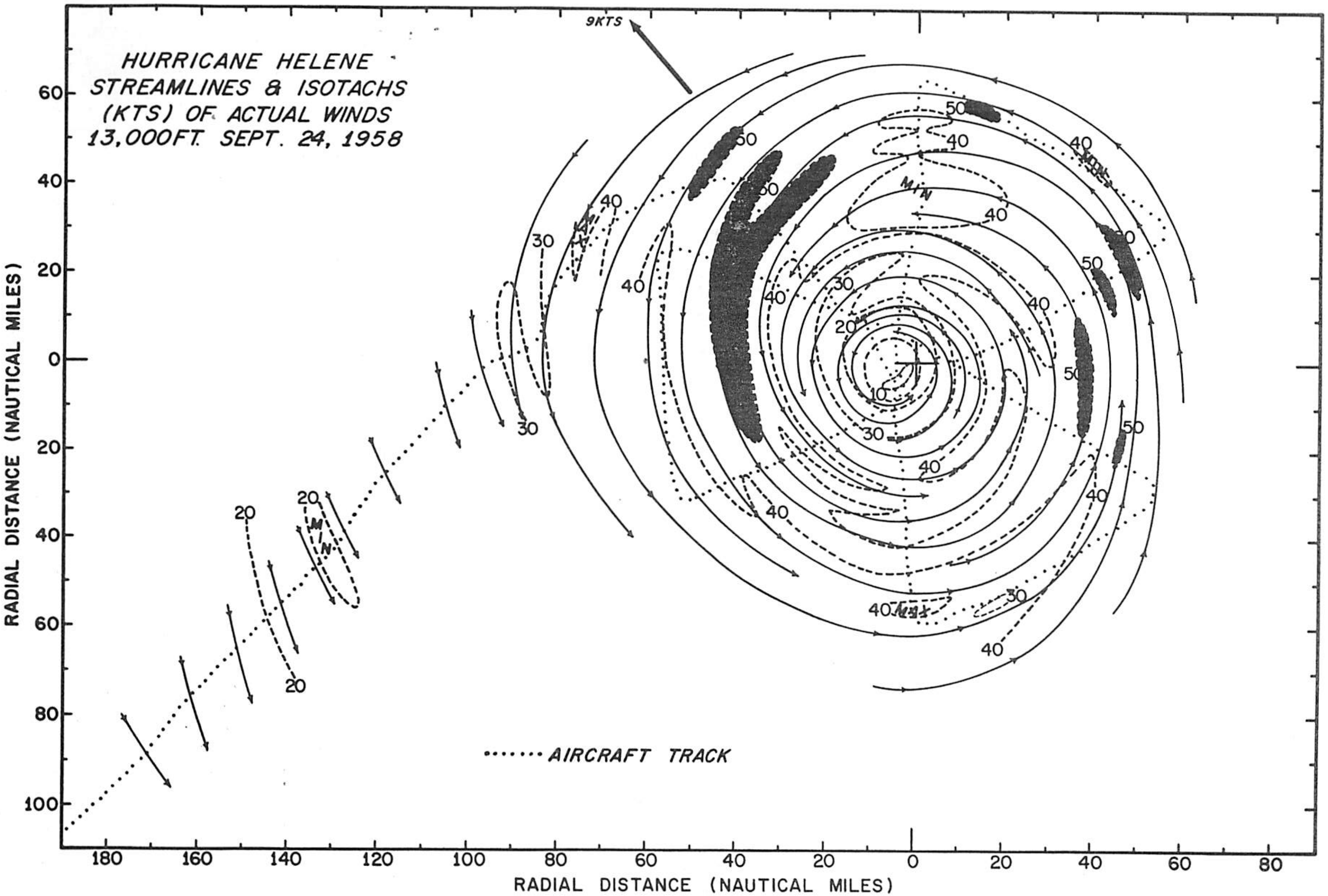

Figure 15. - Wind field at 13,000 ft. (620 mb.), September 24, 1958. Streamlines in solid, isotachs (kt.) in short dashed lines. Dotted path shows the track of the aircraft relative to the storm center. Dark arrow at top indicates the storm motion.

particularly in those parameters that are more directly dependent on convective processes. These features are well documented in spite of shortcomings in some of the measurements. A more thorough discussion of changes in wind, temperature, humidity, and other parameters in hurricane radar bands is given by Gentry [4].

(2) Thermal and moisture fields: The temperature data depicted the typical warm air region in the center. Maximum temperatures in the eye were about 7°C., or 4°C. above the September normal (Jordan [8]). Outside the 30-mi. radius in nearly all directions (see figs. 10 to 14), temperatures were about 3°C. or lower (equal to or somewhat below normal). Warmer air was observed farther out from this cool zone. The data in the western sector, illustrated in figure 16, show temperatures of 4° to 5°C. (1° or 2° above normal) outside the 80-mi. radius. This ring of cool air surrounding the eye core has been observed in all hurricanes investigated by NHRP (Staff NHRP [15], Colón [1], LaSeur and Hawkins [11]). The cool pool extended approximately from the 30 to the 60-mi. radii. At the 9800-ft. level (fig. 9) the data showed clearly that the region of cool air was associated with the region of increased convection and precipitation. At the 13,000-ft. level, since the data do not extend beyond the 60-mi. radius, this connection was not immediately evident, but was probably also true. Probable reasons for this cooling are the evaporation of falling precipitation, reduced radiational heating because of the cloud cover, and adiabatic cooling by expansion of air spiralling inward toward the low pressure center at levels above the warming influence of the sea surface.

The composite horizontal distribution (fig. 16) illustrates the features discussed. The cold ring is observed all around the center. Temperatures less than 1°C., more than 2°C. below normal, are shown in the right semicircle.

Inspection of temperature profiles shows readily the relationship between many of the temperature oscillations and the cloud elements at flight level. Discussion of changes in temperature, humidity, and wind speed in connection with the presence of clouds was included in the Daisy report. The remarks made there are equally applicable to the Helene data. The temperature oscillations and also those of other parameters reflect to a large extent the stage of development of the convective circulations in the cloud cells encountered by the aircraft. Thus, in some cases, one observes increases in temperature in what must be evidently vigorous, buoyant convective cells; in others, the temperature decreases in crossing clouds and radar bands, thus suggesting the presence of precipitating cloud cells in their decaying stage.

The humidity data gave evidence also of the variations in cloudiness at flight level. The dew point invariably decreased inside the 15 or 10-mi. radii, indicating the dry conditions in the subsiding region of the eye. This decrease in humidity coincided with increase in temperature so that the relative humidity decreased to very low values.

(3) Pressure field: Not much can be said about the pressure data. The pressure data gathered by the National Hurricane Research Project during the 1958 season was, of necessity, subjected to various processing steps which smoothed out the minor oscillations in pressure (Hawkins et al. [5]). Thus

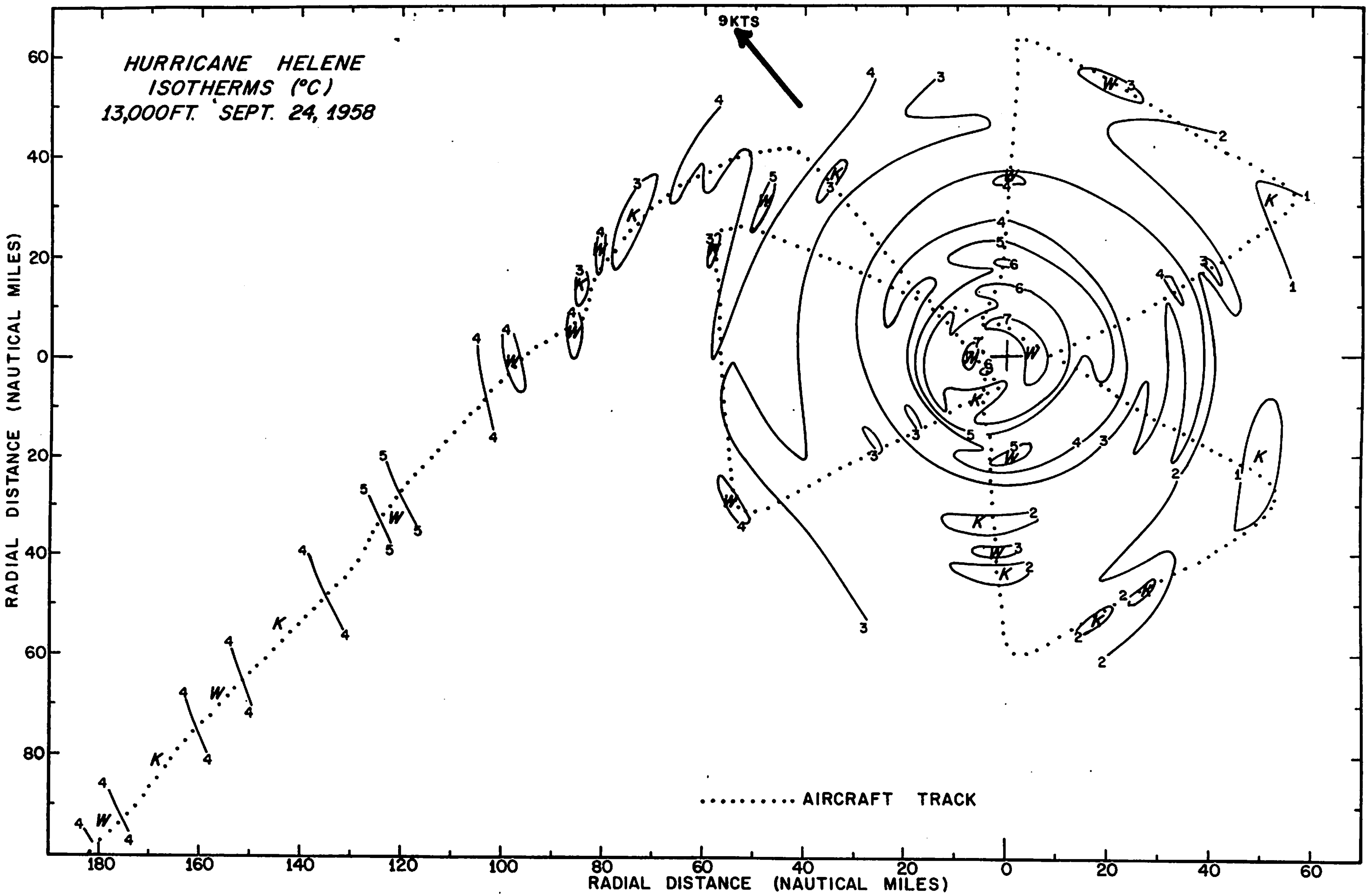

Figure 16. - Temperature field at 13,000 ft. (620 mb.), September 24, 1958. W stands for warmer, K for colder. The track of the aircraft is shown by the dotted path. Dark arrow indicates the storm motion.

we observed only the gross features of the pressure field, characterized by nearly circular concentric isolines with minimum values in the center and maximum horizontal gradients near the eye wall.

4. HURRICANE STRUCTURE, SEPTEMBER 25

Only one flight mission was carried out on September 25. The aircraft approached the storm from the southwest at an altitude of 6400 ft. (800 mb.). It first flew a box around the center (see track in fig. 17) and then penetrated the eye from the southwest. Other penetrations in a somewhat complex and distorted pattern followed, in order to test a radio beacon designed to float in the eye and transmit a signal to aid in tracking. The aircraft track was designed mostly to assist in that experiment.

A. Radar Field

The distribution of radar echoes and bands on September 25 presented some interesting and peculiar features (fig. 17). There were very pronounced changes from the previous day. A large asymmetry was in evidence, with an almost complete void of echoes in the western quadrant. There were two passes through that area and, therefore, ample opportunity for observation. The sector without echoes extended inward into the eye. The eye-wall band had a gap in the western to southwestern sector; the aircraft penetrated from the west with virtually no echoes in the eye wall. Unfortunately, cloud data were not available. It would have been of great interest to see the cloud formations on this penetration.

In the northern, eastern, and southern sectors there were more numerous and prominent bands than on the preceding day. The eye wall itself, except for the gap in the western sector, was very well defined, about 10 mi. thick, with an inner diameter of about 32 mi. and an outer diameter of about 50 mi. (fig. 18). The inner band had an appearance somewhat similar to that shown in figure 8, but with a larger diameter and open to the west-southwest, instead of to the northwest.

The bands shown in figure 17 in the southern and eastern sectors were composited largely from observations taken during the box in the early part of the mission. During the south to north path around this box there was evidence of a rather weak band, just outside the eye wall, at the 32 to 36-mi. radii, and it was included in figure 17. In the later passes through this area this band was not clearly delineated and was not indicated in the radar echoes represented in the cross-sections (fig. 20).

One very interesting feature of the radar field on this day was the various small echoes that seem to have been present inside the eye (fig. 17). They were visible in several radar photographs during more than one penetration into the eye. Unfortunately there were no cloud films available and the properties of the cloud formations that gave rise to these radar echoes remain unknown.

B. Circulation at 6400 ft.

(1) Wind field: The wind field on this day showed more of the characteristic structure of hurricanes. There was a well-defined and distinctive

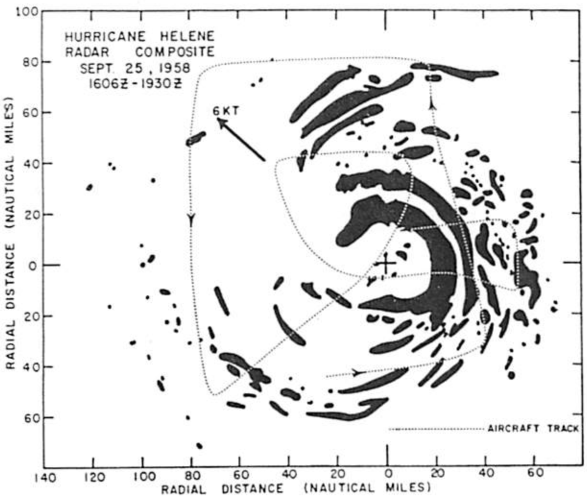

Figure 17. - Composite distribution of radar echoes of hurricane Helene on September 25, 1958.

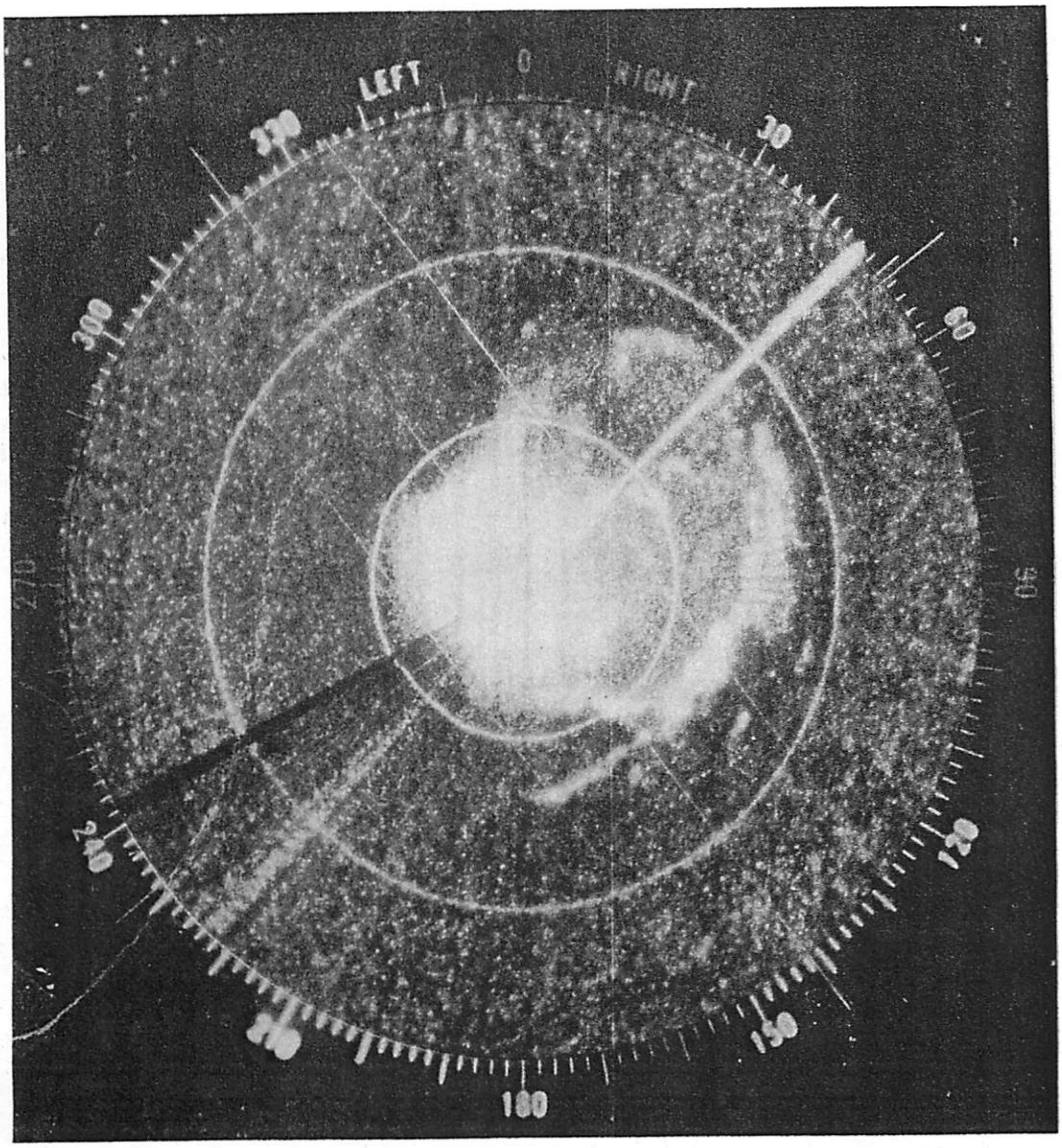

Figure 18. - Photograph of the radar scope taken by the aircraft at an altitude of 6400 ft. (800 mb.) at 1809 GMT on September 25, 1958. Range markers at 20-mi. intervals. The top of the photograph is north.

wind maximum in the periphery of the eye, with stronger flow in the right semicircle. In a penetration into the eye from the southwest (fig. 19) the wind speed increased from about 30 kt. at the 80-mi. radius to a maximum of 49 kt. near the 24-mi. radius, then decreased sharply in the eye. In the right side there was a rapid increase in the eye wall to a maximum of 78 kt. at about the 26-mi. radius, and a slow decrease from there outward. A difference of about 30 kt. in the maximum winds was observed between the left and right sides. The motion of the center was only about 6 kt. (fig. 1) which leaves a net asymmetry of 18 kt. in the magnitude of the relative flow between the two sides of the eye.

The maximum winds were located near the 25-mi. radius on each side of the eye, indicating a wind diameter* of 50 mi. In view of the dimensions of the eye-wall radar band mentioned previously it appears that the maximum winds were located near the outer periphery of the eye-wall band.

The traverse shown in figure 20 was taken from the front-left to the right-rear quadrant in a direction nearly parallel to the motion. It showed a field similar to that observed in figure 19; a distinct speed concentration, with maximum of 75 kt., was observed at the 25-mi. radius on the rear side. In the front side the flow was fairly constant from the 25 to the 60 mi. radii. There was a minor speed peak at the 25-mi. radius. The wind diameter observed on this pass was also around 50 mi.

The profiles obtained later were unfortunately associated with rather sharp and sudden turns in the track and the data could not be represented well in profile form. Some short profiles through the east side followed by a longer one through the south side, on departure, are shown in figures 21 and 22. They show the same structure with weak flow in the eye, rapid increase in the eye wall to a maximum near the 20-25-mi. radius, and gradual reduction outward. One important feature of the wind profiles in hurricane Helene, not found in all hurricanes, was the small value of anticyclonic shear outside the radius of maximum winds (Colón, [1,3])

In the horizontal composite picture (fig. 23) a half-moon-shaped band of winds over 70 kt. bordered the eye in the right semicircle. The streamlines converged gradually into a well-defined circulation center located close to the center of the radar ring. In the left semicircle the flow was generally weaker. Winds of 50 kt. extended to the 70-mi. radius.

(2) Thermal and moisture fields: The temperature data showed the characteristic warmer air in the central core more pronounced on this day than on the previous one. One striking feature of the thermal field on September 25 was the extremely warm pool of air located in the left edge of the eye. This was unmistakably shown in all three passes through the left side (figs. 19, 20, and 22). In the penetration from the southwest (fig. 19) there was a peak of 20°C., 5°C. above normal, located at the 15-mi. radius; figure 20 shows a peak of 21°C., 6°C. above normal in the western edge of the eye at the 22-mi. radius; while figure 22 shows a narrow peak of 10°C. at the 19-mi.

*The term wind diameter is applied to the distance between the radii of maximum of winds on opposite sides of the eye.

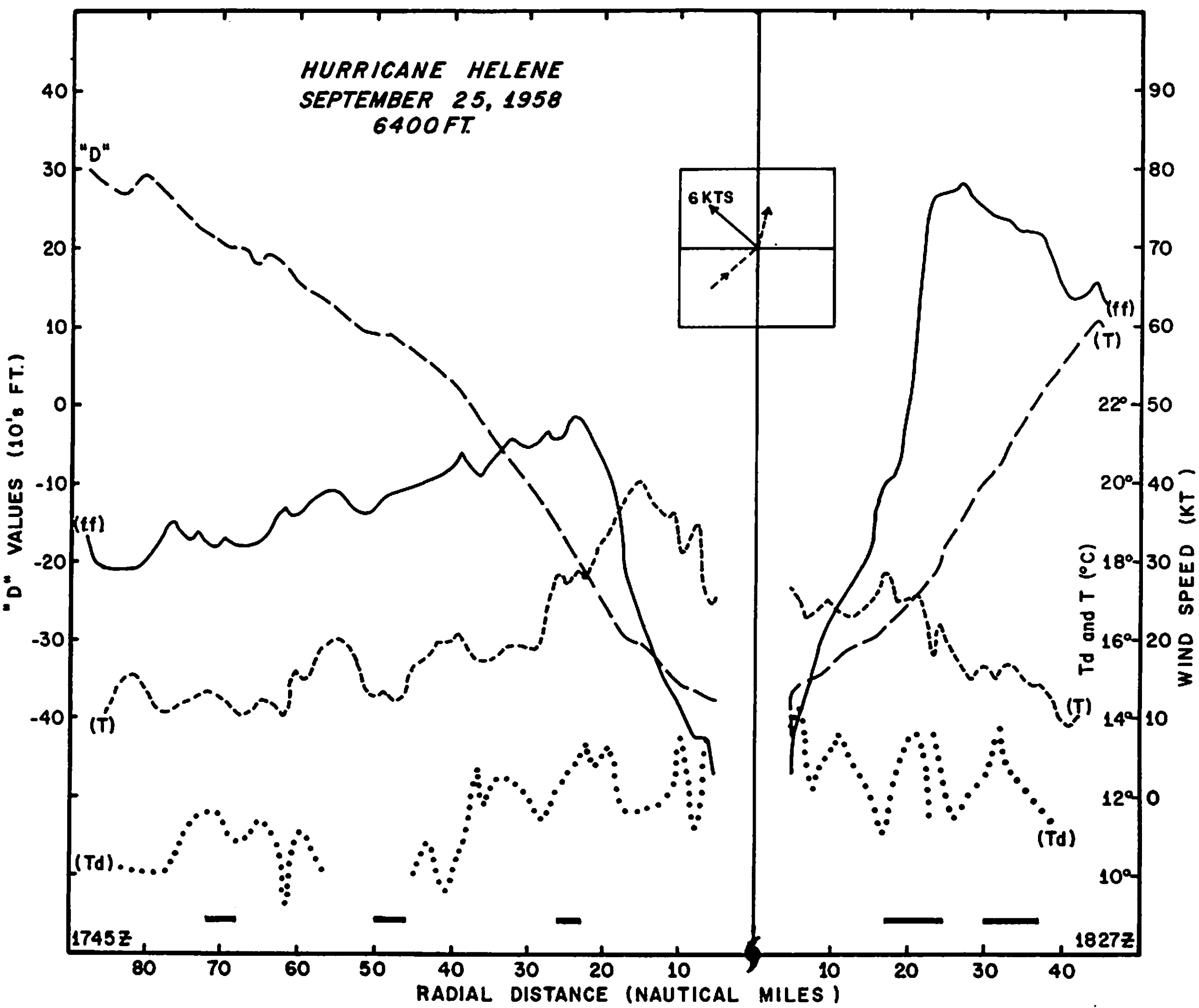

Figure 19. - Data profile at 6400 ft. (800 mb.), September 25, 1958.

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radius. They were all accompanied by a reduction in dew point, which suggests the presence of a concentrated dry, warm current, due probably to subsidence. We may recall, in this respect, that there was also a gap in that sector of the eye-wall radar band, which confirmed the lack of convection in that section of the eye wall. Thus the warm dry pool was apparently associated with a descending current in that sector of the eye wall. This is the first well-documented observation of such phenomena and, interestingly enough, occurred in a growing and intensifying hurricane which in other respects was acquiring a better and more typical organization. This is evidence of complex asymmetries associated with developing hurricanes. One important question that can be raised is whether intensification proceeded in spite of these glaring asymmetries or whether the asymmetries were in any way part of, or a manifestation of, the process of intensification.

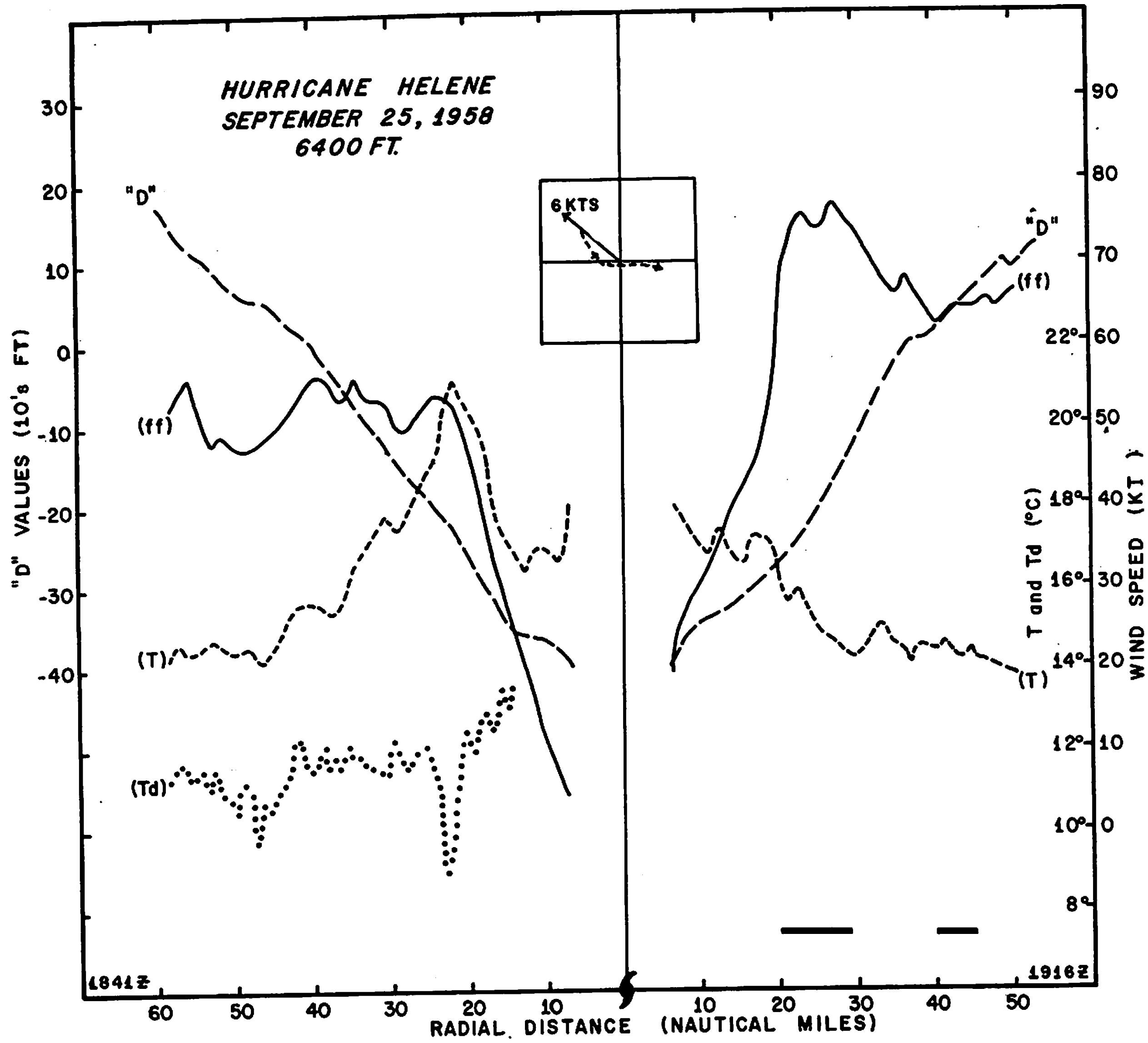

Figure 20. - Data profile at 6400 ft. (800 mb.), September 25, 1958.

Aside from this feature the thermal field showed a warm region in the central core, about 30 mi. in radius, surrounded by a region in which the temperatures were nearly constant or slowly decreasing outward. In figure 19 there is a slight decrease from the 30 to the 60-mi. radii; outside, temperatures are nearly constant at about 14.5°C. In figure 20, temperatures are constant at about 14.5°C. (slightly below normal) outside the 30-mi. radius on the right and the 45-mi. radius on the left.

The horizontal composite in figure 24 shows clearly the warm sector in the left edge of the eye. The warmest temperatures recorded at this altitude were in that area. Above normal values prevailed inside the 30-mi. radius, generally below or equal to normal outside.

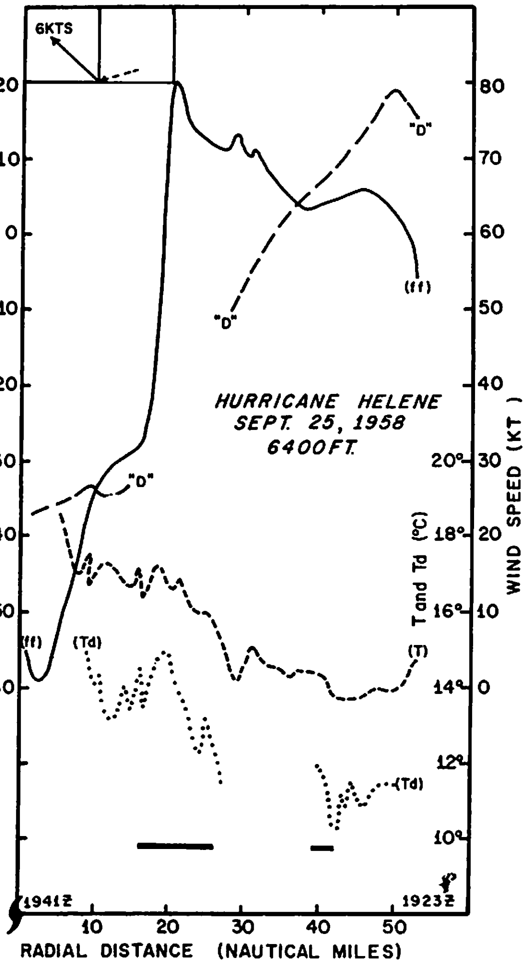

Figure 21. - Data profile at 6400 ft. (800 mb.), September 25, 1958.

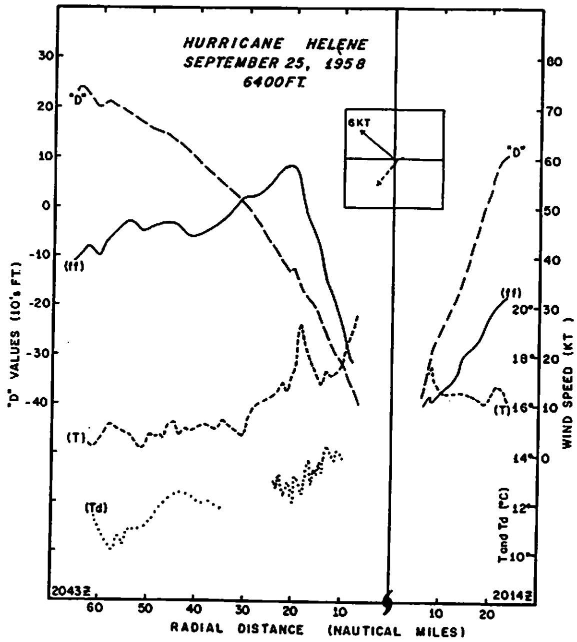

Figure 22. - Data profile at 6400 ft. (800 mb.), September 25, 1958.

The dew point data were missing in some of the crossings of the eye, but what were available did not show much evidence of reduction in moisture content in the eye, as was the case on the previous day. However, the data on September 24 were obtained at a higher level, where the subsiding currents were more likely to prevail. A discussion of the time changes in moisture and temperature in the eye of Helene is contained in a separate report (Colón, [2]).

(3) Pressure field: The minimum D-value recorded at the 6400-ft. level on this day was about -400 ft., which indicates a surface central pressure of around 987 mb. Horizontal pressure charts have not been included since they show only the typical concentric and nearly circular isolines. Some discussion of time changes in the pressure profiles is included in a later section.

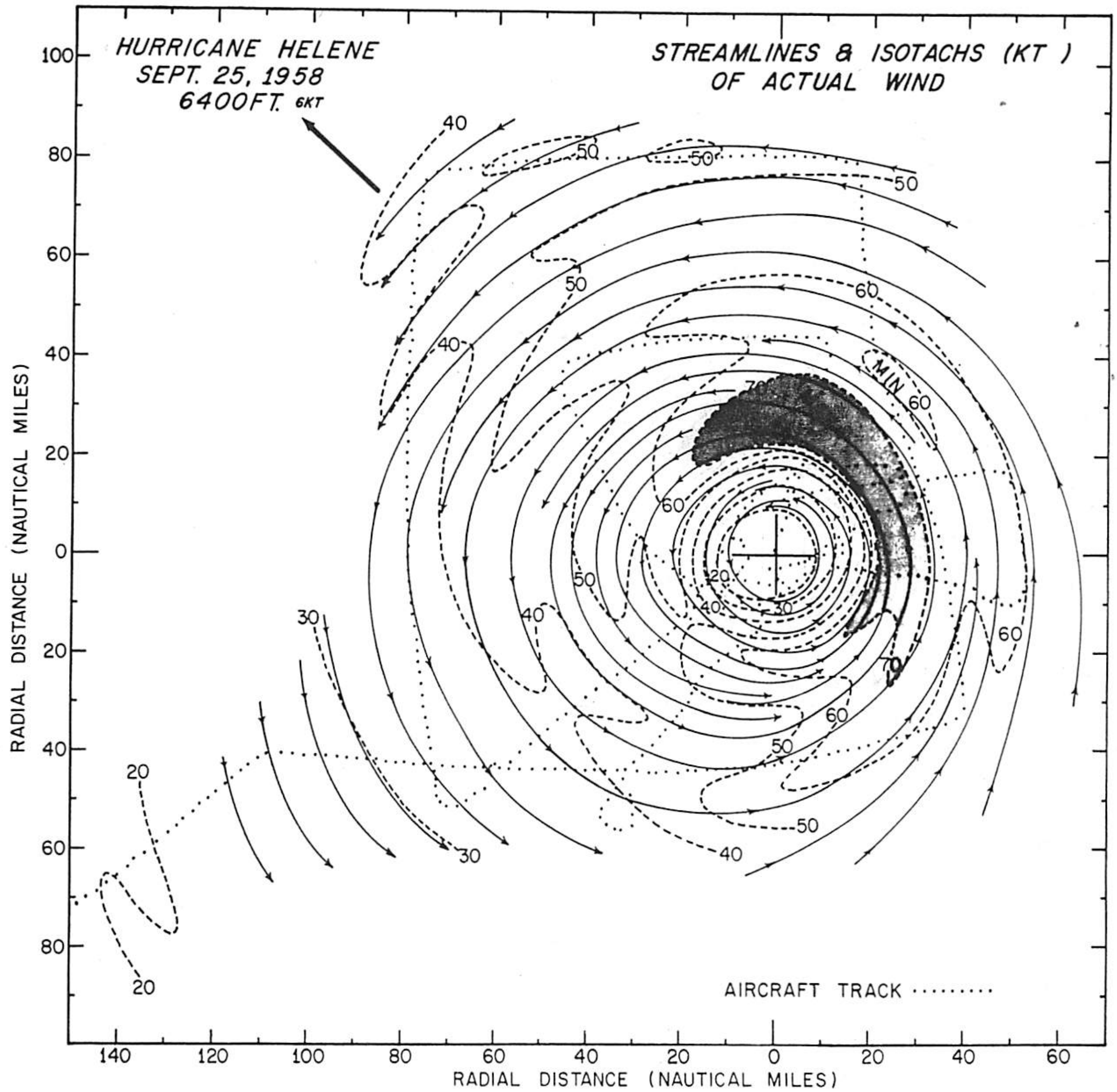

Figure 23. - Wind field at the 6400-ft. level (800 mb.) in hurricane Helene, September 25, 1958.

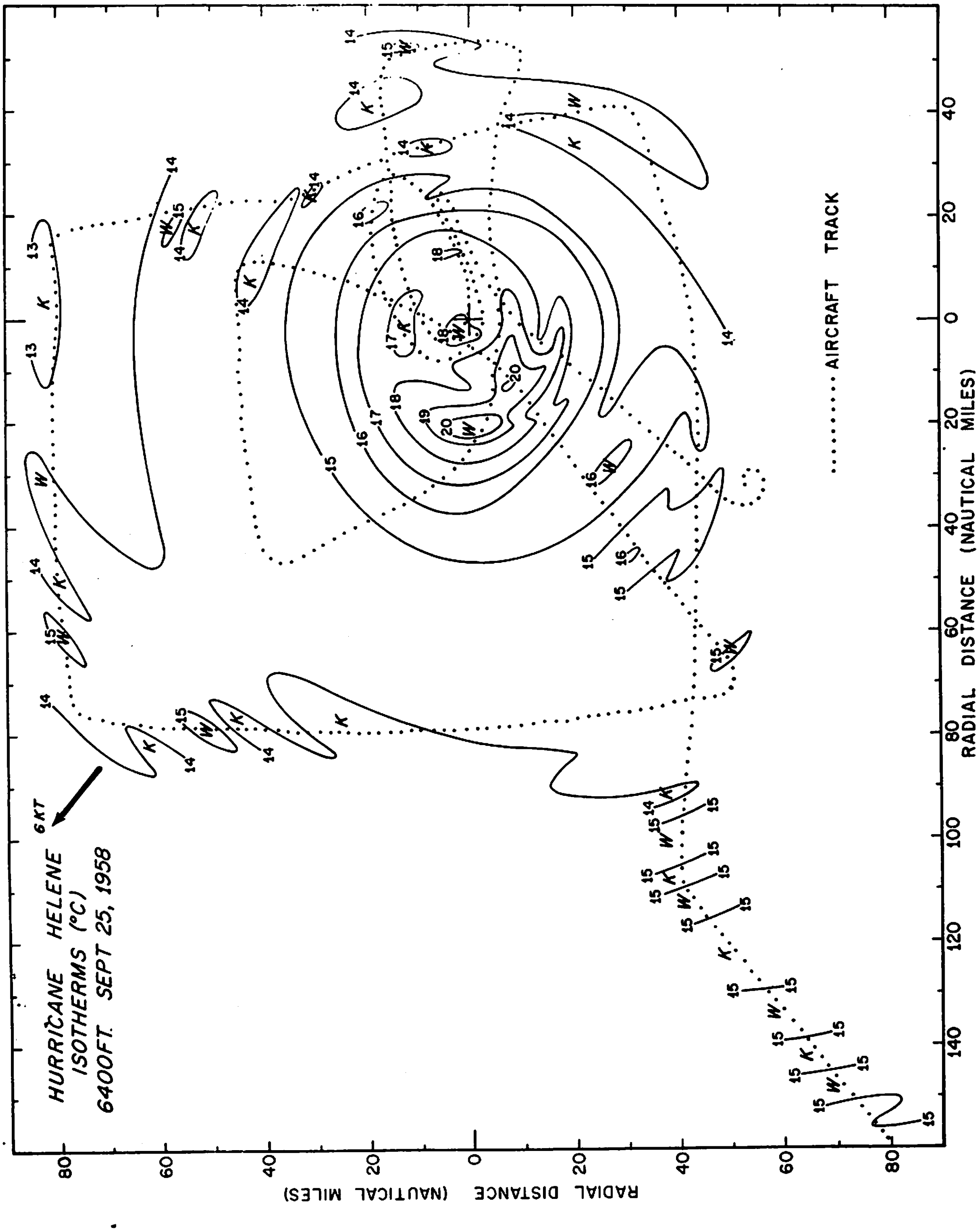

Figure 24. - Temperature field at the 6400-ft. level (800 mb.) in hurricane Helene, September 25, 1958.

5. HURRICANE STRUCTURE, SEPTEMBER 26

At the time of the research missions on the afternoon of September 26, hurricane Helene had almost reached its maximum intensity (see fig. 5). A minimum central pressure of 933 mb. was measured by dropsonde by a military reconnaissance aircraft on the morning of September 27. The D-values measured by the research aircraft during the missions on September 26 indicated central pressures of around 940 to 945 mb. Unfortunately, the tracks flown by the low-level aircraft (figs. 37, 46) were such that large regions of the circulation were not investigated. Nevertheless, enough information was obtained to give a rather complete view of the structure of the hurricane. A successful investigation was made by the jet aircraft at an altitude of 35,000 ft. which revealed important and interesting features of the upper-level circulations in hurricanes.

A. Radar Field

The best radar coverage was obtained by the jet aircraft. As explained in previous reports the radar antenna on the research aircraft are oriented slightly below flight level, so that an aircraft at a high altitude gets a better-integrated view of the precipitation bands. A composite of the echoes observed by the jet plane in the period 1600 to 1900 GMT, September 26, is illustrated in figure 25; a photograph of the eye-wall band is shown in figure 26.

The most striking feature, as compared to that of the previous day, is the greater symmetry in the distribution. Important bands were observed on all sides; the void sector in the left semicircle that existed 24 hr. before was now filled with echoes. In fact the distribution in figure 25 showed more echoes to the west and southwest than on the eastern semicircle.

The photograph of the eye wall (fig. 26) shows one of the most perfect and distinctive radar eye-rings that has been observed in a tropical hurricane. It had an outer diameter of about 36 mi. and an inner diameter of 18 mi., so that the width of the band was about 9 mi. There was in some individual pictures, noticeable in figure 26, a tendency for weaker echoes in the western part of the eye, somewhat similar to the previous day. One should be careful in comparing the appearance of the eye wall band on this day with that of the previous day (fig. 18) because the data were obtained from different altitudes, but there seems to be no question that the diameter was smaller on the 26th. Also, the echoes inside the eye observed on September 25 were not present on the 26th.

There were surprisingly few bands in the eastern sector (fig. 25). Outside the eye-wall band there was a band at about the 40 to 50-mi. radius. Farther out there was concentration of isolated echoes near the 70 and 120-mi. radii. On the whole there were more echoes in the left semicircle. Very prominent bands were observed to the northwest, west, and south.

B. Hurricane Structure at Low and Middle Levels

The tracks followed by the low-level planes on this day were such that none of them by itself gave a complete picture of the horizontal distribution,

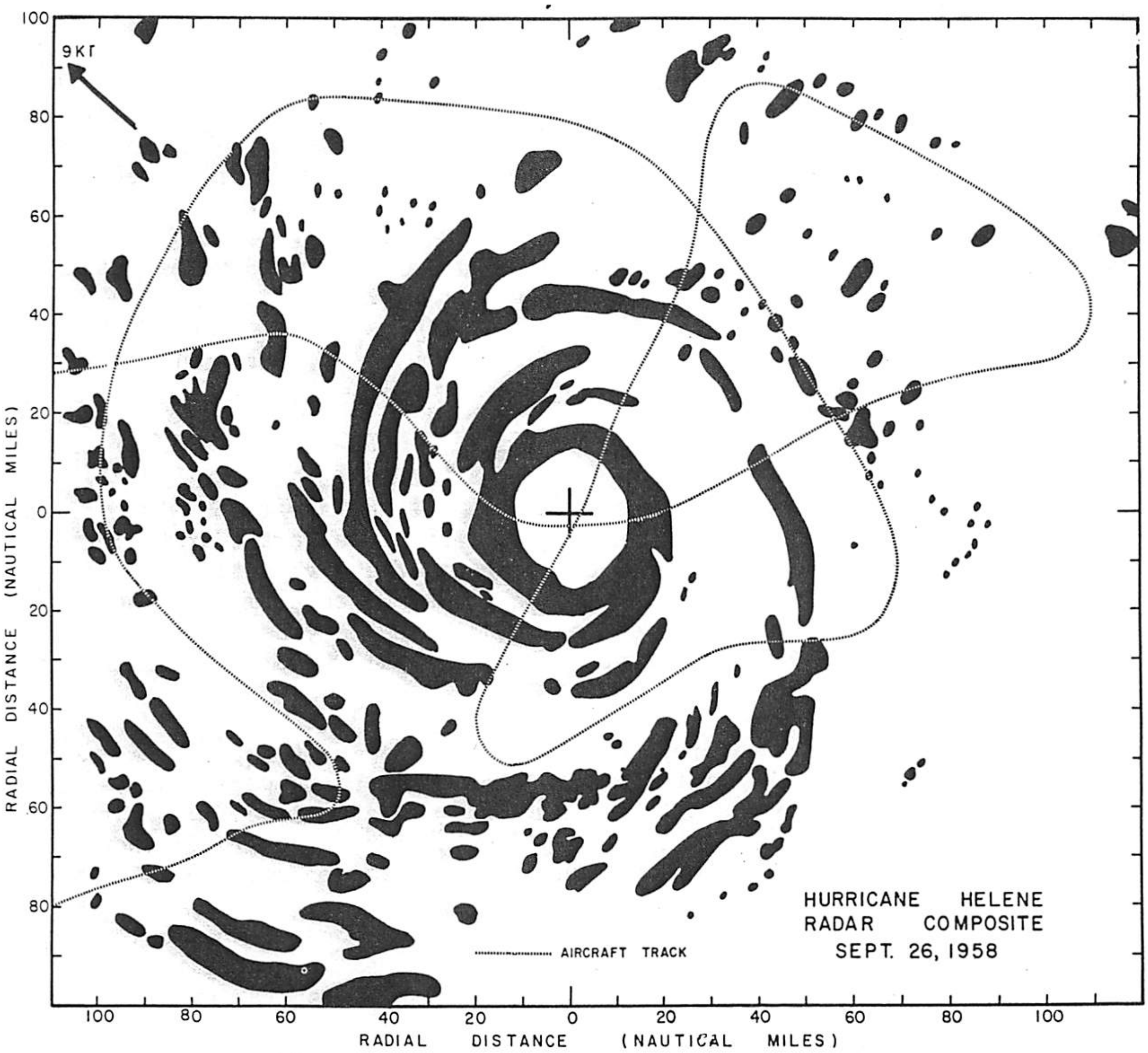

Figure 25. - Composite distribution of radar echoes of hurricane Helene, September 26, 1958. Radar data recorded by jet aircraft from an altitude of about 34,000 ft. (250 mb.).

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but the observations of both planes could be combined to give a fairly good picture of the properties in the levels from 6000 to 15,000 ft. One of the planes flew into the hurricane at 6400 ft. but avoided entirely the high energy core inside the 25-mi. radius. Passes were made from the 25 to 80-mi. radii in all quadrants. The second plane penetrated in a radial pass directly into the eye at an altitude of 9800 ft. (700 mb.). It then ascended in the eye to 15,600 ft., where a thorough investigation was made of the northern and western quadrants. Some limited data were obtained to the southwest, but none in the south to southeast semicircle. The information obtained at this level gave an excellent view of the properties of the high energy core of an intense hurricane.

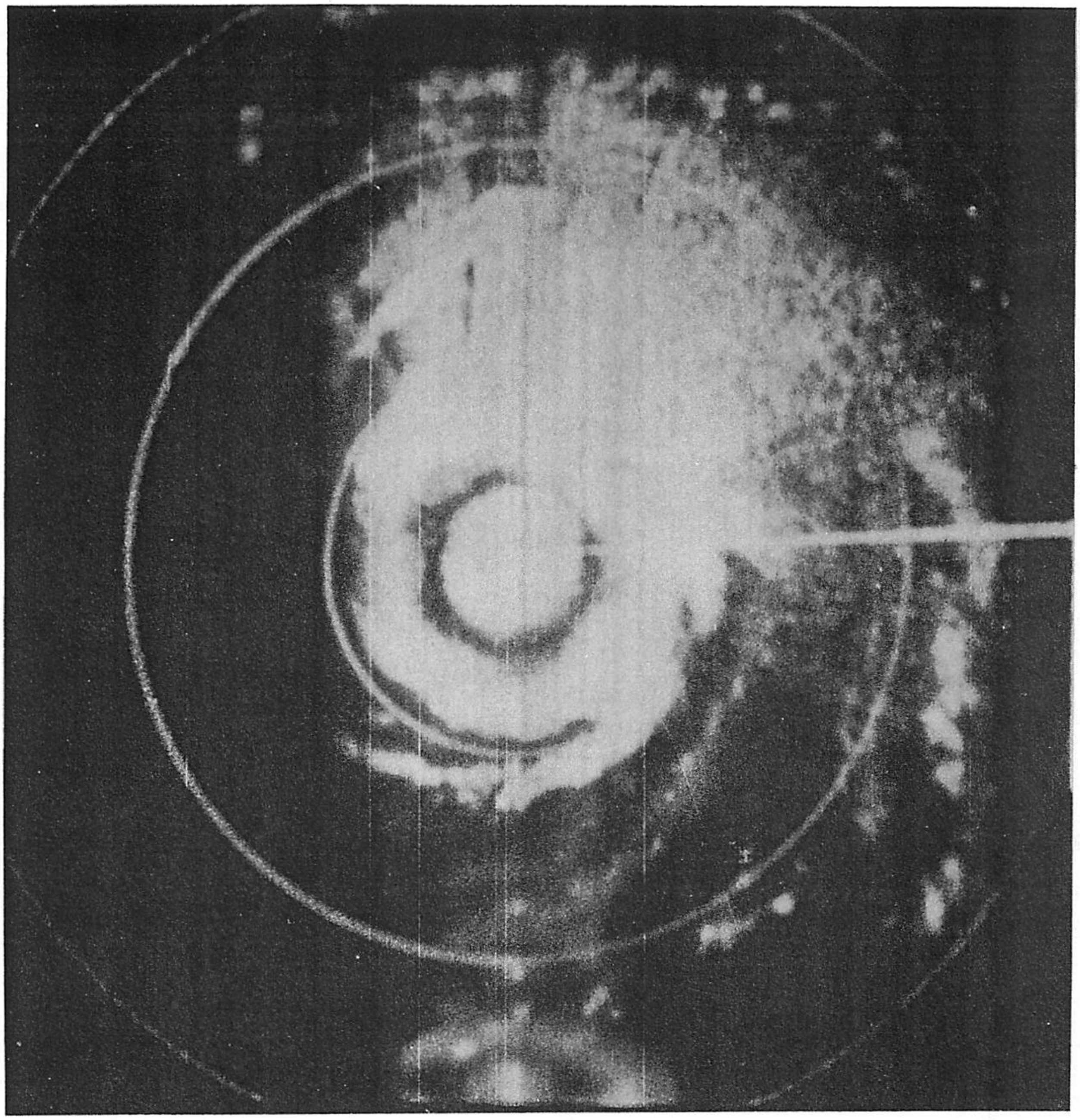

Figure 26. - Photograph of the radar scope showing the eye system of hurricane Helene at 1729 GMT, September 26, 1958, taken at an altitude of 34,000 ft.

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(2) Wind field: The data profiles for the lower levels are shown in figures 27 to 36. Although some of the tracks deviated from the radial direction, plotting of the data in profile form gave a realistic picture of the radial variations. At the 6400-ft. level the wind speeds were generally constant with radius in the region outside the 40 to 50-mi. radius. Inward from this position there was a rather sharp increase in speed toward the maximum at the periphery of the eye, which was not measured at this level (see

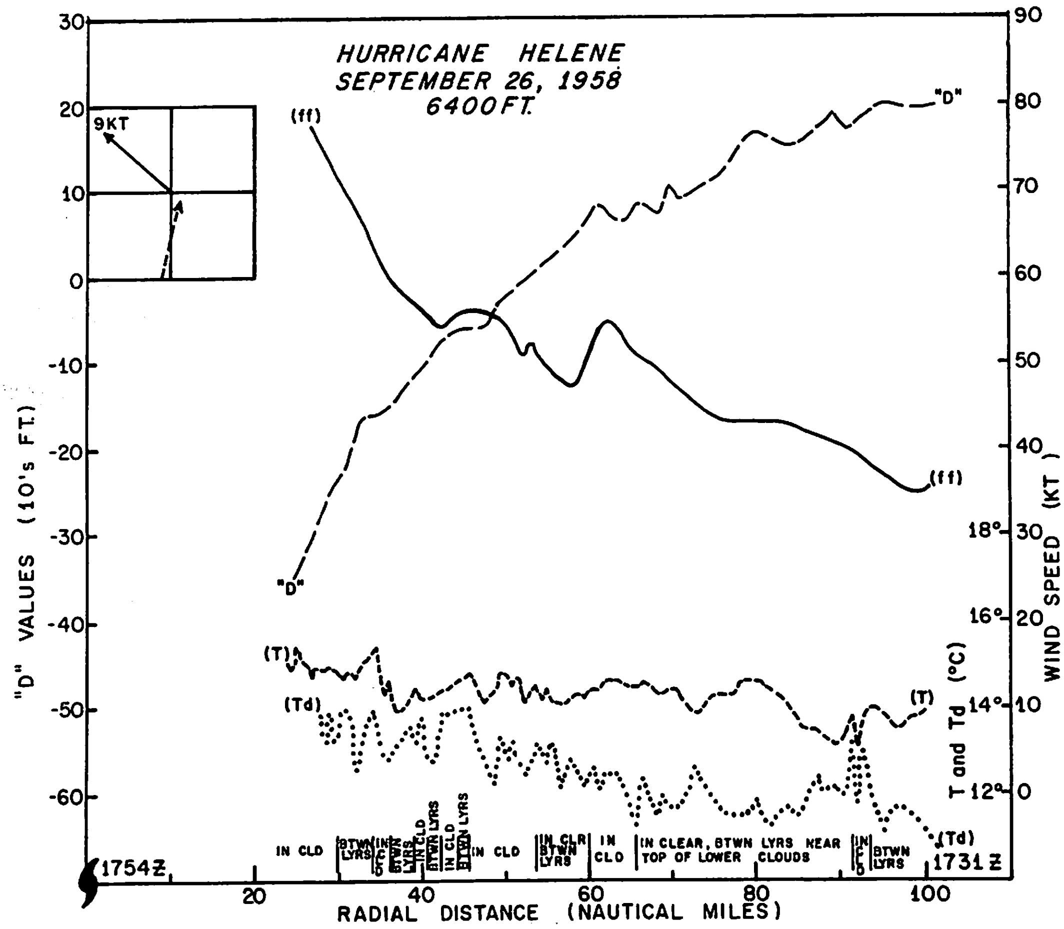

Figure 27. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

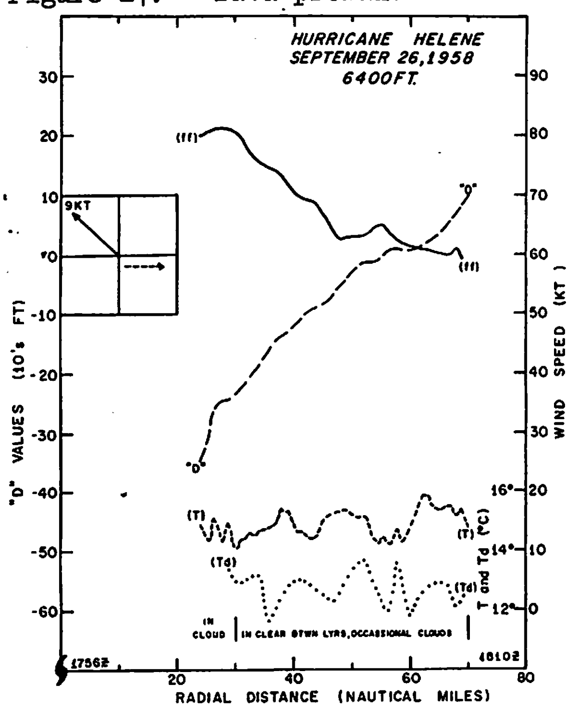

Figure 28. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

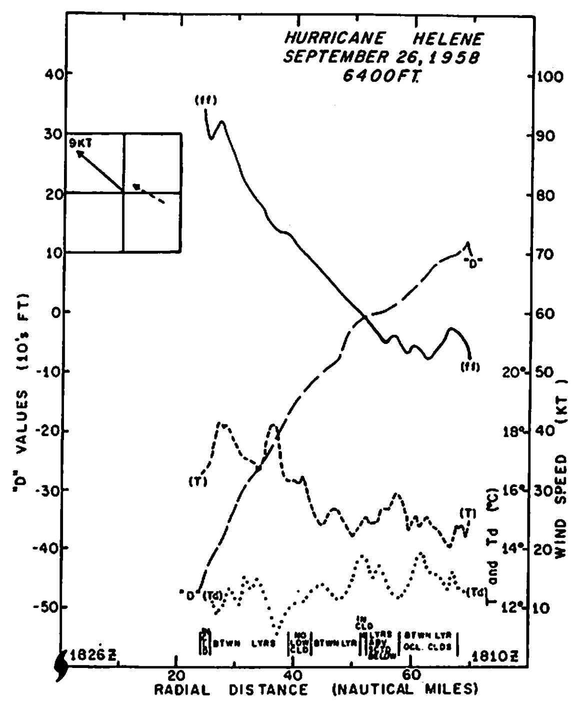

Figure 29. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

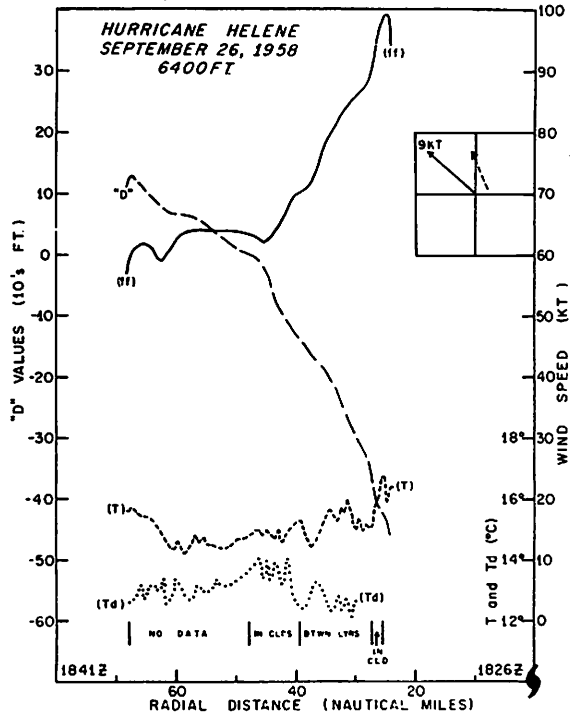

Figure 30. - Data profile at 6409 ft. (800 mb.), September 26, 1958.

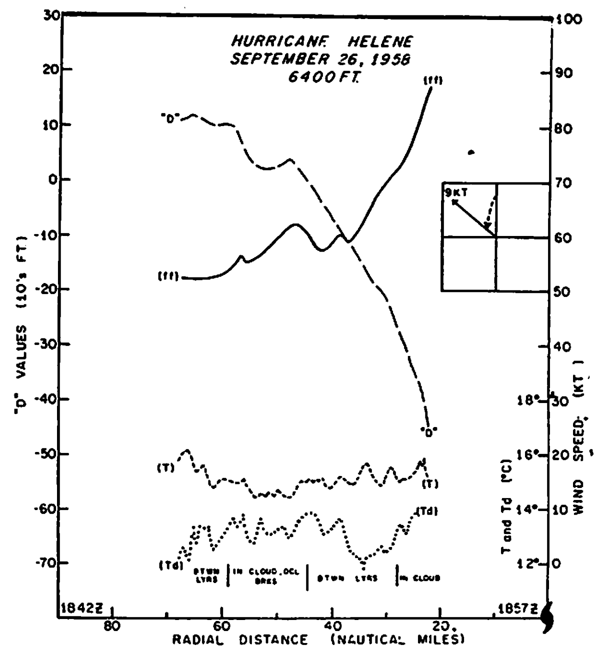

Figure 31. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

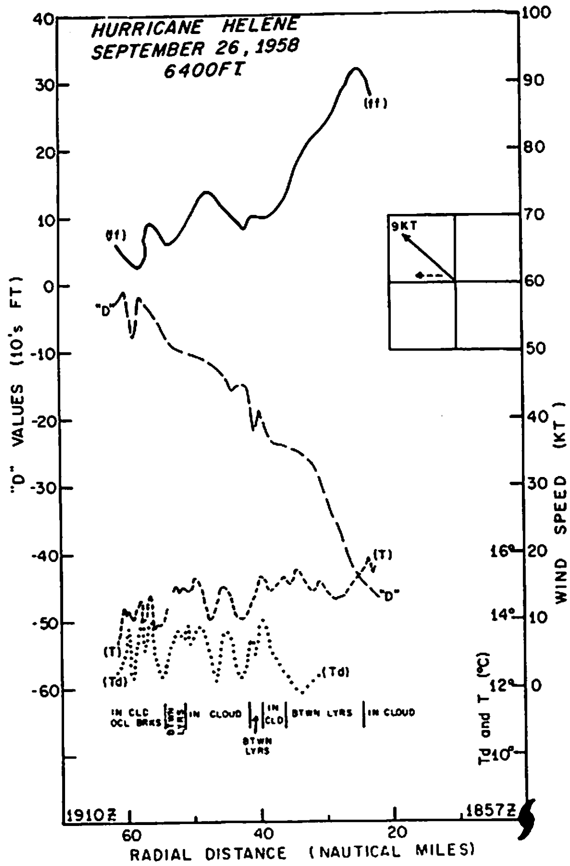

Figure 32. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

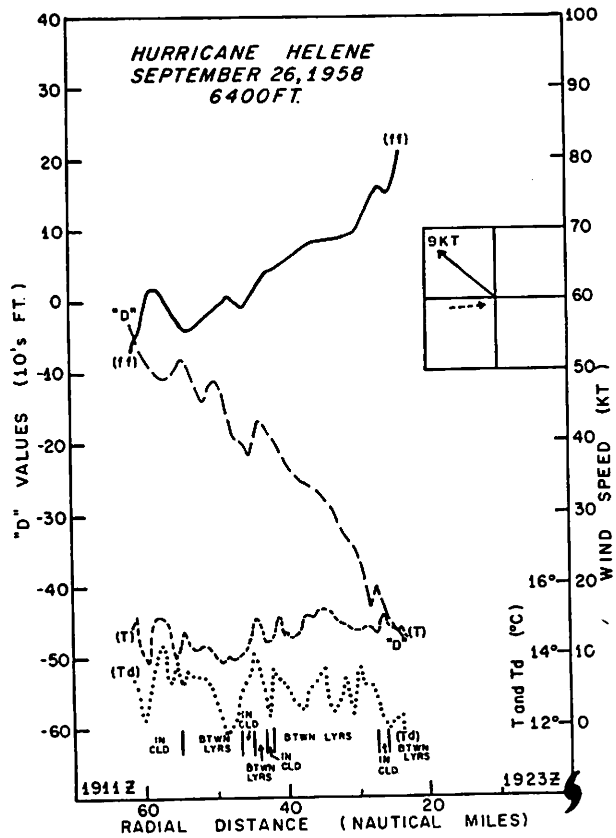

Figure 33. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

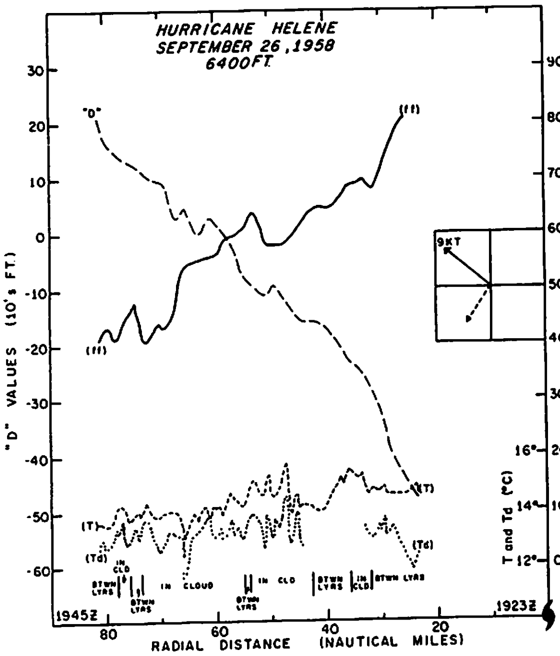

Figure 34. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

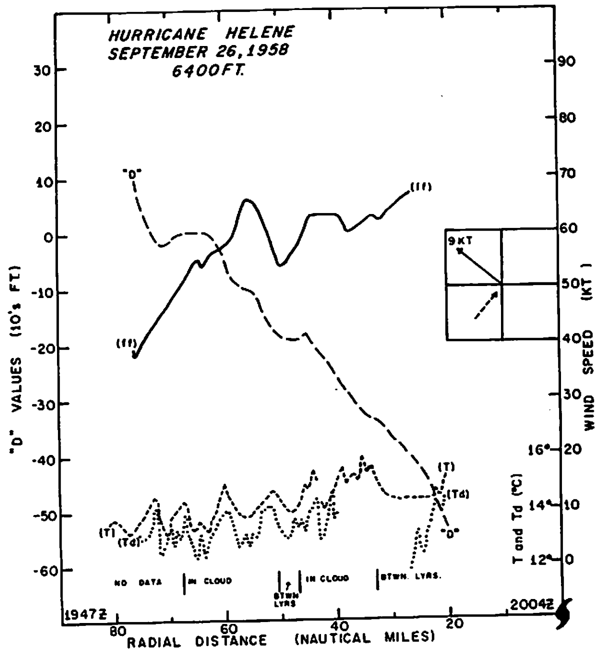

Figure 35. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

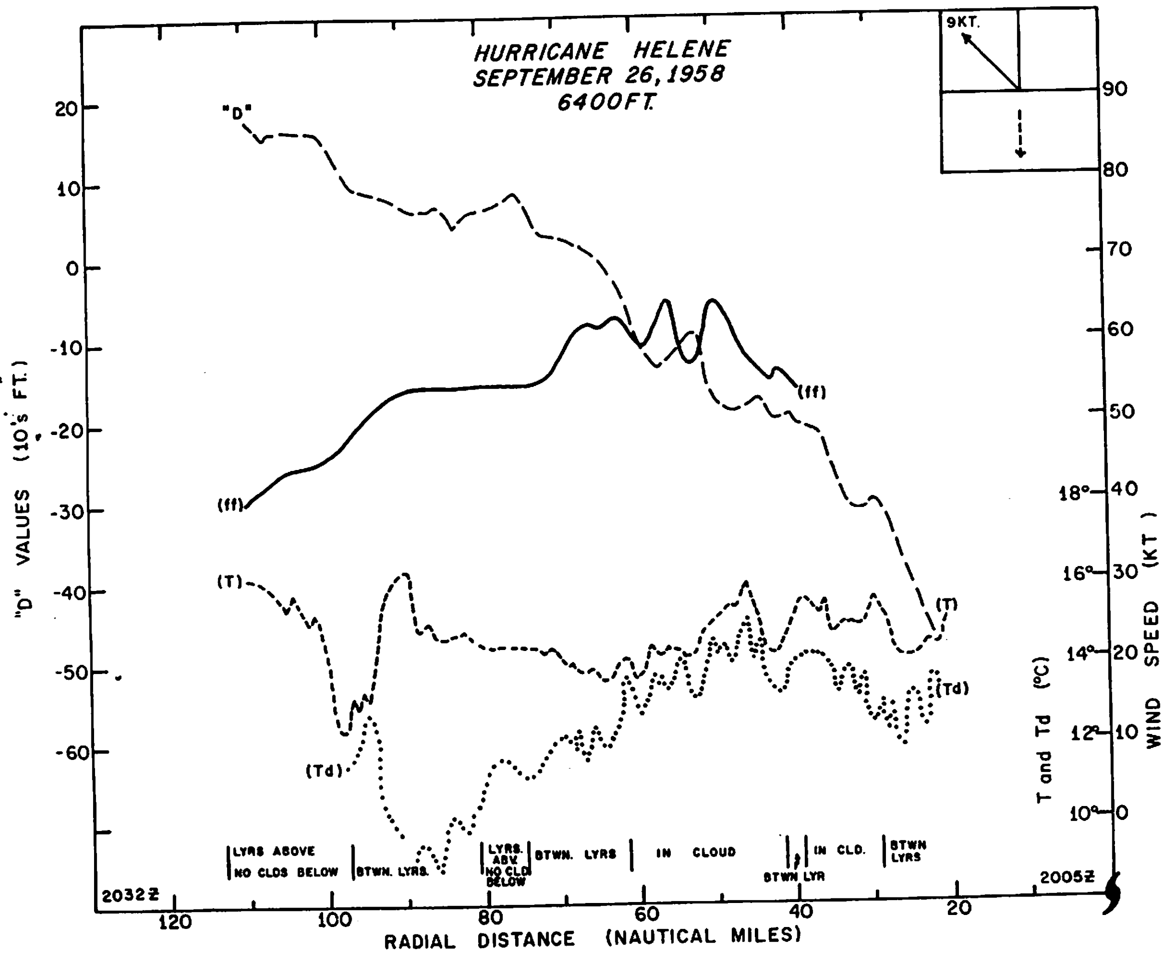

Figure 36. - Data profile at 6400 ft. (800 mb.), September 26, 1958.

figs. 27, 29, 30, 31). The data at the 15,600-ft. level (figs. 40-45) indicated a zone of maximum winds extending generally from the 15 to the 20-mi. radii. In one case (fig. 42), a distinct single peak was recorded at the 16-mi. radius. The maximum speed measured at 15,600 ft. on the right side was 120 kt. At 6400 ft. the maximum was probably higher, and located at about the same radial position. As indicated by previous studies of hurricanes reconnoitered by the National Hurricane Research Project, the position of the radius of maximum winds shows little or no change with altitude and not much reduction in the magnitude of the maximum winds in the levels up to 20,000 ft.

At the upper levels outside the 60-mi. radius the wind speed was relatively constant with radius. At the 700-mb. level (fig. 39), speeds of 40 to 50 kt. were recorded from the 110-mi. to the 60-mi. radii. From this point inward there was a steady increase to a maximum of 100 kt. at the 20-mi. radius. Another peak of close to 100 kt. was observed at the 14-mi. radius. As mentioned previously, a similar type of structure at the zone of maximum winds, as well as a tendency for nearly constant speed with radius outside the 60-70 mi. radius was observed at the 15,600-ft. level (fig. 45).

Inspection of the profiles revealed a greater degree of minor-scale variations in wind speed at middle levels. This property was also noted on September 24 and was also observed in the Daisy data (Colón [1]). As was discussed previously, many of the sudden variations in wind speed occurred in association with precipitation bands and the greater amount of irregularities at the middle levels might be due to the presence of stronger and more variable vertical currents in the middle and upper regions of the convection cells. Some examples of significant wind variations associated with radar bands are indicated at the 99-mi. radius where a drop of over 15 kt. in speed coincided with penetration into a radar mass. A sudden and short-lived change is also observed at the 85-mi. radius.

(2) Thermal and moisture fields:. The temperature data at the 6400-ft. level did not reveal the characteristic warm region of the eye because of the data void in the center. In fact, even though data were available to within only 25 mi. from the center, it was not readily evident that one was dealing with an intense hurricane. Most of the profiles showed relatively constant temperatures with radius. Only in figures 27 and 29 is there evidence of a temperature increase inward - in figure 27 an increase from 13°-14°C. near the 100-mi. radius to 15°C. at the 25-mi. radius. The normal temperature for the level is 15°C. so that all the values outside the 25-mi. radius were below normal. In the profile on the east side shown in figure 29, temperatures of about 18°C., 3° above normal, were recorded near the 30-mi. radius, the warmest region investigated at this level. A slight decrease in dew point was also recorded, and, consequently, decrease in relative humidity. A decrease in dew point in the inner regions was also noted in some of the other profiles at this level.

The profile in figure 36 showed data up to the 110-mi. radius and was taken, on departure, in an azimuthal direction not too different from that of the profile in figure 27 (see the track in fig. 37). Some idea of time variations could be obtained by study of these two profiles. The temperature and humidity observations in the later pass showed some interesting oscillations, quite different from those observed earlier. From the 20 to the 50-mi. radii there were oscillations of 1° or 2°C. in range with mean values around 15°C.,

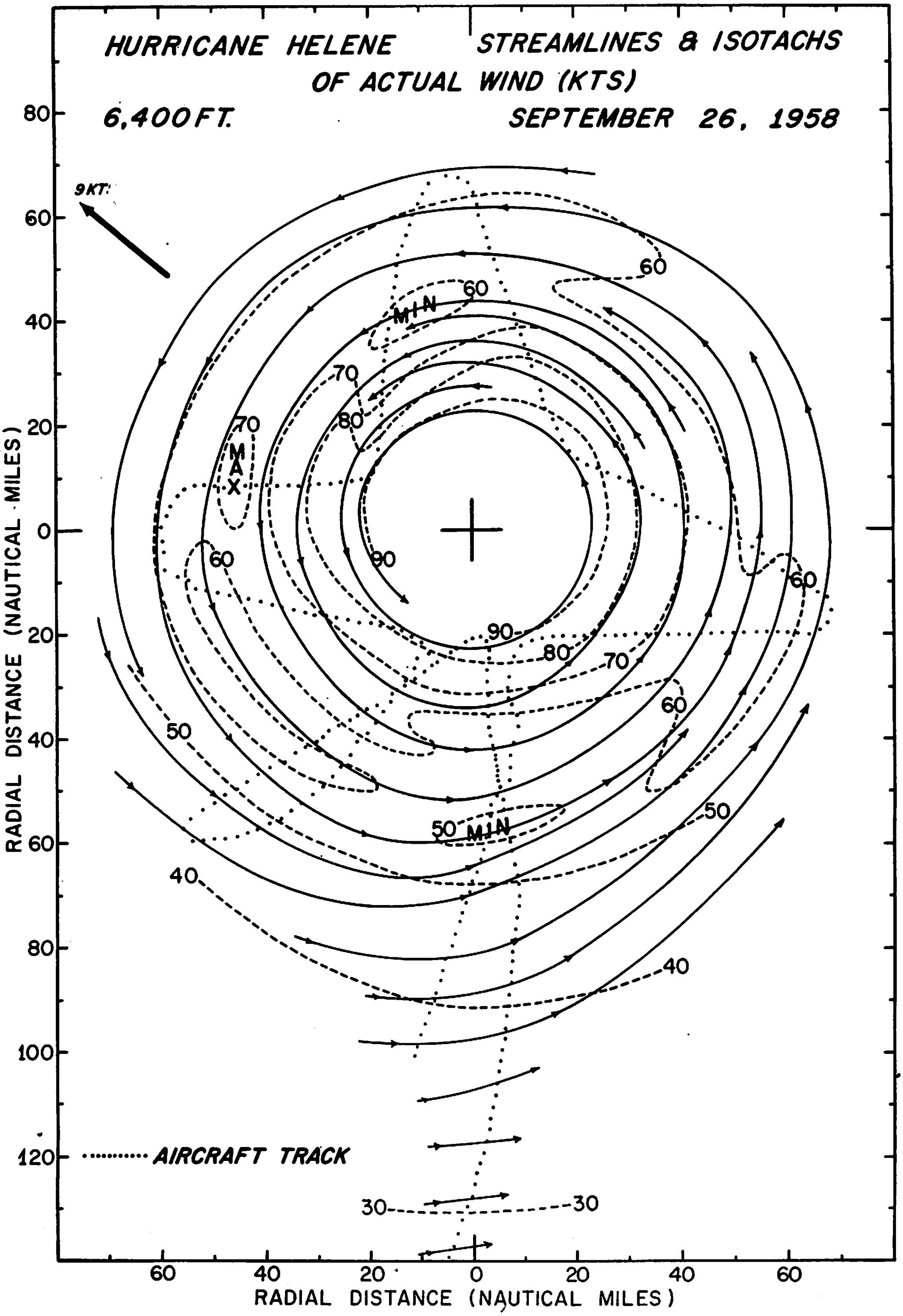

Figure 37. - Wind field at 6400 ft. (800 mb.), hurricane Helene, September 26, 1958.

or near normal. Through most of this section the aircraft was in clouds and the dew point temperature spread was low (relative humidity was high). From the 50 to the 88-mi. radii the temperature increased from about 14°C. to 15°C. The dew point decreased sharply, as the aircraft remained in the clear through most of that sector. From the 88 to the 100-mi. radii, there was a very pronounced variation in temperature. The temperature first increased rapidly to a peak of 16.3°C. at the 90-mi. radius, then decreased to a minimum of 12.3°, a 4° drop, at the 98-mi. radius. This was followed by an increase, first rapid, then more gradual, to a value of 16°C. at the 108-mi. radius. There were also variations in dew point, which at first appeared to be out of phase with the temperature. Changes of this magnitude were not present in the earlier data shown in figure 27. There were, instead, some rather small oscillations in temperature and dew point, in phase, when the aircraft went through a cloud near the 92-mi. radius. The oscillation shown in figure 36 has added interest in view of the cloud data. The cloud remarks in figure 36 indicate that the aircraft was essentially in the clear between layers from the 81 to about the 92-mi. radii. From there on the aircraft went in and out of clouds rapidly; however, none of the clouds was large enough so that, within the accuracy with which these measurements can be made, it could be said that the aircraft was in clouds. At the 97-mi. radius (the point of minimum temperature) this diffuse cloud area terminated abruptly and from there on the aircraft was in the clear, with layers above and no clouds below. Unfortunately, there were no radar data to verify the presence of precipitation bands.

The temperature and humidity traces contain numerous oscillations of smaller amplitude and range, some in phase, others out of phase, that can be associated with the cloud field at flight level. These can be studied in the profiles.

The horizontal distribution at the lower level (fig. 38) reflected many of these minor-scale variations in the thermal field. The isotherms in the peripheral areas showed a large number of small warm and cool pools; the cool areas were mostly on the order of 1° or 2° below normal. In the central core more smooth and circular isotherms were indicated. A more complete view of the thermal field in the central core was shown by the data at the upper level (figs. 39 and 47).

The data gathered at the 700-mb. and 500-mb. levels, although it left important regions of the circulation uninvestigated, revealed one of the most interesting and striking views ever obtained of the thermal properties of an intense hurricane. As discussed previously, at the 800-mb. level, data recorded only 25 mi. from the center of the eye failed to reveal the characteristic warm core normally associated with hurricanes. The reason for this is evident in figures 39 to 45 which show the intense warm region limited to the eye and its immediate vicinity. In the penetration into the center at the 700-mb. level (fig. 39) oscillations of about 2°C. in range were recorded from the 110-mi. radius to the 30-mi. radius, but the gross thermal field indicated essentially constant temperatures with a mean value of about 9°C., close to normal for that level. At the 30-mi. radius a significant change in gradient was noted and from that point inward there was a steady and pronounced temperature increase to a value of 20°C., about 11°C. above normal, recorded at the 4-mi. radius. With minor variations this same picture is duplicated in all profiles at the 560-mb. level. The data in figure 40 show the tempera-

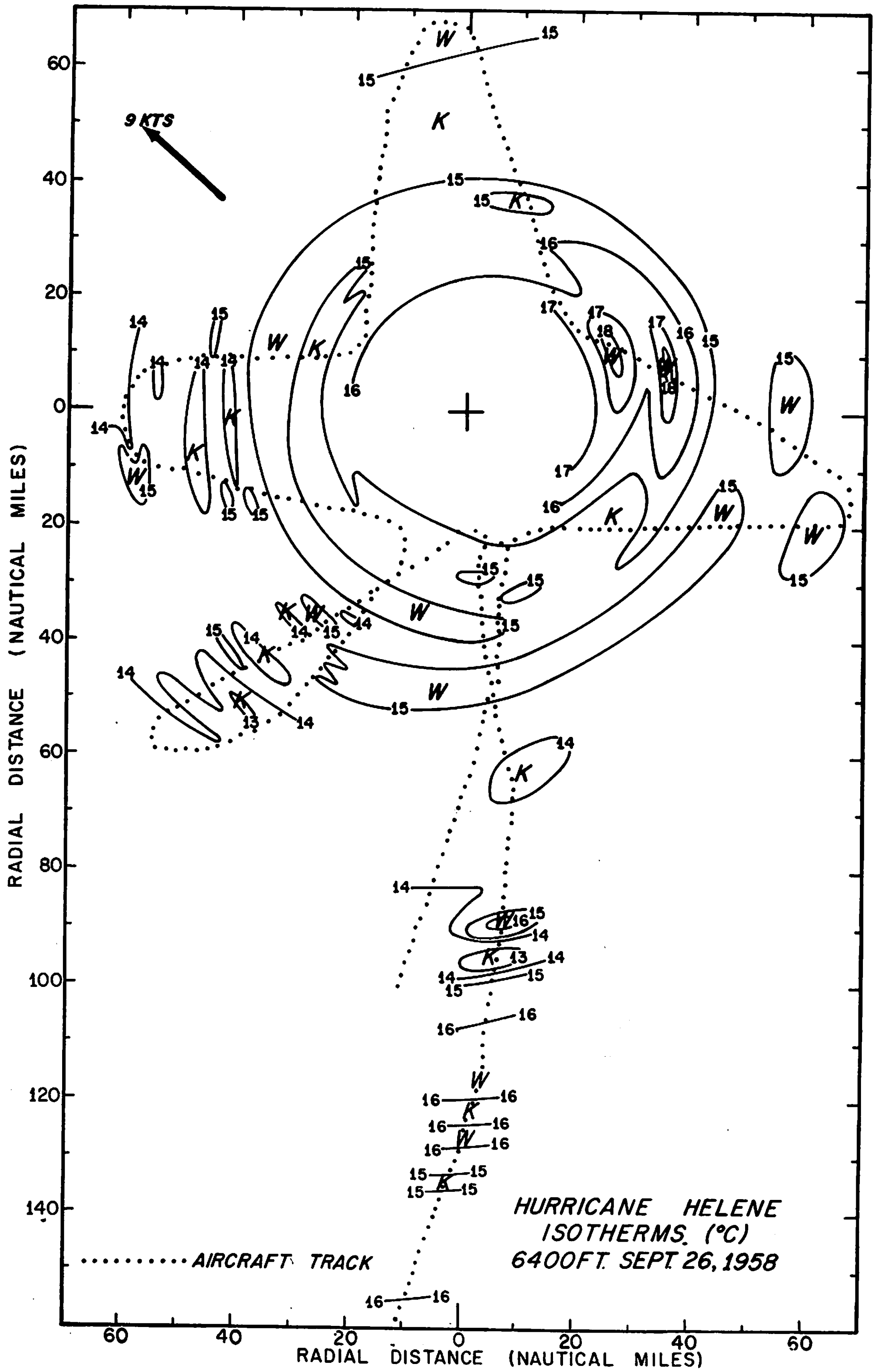

Figure 38. - Temperature field at 6400 ft. (800 mb.), hurricane Helene, September 26, 1958.

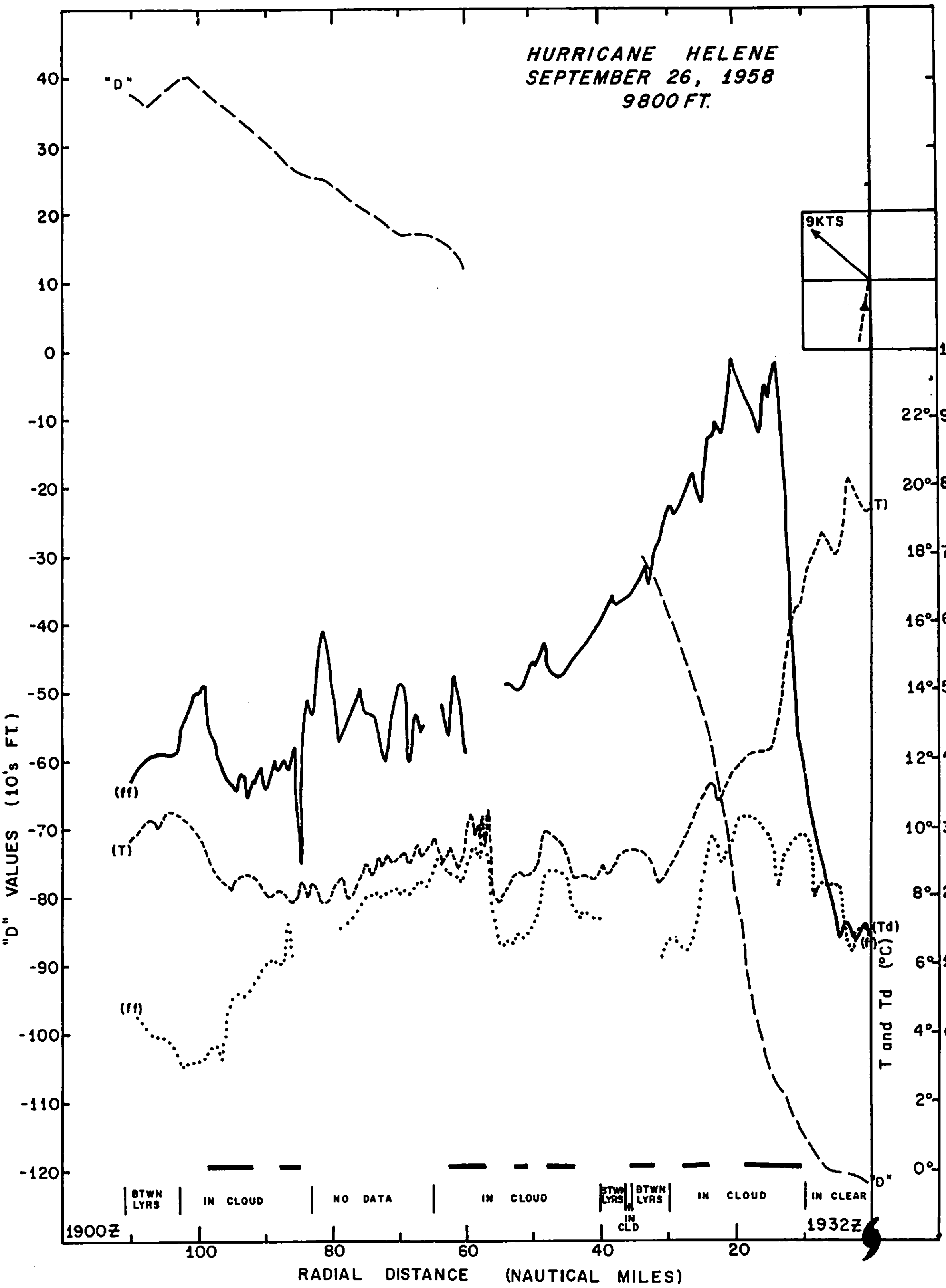

Figure 39. - Data profile at 9800 ft. (700 mb.), September 26, 1958.

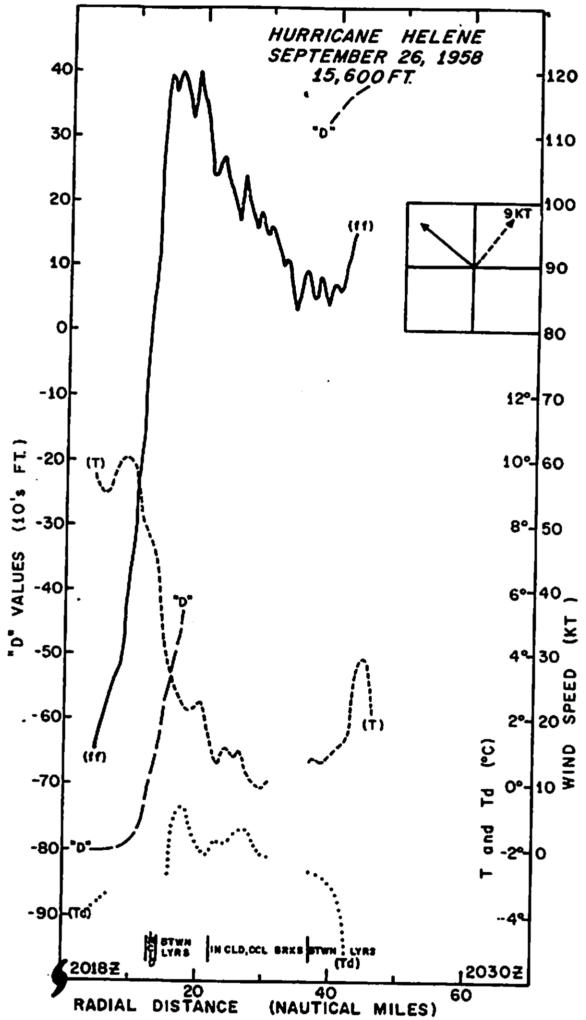

Figure 40. - Data profile at 15,600 ft. (560 mb.), September 26, 1958.

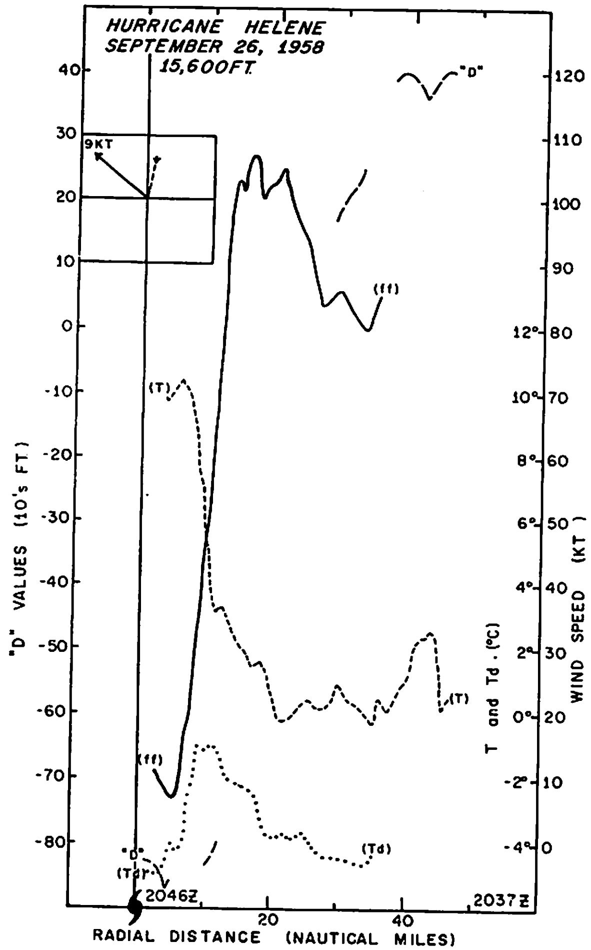

Figure 41. - Data profile at 15,600 ft. (560 mb.), September 26, 1958.

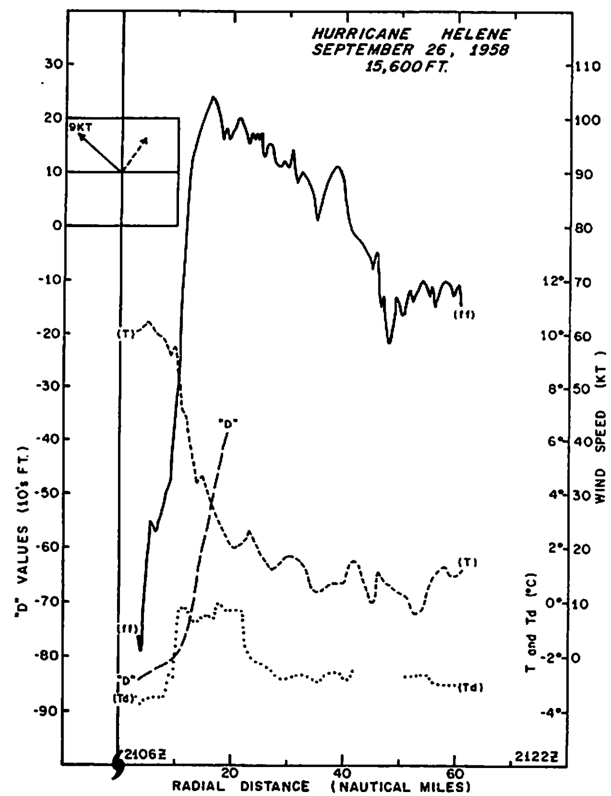

Figure 42. - Data profile at 15,600 ft. (560 mb.), September 26, 1958.

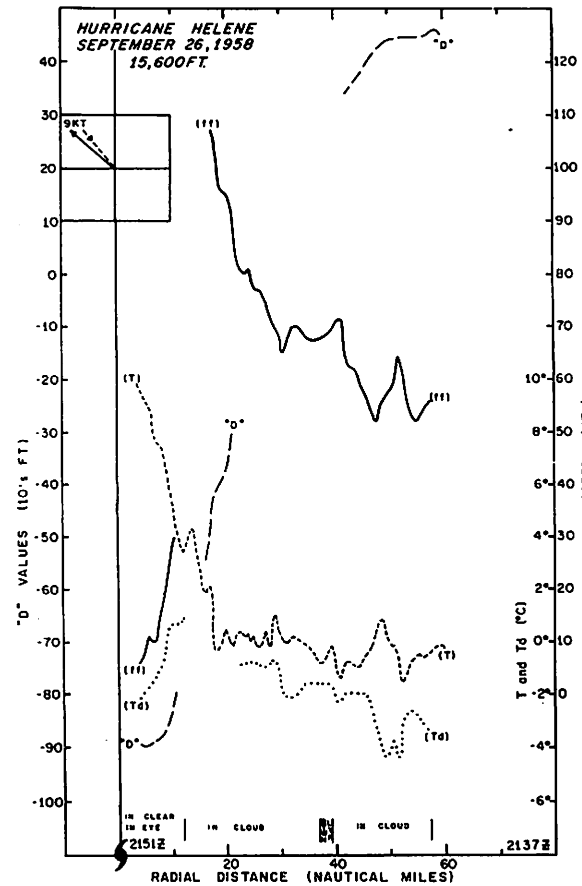

Figure 43. - Data profile at 15,600 ft. (560 mb.), September 26, 1958.

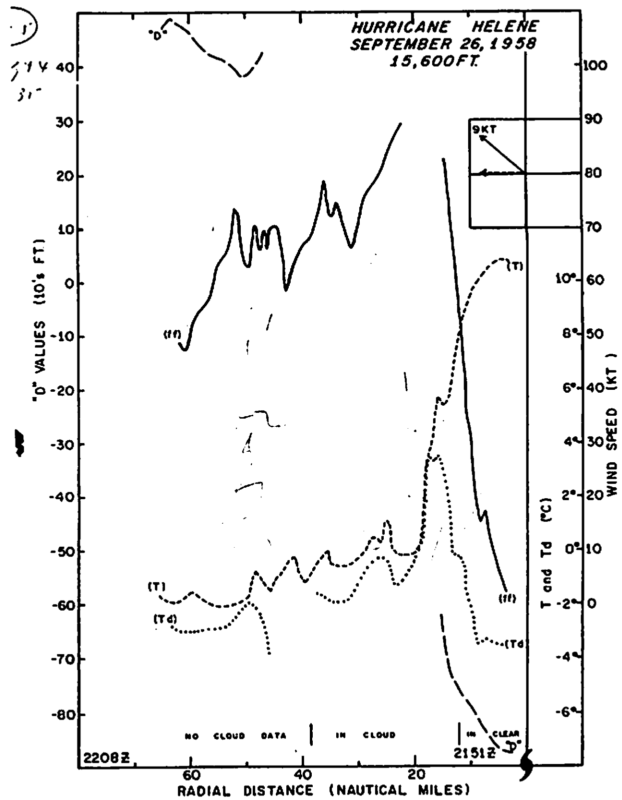

Figure 44. - Data profile at 15,600 ft. (560 mb.), September 26, 1958.

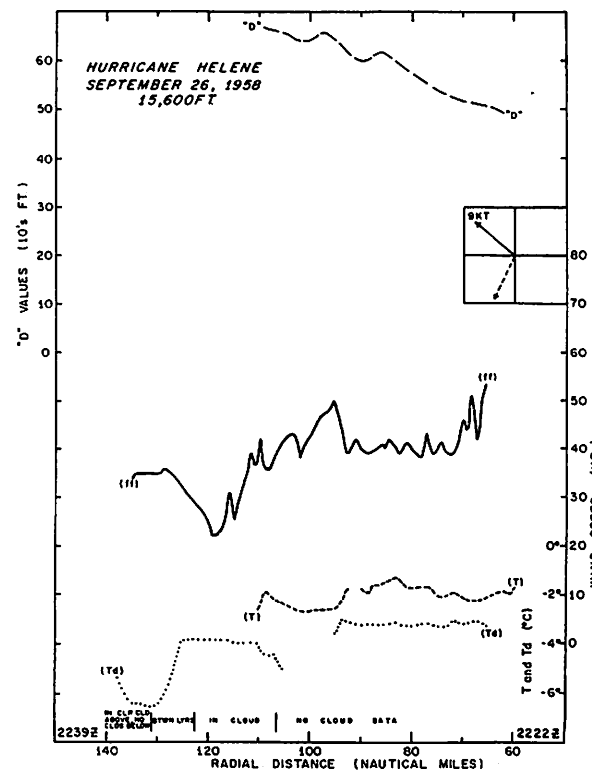

Figure 45. - Data profile at 15,600 ft. (560 mb.), September 26, 1958.

ture increase starting at the 30-mi. radius; in figures 41, 43, and 44 it starts at the 20-mi. radius; in figure 42 the picture is not as clear as in the others but the point of change in thermal gradient can also be taken as the 20-mi. radius. The maximum temperature recorded in the eye at the 700-mb. level was about 20°C., for a positive anomaly of 11°C. At the 560-mb. level the maximum was about 11°C., a positive anomaly of 12.5°C.

Thus it was only in the eye and its immediate vicinity that the extreme warm characteristics of the hurricane were observed. This is evidence of the importance of events in the eye system* in hurricane dynamics. The point of discontinuity in the radial thermal gradient was located near the outer periphery of the eye-wall band, which, as mentioned previously, had an outer diameter of about 36 mi. It was also located at a greater radial position than the maximum of winds. Thus, the bulk of the ascent in the eye-wall band had a temperature higher than that in the neighboring sections of the rain area, but lower than was observed in the edge and center of the eye.

Outside the eye system the gross thermal gradients were generally small, but there were, nevertheless, some rather significant oscillations of about 2° or 3°C. in range. At 700-mb. (fig. 39) some important variations were noted near the 100-mi. radius, associated with a penetration into a cloud mass and precipitation band. The temperature decreased and dew point increased inside the cloud. Another significant oscillation in temperature and humidity was observed in connection with a cloud and precipitation band near the 60-mi. radius. There, the temperature first decreased then increased sharply by about 2°C. while the aircraft was still in cloud. One could notice also that the point of change in the thermal gradient, near the 30-mi. radius, coincided with penetration into the cloud mass associated with the eye wall band.

Other interesting variations in temperature and humidity in the rain area were observed at the 15,600-ft. level. In figure 40 a warm region appears at the 45-mi. radius, which was duplicated in about the same radial position in figure 41, recorded about 20 mi. downstream. Space continuity downstream around the circulation in certain minor-scale features of the wind, thermal, and humidity fields such as these have been observed also in other hurricanes. On the other hand the profile in figure 42 was taken in about the same azimuth direction as the one in figure 40, only 50 min. later, and does not show such a pronounced warm spot at the 40-45-mi. radius, evidence, in turn, of large time variations.

The composite horizontal field (fig. 47) showed nearly circular isolines in the central core and a more irregular distribution in the outer areas. A relatively warm pool was analyzed near the 40-mi. radius in the right side. Aside from that sector, all values shown outside the 20-mi. radius ranged from 0°C. to -2°C. The normal for this level in the undisturbed tropical atmosphere is -1.5°C. No data were obtained in the southern semicircle, but the picture there should differ little from what was shown for the northern semicircle.

*To avoid confusion in terminology and understanding, we have used the term 'eye system' to refer to the total of the eye wall precipitation band and the clear, calm area inside (that is, the whole system shown in figure 26), leaving the term 'eye' for the area of calm warm air in the center.

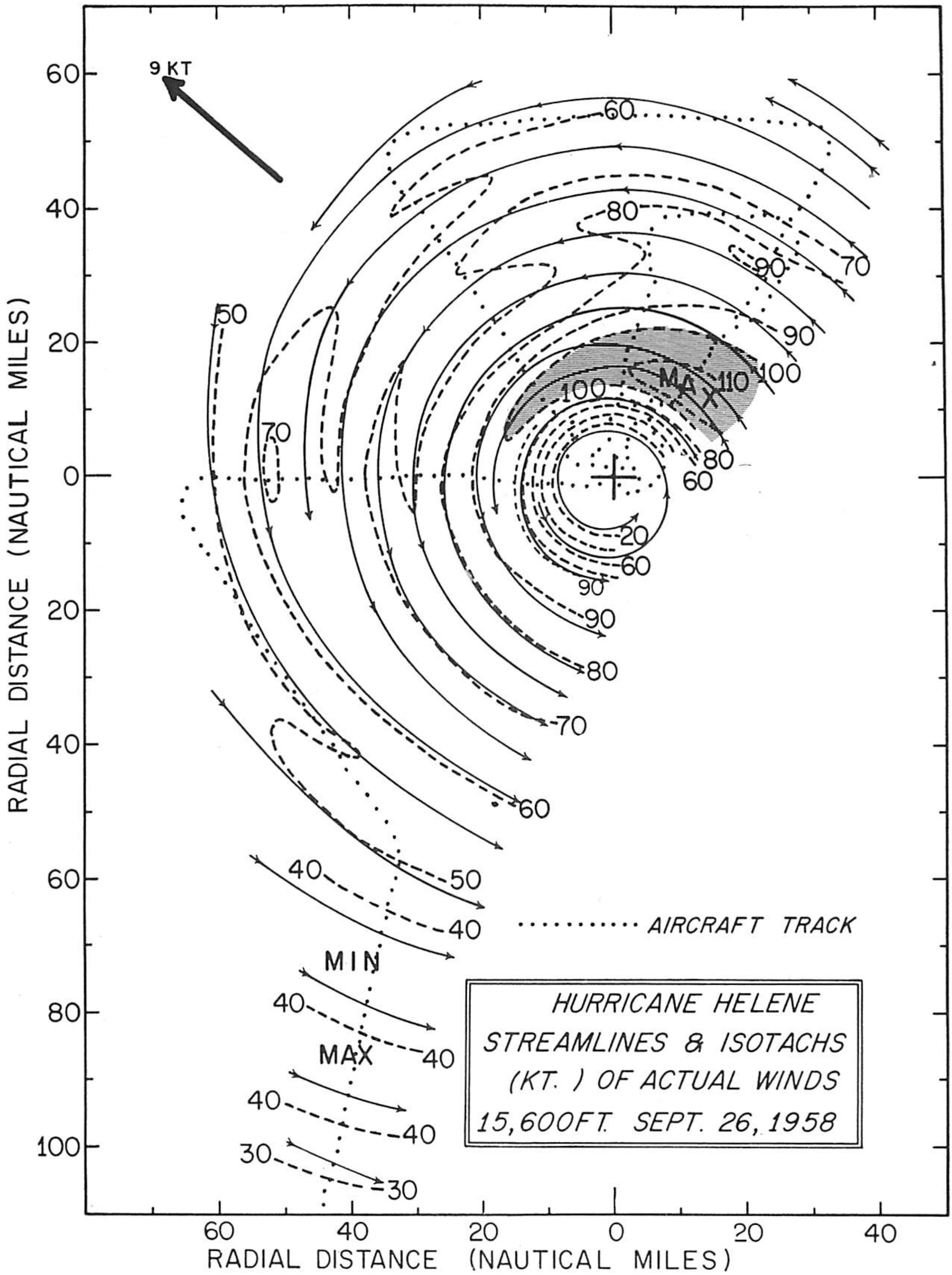

Figure 46. - Wind field at 15,600 ft. (560 mb.), hurricane Helene, September 26, 1958.

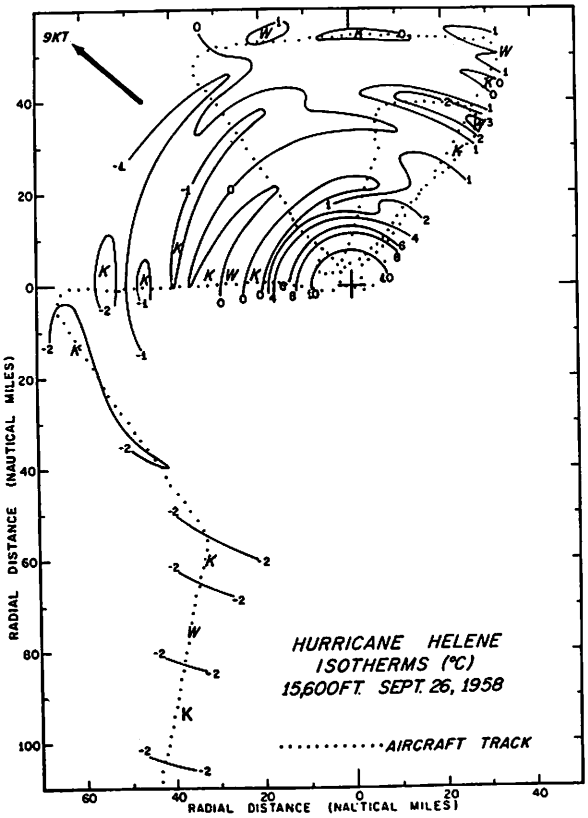

Figure 47. - Temperature field at 15,600 ft. (560 mb.), hurricane Helene, September 26, 1958.

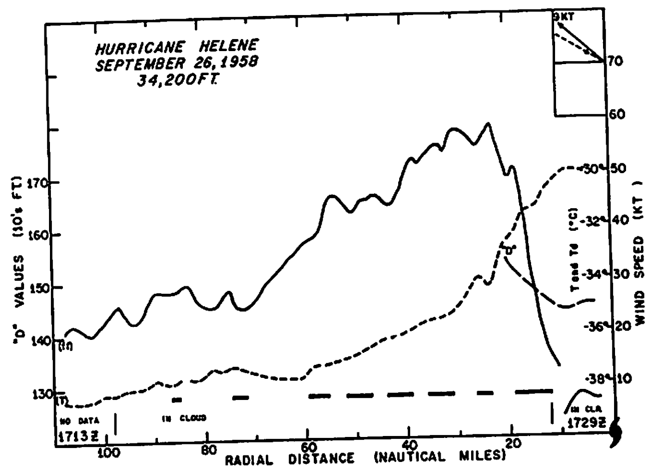

Figure 48. - Data profile at 34,200 ft. (250 mb.), September 26, 1958.

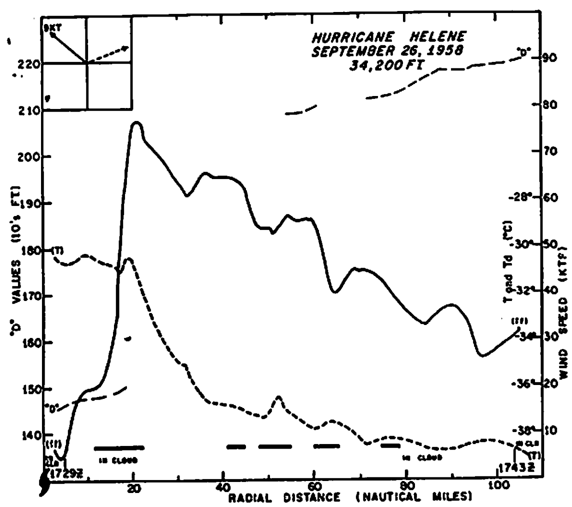

Figure 49. - Data profile at 34,200 ft. (250 mb.), September 26, 1958.

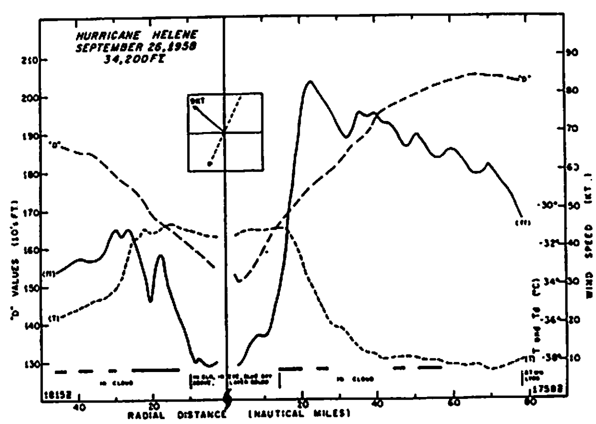

Figure 50. - Data profile at 34,200 ft. (250 mb.), September 26, 1958.

(3) Pressure field: Because of the gaps in the D-value data, none of the profiles gave a complete view of the pressure field. The profile at the 700-mb. level (fig. 39) showed a steady decrease in pressure inward from the 100-mi. radius. The horizontal pressure gradient became steeper toward the center. The maximum gradients were observed near the 20-mi. radius, in the zone of maximum winds. This is, to a large extent, the picture recorded in all other hurricanes investigated by NHRP and is also what one should expect from the observed wind field. The minimum D-values recorded at 700 mb. were -1170 ft., which with use of the Jordan's central pressure nomogram [9], gives a surface pressure of 942 mb. The minimum value recorded at the 15,600-ft. level was -890 ft., which gives a central pressure of 947 mb. There might have been small time changes of this nature, but the 5-mb. difference is certainly within the limits of accuracy of the D-value measurement, on the one hand, and of the extrapolation diagram on the other. We can conclude that the central pressure at the time of these missions was of the order of 940 to 945 mb.

C. Circulation at 34,000 ft. (250-mb. Level)

The flight in the upper torposphere was centered at the 34,200-ft. level (approximately 250 mb.) and was carried out between 1600 and 2100 GMT. The flight track (fig. 51) included two passes through the eye. One penetrated from the northwest in a direction close to the direction of motion and departed to the northeast, in the right-rear quadrant. The other went across from north to south in a direction close to the perpendicular to the motion. The data obtained on these two passes provide one of the few well-documented pictures available of the wind and thermal structure of a hurricane at these upper levels. Other successful upper-level missions in hurricanes were obtained by the research aircraft in hurricanes Carrie of 1957 (Staff, NHRP [15]), Daisy of 1958 (Colón [1]), and Cleo of 1958 (LaSuer and Hawkins [11]).

(1) Wind field: A well-defined cyclonic vortex was observed extending to 60 to 80 mi. from the center (fig. 51). From there on outward the flow was generally anticyclonic. To the east and north the cyclonic curvature was small outside the 40-mi. radius and decreased rapidly outward. Streamlines in figure 51 have been drawn cyclonically divergent outside the 20-mi. radius and convergent in the eye, but these features were not unmistabably evidenced by the data. The data were not adequate to determine this property of the flow with precision, and figure 51 shows the analyst's interpretation of how the flow probably looked.

On the approach into the center from the northwest (fig. 48) winds of about 25 kt. were recorded outside the 70-mi. radius. From the 70 to the 30-mi. radii there was a steady increase in speed. A zone of maximum winds, close to 60 kt., extended from the 30 to the 23 mi. radii; the speeds then decreased steadily into the eye. Winds of less than 10 kt. were recorded in the eye over an area of about 16 mi. diameter. In the right semicircle (fig. 49) the wind increased rapidly in the eye-wall to a maximum of 77 kt. at the 21-mi. radius, followed by a steady decrease outward. Winds of 30 kt. were measured at the limits of the data near the 100-mi. radius. A similar picture was recorded in the traverse from north to south (fig. 50). A maximum of 83 kt. was observed at the 22-mi. radius on the right side; on the left side

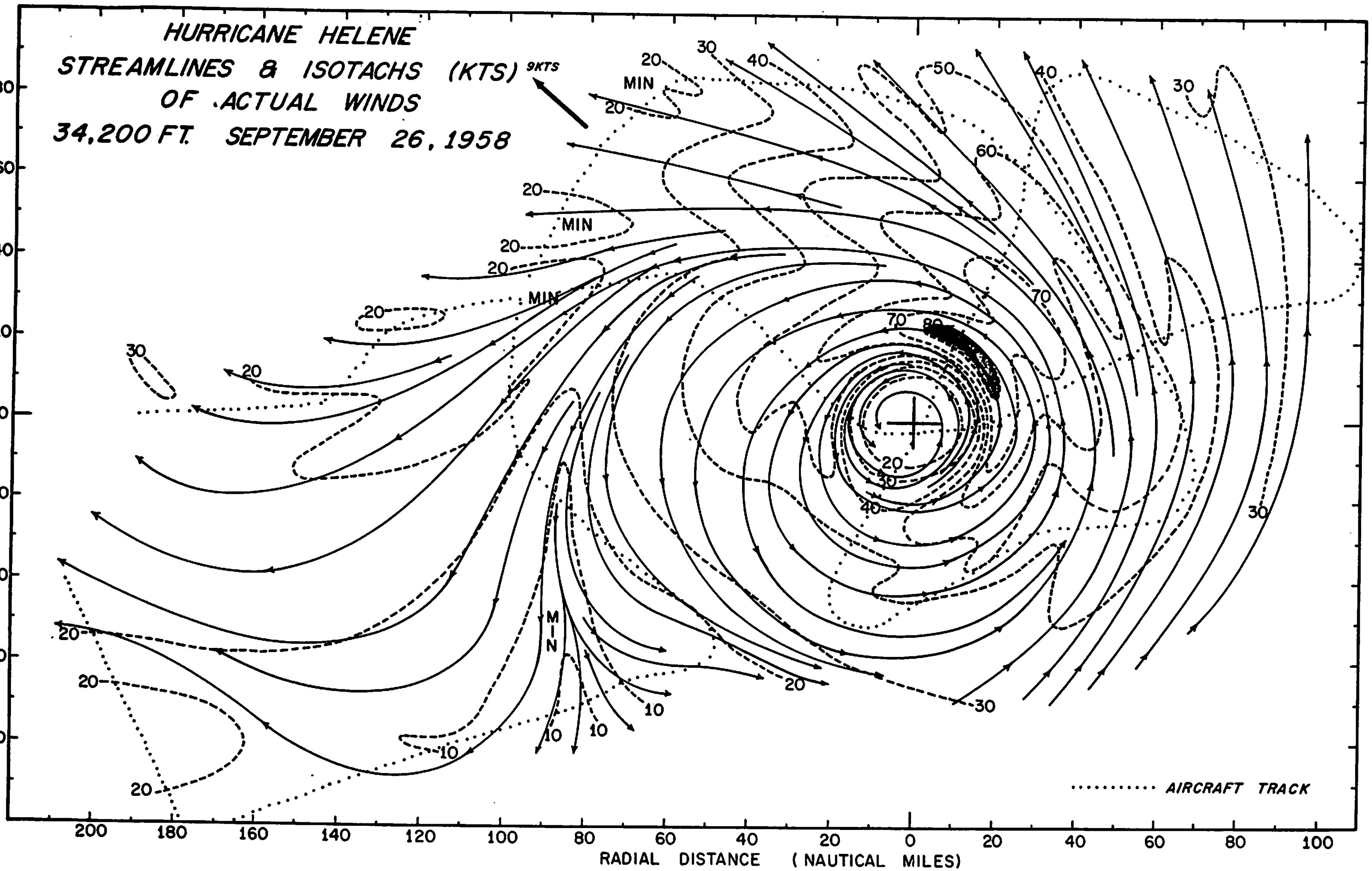

Figure 51. - Wind field at 34,200 ft. (250 mb.), hurricane Helence, September 26, 1958.

the flow was rather weak; speeds of about 40 kt. were recorded from the 25 to the 30-mi. radii. There was a difference of about 38 kt. in the maximum winds in opposite sides of the eye, which indicated an asymmetry of about 20 kt. in the magnitude of the relative winds.

The magnitude of the maximum winds decreased from 120 kt. at the 15,600-ft. level to 83 kt. at 34,200 ft., a decrease of about 33 percent. This compared well with a decrease of 40 percent observed in hurricane Daisy on August 27, 1958 between the levels of 13,000 and 34,200 ft. (Colón [1]). Hawkins [6] reported a decrease of about 65 percent in the maximum winds between 16,000 and 34,000 ft. in hurricanes of 970-980 mb. in central pressure.

The wind diameter, i.e. diameter of the zone of maximum winds, at the 250-mb. level was about 10 mi. larger than at the 560 and 700-mb. levels. A somewhat similar observation was made in the case of hurricane Cleo (LaSeur and Hawkins [11]). However, in hurricane Daisy (1958) the radius of maximum winds at the 250-mb. level was about equal to that at the 620-mb. level.

There were some minor oscillations in wind speed in the profiles at the upper level, but they were not as apparent as in the lower levels. This was largely due to the sampling differences, with a much faster plane at the upper level. The wind and radar data showed some negative departures in wind speed associated with radar bands; for example, at the 73, 50, 43, and 33-mi. radii in figure 48; at the 51 and 64-mi. radii in figure 49, and the 48 and 55-mi. radii in the right of figure 50. There were also other minor peaks and valleys not apparently associated with precipitation bands. At this level, the aircraft flew through the upper parts of, or above, the convective systems while the precipitation was occurring below flight level so that any association between variations in wind speed or temperature with precipitation bands would be of a different nature than at low levels.

(2) Thermal and moisture fields: The temperature profiles (figs. 48-50) depicted a rather interesting picture of a very warm core of air in the center surrounded by a region of small horizontal temperature gradients. A similar picture was observed at the lower levels, but at the 250-mb. level the diameter of the warm core was larger than below. In the penetration from the northwest (fig. 48) there was a gradual warming of about 1°C. from the 110 to the 60-mi. radii. The temperature increased more rapidly inward from the 60 to the 30-mi. radii, and even more rapidly from there inward. From the 10-mi. radius on the forward side to the 20-mi. radius on the right side (fig. 49) temperatures were nearly constant. Outside this warm zone, figure 49 shows a distribution similar to that shown in figure 48. In the pass from north to south (fig. 50) the warm plateau extended from the 15-mi. radius on the right side to the 25-mi. radius on the left side. These observations indicate the core of warm air was displaced to the southeast or left rear quadrant of the eye. However, the apparent asymmetry may be spurious and could have resulted from a lag in the temperature element, which, with a fast moving aircraft and such a sharp thermal gradient, would not be unexpected. Such a lag in the temperature element, suggested also by the temperature data at the 15,600-ft. level, will be discussed further in the next section.

The maximum temperature recorded at this level was -30°C. on the forward side (fig. 48). The maximum during the north-to-south pass was -30.7°C. The temperature values at the point of intersection between the two passes was -30.4°C. on the west-to-northeast pass and -31.3°C. on the north-to-south pass, a difference of 1°C., which might easily have been due to time variations, but could be considered within the limits of accuracy of the measurements. The normal temperature at this level in the undisturbed atmosphere is -43°C., so that the positive anomalies in the eye were 12°-13°C., the same magnitude observed at the 560-mb. level.

The horizontal distribution (fig. 52) showed the center of the warm air core displaced slightly to the south. As mentioned previously, this feature may be unrealistic and due to a lag in the temperature probe. A fairly flat field with relatively small gradients and with magnitudes ranging from -37°C. to -40°C. was observed throughout the periphery. The coldest temperatures indicated in figure 52 are about -40°C., which are still over 2°C. above normal.

(3) Pressure field: The D-value data in the north-to-south diameter pass (fig. 50) showed a pressure vortex with minimum value of close to 1500 ft. at the center increasing to about 1900 to 2050 ft. in the periphery. An asymmetry is revealed, with a larger total gradient on the right side in accordance with the wind field. On the northwest-to-northeast pass the pressure data were missing for most of the pass, but the few data available across the eye (figs. 48 and 49) suggest an inverted plateau-type structure, as has been recorded in other hurricanes.

6. DISCUSSION OF THE MAIN ASPECTS OF THE HELENE DATA

After the afternoon of September 26, hurricane Helene began to recurve toward the north and northeast in a rather wide curve that took the center very close to the coasts of North and South Carolina (fig. 1). The maximum intensity of 933 mb. central pressure was reached early on the 27th. Helene began affecting the coastal areas from Charleston to Hatteras on the 27th, causing considerable property losses. A study of the surface wind field of hurricane Helene during September 27, before and during the time it was affecting the coastal areas, was made by Schauss [14].

There are two main features shown by the Helene data that stand out among all others and are of considerable interest from the point of view of the hurricane problem in general. One is the manner in which the intensification process altered the organization of the system, with a steady reduction of the eye diameter or radius of maximum winds. The second is the radial distribution of winds, characterized by a broad zone of maximum flow with rather gradual weakening of the winds with radius. The anticyclonic shear outside the radius of maximum winds was relatively small and as a result the Helene circulation turned out to be quite extensive, with strong winds extending quite some distance away from the center. This property of Helene was an important factor in causing the heavy damage inflicted on the coastal sections of the United States on September 27.

In the following sections we shall look more closely into some of these aspects of the Helene circulation and their time changes, as well as into the

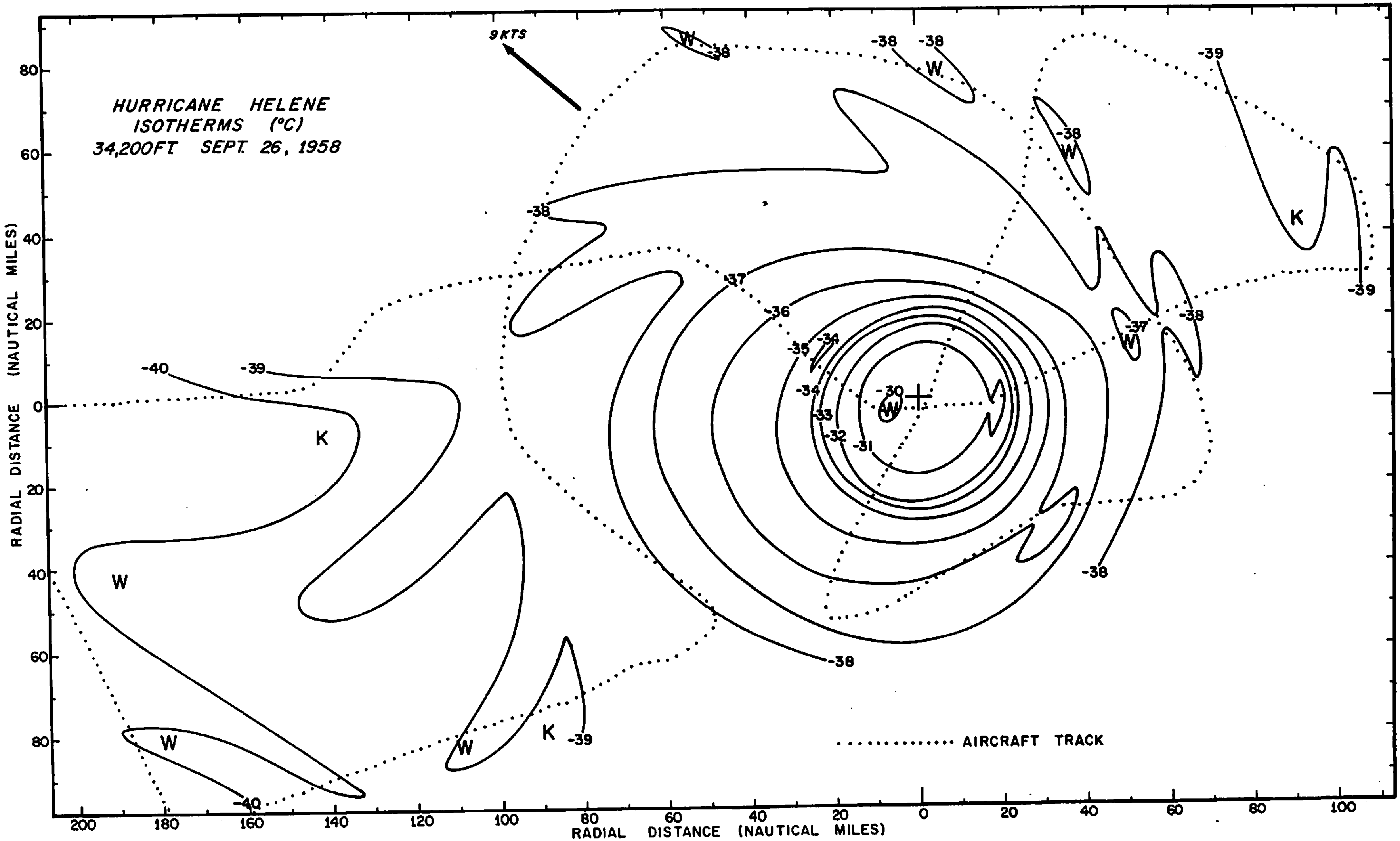

Figure 52. - Temperature field at 34,200 ft. (250 mb.), hurricane Helene, September 26, 1958.

vertical and horizontal distribution of the various parameters at the time of maximum intensity. Some comments are also included on how these properties are indicative of hurricanes in general. First, it is worthwhile to discuss briefly some points concerning the accuracy and representativeness of the aircraft data.

A. Accuracy and Representativeness of Aircraft Data

Those people familiar with the National Hurricane Research Project operations are aware of the characteristics of the various probes aboard the aircraft and of the merits and weaknesses of the recorded data. Some previous publications in the NHRP Series have discussed these problems. The reports by Hilleary and Christensen [7] and Hawkins et al. [5] contained technical descriptions and accuracy ranges of the various probes. Additional information on the processing and analysis methods applied to the data was given in the reports by Staff, NHRP [15], Riehl and Malkus [13], and Colón [1].

In the discussion of the Daisy data, we made some comments concerning some aspects of the wind and temperature data, which have been considered by some people to be indicative of errors or unrepresentativeness in the measurements. To date it has not been possible to detect or assess with certainty the presence of these errors. These concern in part the coolness of the temperature readings in some sections of the rain area, particularly near precipitation, and possible inaccuracies in the wind speed measurements biased to the low side - due in part to the fact that the assumption of zero motion of the water level, inherent in the measurements of winds by the Doppler navigation system, may not hold in the high kinetic energy regions of the hurricane circulation. In the analysis of the Daisy data no instances were found by this writer which pointed unmistakably to clear and serious deficiencies in the wind or temperature data. In regard to winds the same conclusion can be stated about the Helene data. However, in regard to temperature there is a peculiar fact of observation noted in the data at upper levels on September 26 which indicates a significant effect due to lag in the thermal probe. The temperature readings in the inner core of the hurricane recorded at the 15,600-ft. level on September 26 are shown in table 1.

From about the 8 to 25-mi. radii the temperature on passes 1, 3, and 5 are consistently higher than those on passes 2 and 4. The essential difference between them is that in the former group the aircraft was flying outward from, and in the latter it was flying inward toward, the eye. This points clearly to spurious and unrealistic differences, which can be ascribed to lag in the vortex thermometer in the region of large thermal gradients in the eye wall. With a fast-moving observation platform such as an aircraft, the presence of lag errors is not surprising and has been suspected for some time. However, this is the first instance in which we have been able to detect such serious effects in the temperature data. A similar observation was noticed also in the temperatures measured by the jet aircraft at the 250-mb. level; the readings across the eye at the 34,200-ft. level can be discerned by study of figures 48-50. In the passes across the eye-wall, when the aircraft was flying outward from the eye, higher temperatures

Table 1. - Temperatures (°C.) at indicated radial distances, hurricane Helene, September 26, 1958, 15,600 ft. (560 mb.)

Pass No.	Time (GMT)	Direction of Flight	Radial Distance (n. mi.)										
			4	6	8	10	12	14	16	18	20	25	30
1	2019-2031	outward	9.6	9.0	9.9	9.9	7.8	6.5	3.4	2.4	2.5	1.0	-0.1
2	2036-2046	inward	9.8	10.4	9.2	5.4	3.3	2.5	1.9	1.6	0.5	0.4	0.9
3	2106-2122	outward	10.2	10.2	9.7	9.3	6.6	4.2	3.9	2.9	2.1	1.9	1.7
4	2137-2151	inward	9.7	8.9	7.5	5.4	3.5	4.2	2.0	-0.3	0.4	0.2	0.3
5	2152-2208	outward	10.8	10.7	10.2	9.5	8.2	5.7	5.5	2.9	-0.1	1.1	-0.3

were obtained, at the same radius, than when it was flying inward. The differences are not as large as at the 15,600-ft. level, but also the temperature gradient was not as great. The asymmetry in the distribution around the center of the warm air pool, shown by the data, might be due to this effect. This behavior of the temperature data was not noticeable in the flights made on the previous two days, but the temperature gradients were then not large.

This feature of the temperature data does not invalidate the conclusions concerning the properties of the hurricane field that have been discussed so far in this report. In a way it points even more dramatically to the extreme horizontal thermal gradients that existed in the eye wall in hurricane Helene. Other interesting conclusions concerning the properties of hurricanes can be drawn from the data in spite of the deficiency noted above.

B. Time Changes in the Helene Circulation

At the time of the first aircraft mission on September 24, Helene was just reaching hurricane intensity. The observations from September 24 to 26 traced the intensification stage, which in 48 hr. evidenced a drop of about 60 m. in central pressure (fig. 5). The time changes in the wind structure are summarized in figure 53, where representative wind profiles recorded on each day are reproduced. They were obtained at different levels and some small allowance must be made for vertical space differences in the intensity of the maximum winds.

The most important feature is perhaps the decrease in the radius of maximum winds which accompanied the growth in strength. The maximum winds increased from 55 kt. on the first day, to 80 kt. on the second, to 105 kt. on the third, (120 kt. were measured on a different pass) while the radius of maximum winds decreased from about 45 mi. on the 24th, to 25 mi. on the 25th, to 16 mi. on the 26th. This characteristic of the development process has been observed also in some other hurricanes (Colón, [3]).

Another interesting property of the Helene circulation, not generally observed in all hurricanes, is that development of the wind distribution was characterized by fairly small values of anticyclonic shear outside the radius of maximum winds. As a result the hurricane was quite extensive in area, with gale winds extending quite far from the center. This can be contrasted to other hurricanes which were just as intense in strength of the winds, but were small in size as a result of very large anticyclonic shear outside the radius of maximum winds.

The time changes in the pressure field are illustrated in figure 54, in terms of the depression of the 700-mb. level. In the preparation of this chart data for September 24 at the 13,000-ft. level, and for September 25 at the 6400-ft. level, were adjusted to the 700-mb. level under the assumption that the horizontal distribution did not change significantly with height and with a modification of the minimum D-value at the center on the basis of the extrapolation diagram introduced by Jordan [9]. The results in figure 54 show a larger reduction in D-values at the center than outside. Between September 24 and September 26 the depression of the 700-mb. level at the cen-

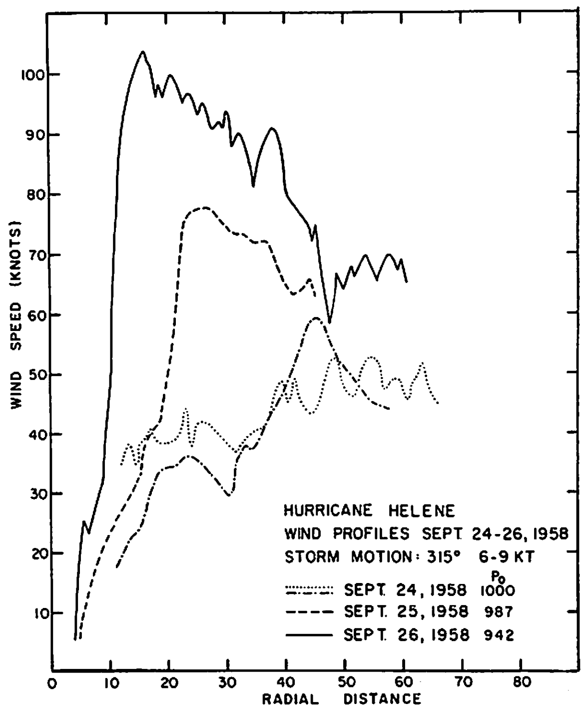

Figure 53. - Selected wind profiles for hurricane Helene, September 24-26, 1958. Data for September 24 at 13,000 ft.; for September 25 at 6400 ft.; and for September 26 at 15,600 ft. The dot-dashed profile for September 24 was obtained in a direction just to the left of the direction of motion; all others were at right angles to the direction of motion in the right semicircle.

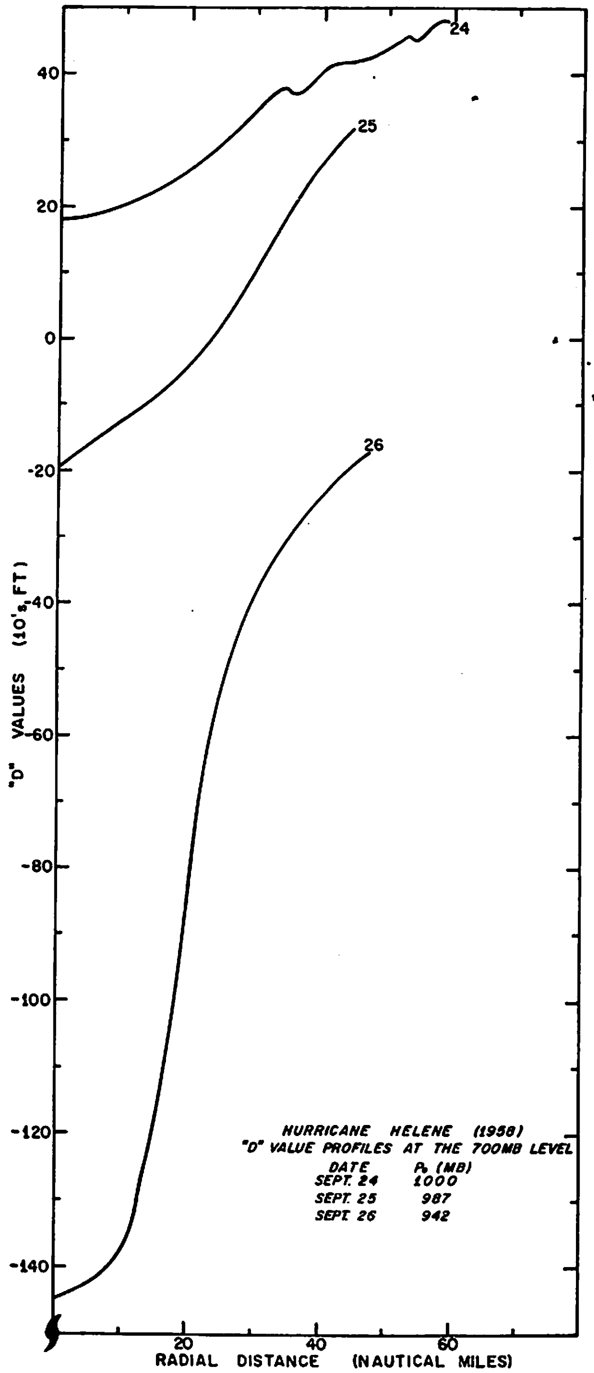

Figure 54.- Profiles of "D" values at the 700-mb. level in hurricane Helene from September 24 to 26, 1958.

ter was 1630 ft.; at the 50-mi. radius it was 600 ft. In view of the changes in the wind field one would expect also a reduction with time in the radius of the point of maximum horizontal pressure gradient, which is also evident in figure 54. Initially there was a fairly flat pressure field in which one cannot detect much change in pressure gradient with radius. With the larger reduction at the center the changes in the configuration of the pressure profile were such that the point of maximum gradient was displaced inward with time.

A comparison of the temperature profiles to bring out the changes with time is more difficult than in the case of winds and D-values, since variations introduced by the differences in the altitude of the levels of observations cannot be disregarded and there is no simple way to adjust the data to a common level. Nevertheless, important points can be appreciated by study of some of the data available. Average profiles of temperature anomalies at the 13,000-ft. level (620 mb.) on September 24, and the 15,600 ft. level (560 mb.) on September 26, are shown in figure 55. The data for the region inside the 10-mi. radius constitute averages of all the observations available in the eye. The averages were made for intervals of 2 mi. in radial distance. The data outside the 10-mi. radius are averages of the various profiles made on the right semicircle at the indicated levels and dates. For September 26 the average was made of two radial passes in which the aircraft was flying inward and two in which it was flying outward, so that the bias introduced by lag in the probe was partly corrected. Normally there is an increase in the magnitude of the temperature anomalies with altitude, but since the levels of observation were not far apart we can disregard the effect due to the vertical differences and consider the changes observed in figure 55 as being representative of the time variations in middle levels between the two days.

There was a net warming of over 8°C. in the eye, of about 1°C. at the 20-mi. radius (just outside the eye-wall radar band), and of 2°-3°C. in the rain area as a result of the process of intensification. Except for the reduced warming in the eye-wall, this distribution of warming is similar to that observed in hurricane Daisy. The minimum warming near the eye-wall resulted from the reduction in the diameter of the eye.

The moisture data show very little radial change in moisture content on September 24. Mixing ratio values of about 6.5 gm. kg.$^{-1}$ were recorded in the eye and eye-wall and slightly less in the outer part of the rain area. On September 26 the radial distribution showed a maximum in the eye-wall with decreasing values into the eye and into the rain area. There was a slight increase in moisture anomaly in the rain area, a very sizable increase in the eye-wall band, and no appreciable change in the eye. As a result of these variations in temperature and humidity, the profile of relative humidity showed a large decrease in the eye (large increase in temperature with no increase in moisture content), a small increase in the eye-wall zone (increase in moisture content with small increase in temperature), and a decrease in the rain area (larger increase in temperature than in moisture).

These changes in temperature and humidity distribution in the horizontal during intensification are consistent with the classical picture of

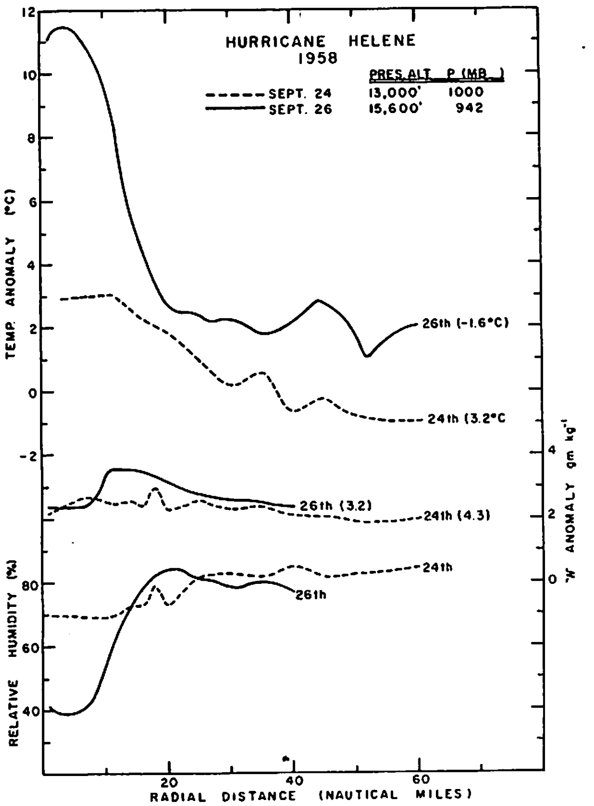

Figure 55. - Radial profiles of temperature and mixing ratio anomalies and relative humidity in the right semicircle of hurricane Helene, September 24 and 26, 1958. Values in parenthesis denote the normal value of the parameters involved.

the hurricane, consisting of a ring of extremely violent convection in the eye wall, pronounced convection in the rain area, and a subsiding current in the eye. However, the magnitudes of some of the observed changes were to some extent unexpected. For example, with the increase in convection in the rain area, one might expect a more pronounced increase in moisture in the region outside the 25-mi. radius. At the same time with the development and strengthening of the subsiding current in the eye, one would also expect a decrease in moisture content to be observed in the eye. The anticipated decrease in relative humidity in the eye with intensification was solely due to the variation in temperature and not to humidity. It seems then that there was moisture from some source entering the eye. This must have come from the eye-wall cloud system by lateral mixing by eddy motions.

A more thorough discussion of the vertical distribution of properties in the eye of hurricane Helene and its changes with time during the intensification and dissipation stages was included in a previous report (Colón [2]).

C. Vertical Structure of Helene on September 26

The distribution of properties in the radial and vertical directions for hurricane Helene on September 26 is shown in figures 56-58. These charts represent conditions along a diameter more or less perpendicular to the direction of motion. Whenever possible averages of two or more individual profiles were used. For the thermal cross-section (fig. 57) an equal number of inward and outward radial passes was taken at the 560-mb. and 250-mb. levels in order to minimize the bias in the data at the eye-wall. Many of the minor-scale irregularities were smoothed out.

The data that entered into these cross-sections were gathered over a period of about 5 hr. The analysis implies the assumption of steady state conditions during that time interval. It is also assumed that a certain amount of space continuity downstream holds over a small sector of the circulation. The wind cross-section (fig. 56) shows in the left side a pattern of vertical variations that deviates considerably from the normal. This was brought about primarily by the fact that the wind speed in the vicinity of

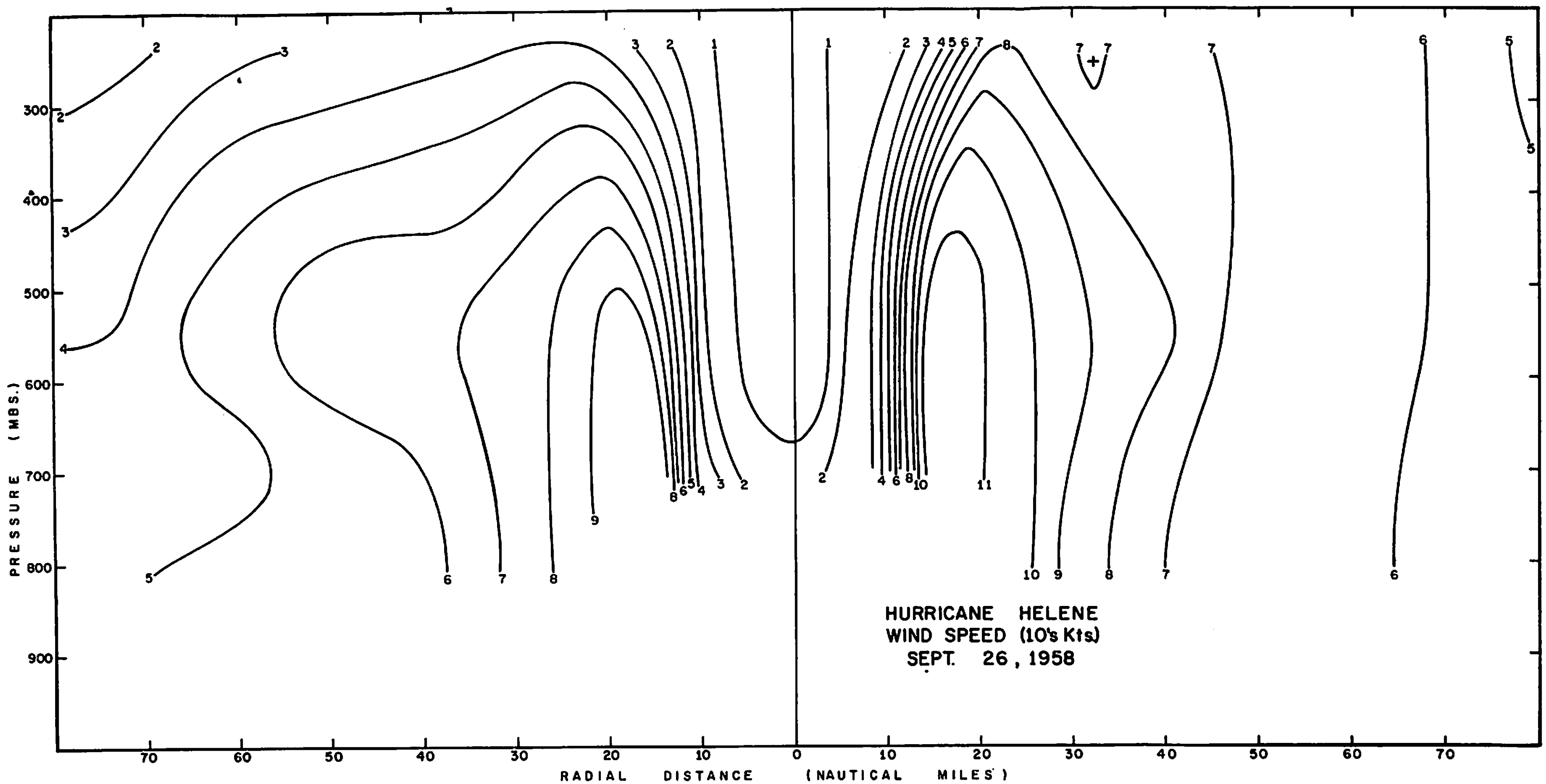

Figure 56. - Vertical cross-section of wind speed in a direction perpendicular to the direction of motion, hurricane Helene, September 26, 1958.

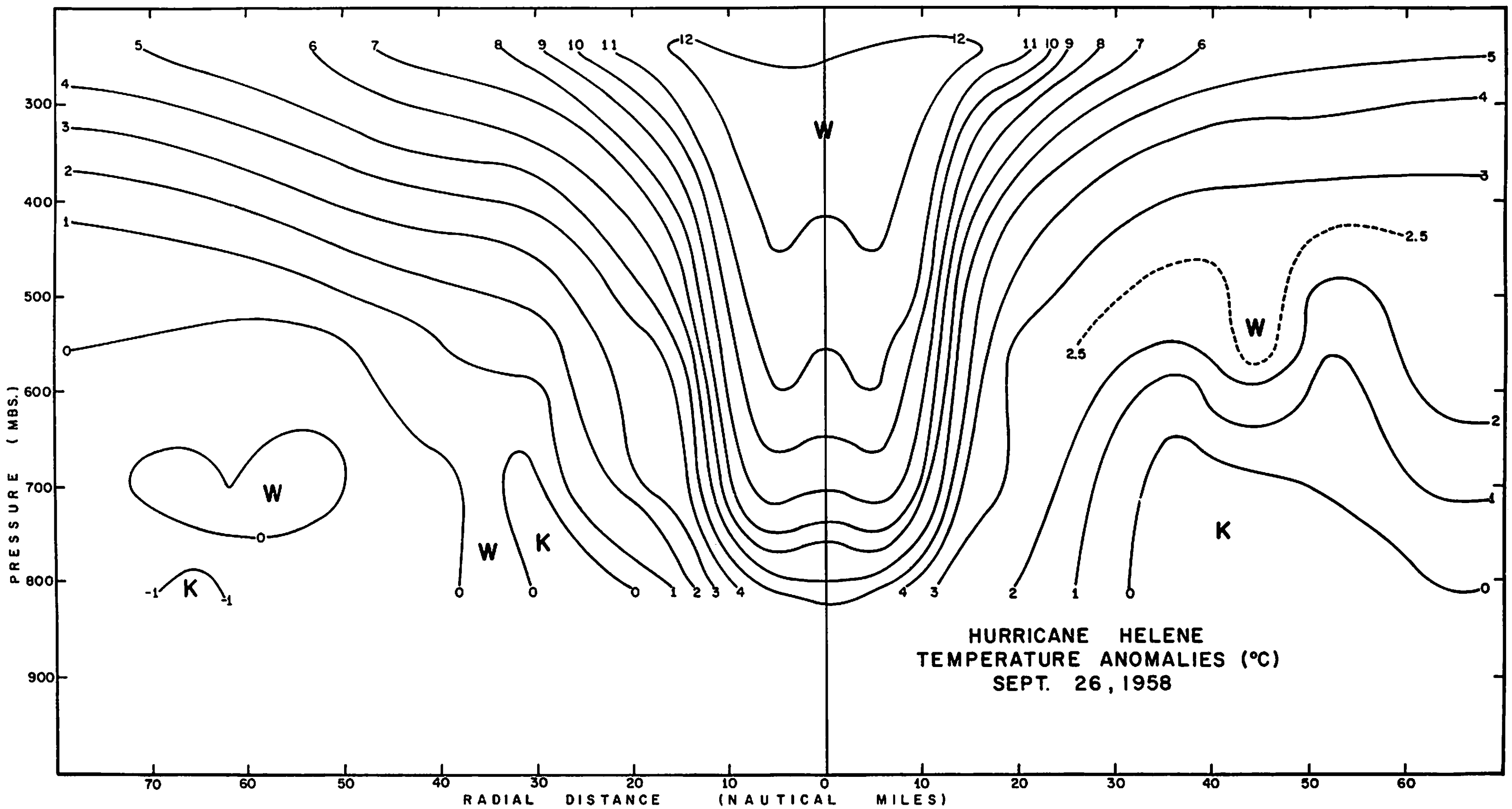

Figure 57. - Vertical cross-section of temperature anomalies from mean September atmosphere, hurricane Helene, September 26, 1958.

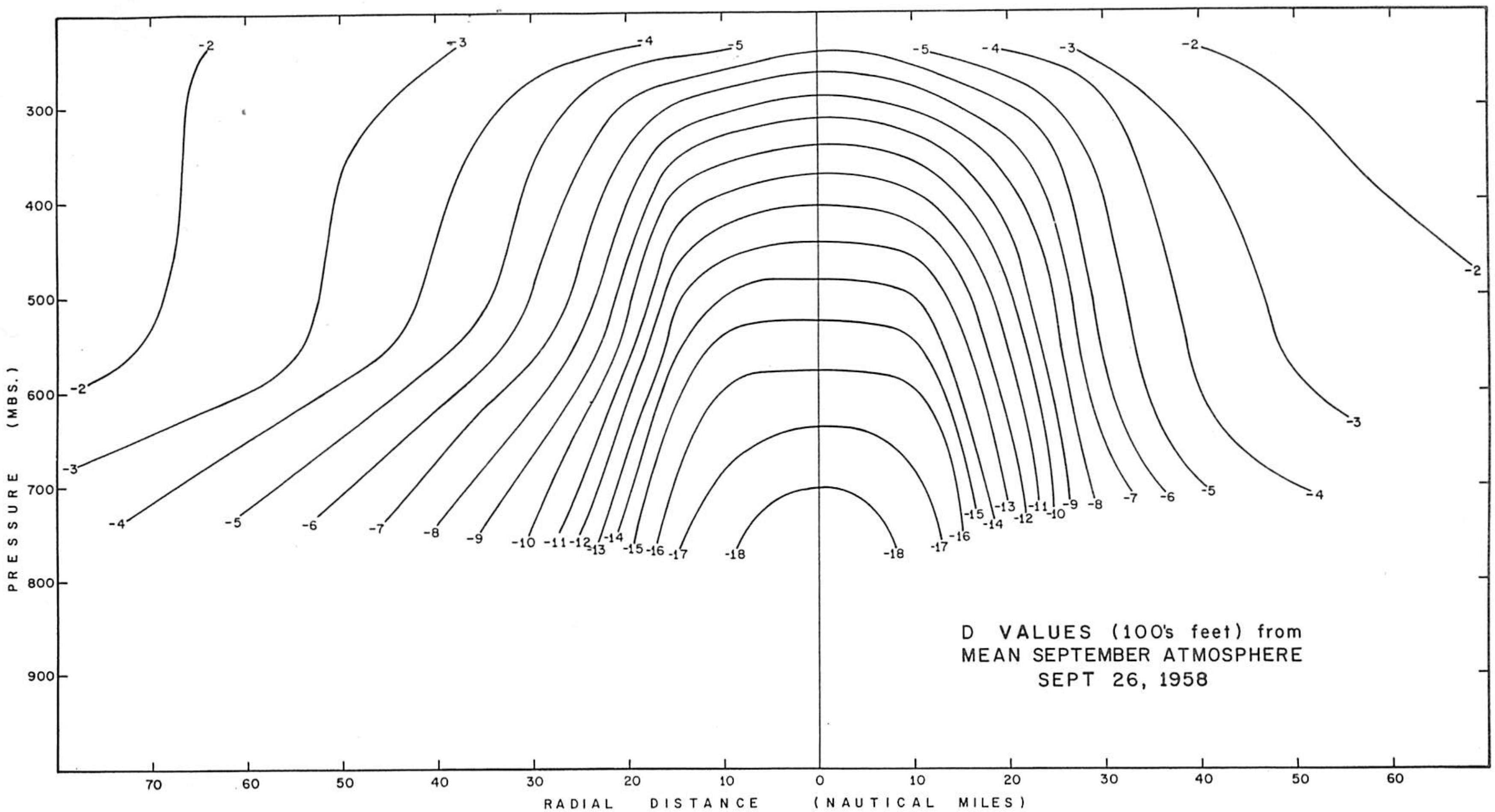

Figure 58. - Vertical cross-section of "D" values departures from mean September atmosphere, hurricane Helene, September 26, 1958.

the 50-mi. radius was higher at the 560-mb. level than at the 700-mb. level. On the right side of the chart there was also a similar, but less pronounced, indication of speed increase with height in the lower troposphere. Similar observations have been recorded in other hurricanes. Since the observations are, in most cases, not simultaneous, one might be inclined to consider them as being reflections of unsteadiness in the flow. However, there is increasing evidence that in sections of the rain area the temperatures are warmer in the inside, and, therefore, some increase of wind speed with height might reasonably occur.

The wind cross-section (fig. 56) showed a maximum of over 110 kt. extending over a wide radial section centered at about the 17-mi. radius. A slight outward slope with height was shown, as suggested by the observations at the two uppermost levels. Higher wind speeds probably existed at lower levels, but no direct evidence was available. Schauss [14] evaluated surface winds of about 90 kt. in the eye-wall of hurricane Helene during September 27. Stronger winds must have existed above the friction layer. The vertical speed gradient at upper levels was concentrated in the layers from 500 to 250 mb. in accordance with what has been generally observed during the course of NHRP studies.

Winds of 50 kt. or more extended outward at upper levels to about 80 mi. on the right, much less on the left semicircle. At lower levels 50-kt. winds appear to about the 60-mi. radius on the left side; presumably they extended much farther outward on the right side. Winds of 40 kt. extended to at least the 110-mi. radius on the left side. The 10-kt. isotach in figure 56 seems to extend downward in the eye to near the 700-mb. level. This was indicated by the data, but it is difficult to assess its significance.

The field of temperature anomalies (fig. 57) showed maximum values in the upper levels of the eye. A center of +12°C. in magnitude extended vertically from 400 to 250 mb. and extended outward more at the 250-mb. level than below. The maximum horizontal gradients were located in the eye-wall region from the 10-20-mi. radii. The maximum vertical gradients were located at lower levels in the center of the eye, and at middle and upper levels in the rain area. A picture largely similar to that in figure 57 has been observed in other hurricanes investigated by NHRP.

The maximum anomaly of +12°C. obtained in hurricane Helene compares well with that recorded in hurricanes Daisy (1958) and Cleo (1958). Other features of interest in the thermal field are the centers of below normal temperatures recorded in the lower levels on both sides of the circulation, similar to what has been observed also in other hurricanes.

Of special interest in the case of Helene was the slope outward of the eye at upper levels, which, as shown in figure 57, caused the warm air aloft in the eye to extend outward above the eye-wall. Such a slope in the warm region of the eye has been invoked by many writers to account for the surface pressure reduction in the eye core. It evidently existed in hurhurricane Helene, but has not been observed in all hurricanes investigated by NHRP.

In the preparation of the D-value cross-section (fig. 58) the recorded data at the various levels were used with a minor modification. The recorded D-value gradients were maintained but the magnitudes were modified slightly so that hydrostatic balance was maintained in the eye. The eye sounding evaluation was carried out by combination of the aircraft data and dropsonde soundings (Colón [1]). The required modification of the observed magnitudes was insignificant at the 700-mb. level and amounted to about -280 ft. at the 250-mb. level, which, considering the approximations involved in the process, is not unreasonably large. Thus, the D-values in the center in figure 58 are hydrostatically consistent with the temperatures in figure 57 and the moisture observations, but the same may or may not be true for the data at other radii. This, however, does not detract seriously from the usefulness for which the cross-section chart is intended.

The D-value data showed the typical distribution for an intense and concentrated warm-core system. Maximum deviations in the center near the surface amount to about -2000 ft. These decreased rapidly upward and outward. The maximum horizontal gradients were observed in the 10-20-mi. radius, i.e. the eye-wall zone. The maximum vertical gradients were located in the upper troposphere.

7. SUMMARY AND CONCLUSIONS

The data recorded by the Weather Bureau research aircraft in hurricane Helene (1958) have provided one of the best pictures available of the transformation of a hurricane during the intensification stage. The wind data depicted in the initial stages a well-defined vertical circulation, but with a large degree of asymmetry and disorganization in the speed field. With time the inner core of the circulation became better organized; the speed field acquired the typical distribution of maximum flow concentrated close to the center and speed decreased inward and outward. The thermal data showed the development with time of extreme warmth concentrated in the hurricane eye. Similarly, radar information depicted the organization and evolution of the eye-wall band, culminating, as shown in figure 26, in one of the best radar eye-rings that has been observed in a hurricane. A fairly complete discussion and illustration of the major features of these data was included in sections 3 to 5, while a summary presentation of time changes during the intensification stage and of the structure in its intense stage was given in section 6.

The Helene data provided unmistakable evidence of the reduction in the radius of the eye, i.e. radius of maximum winds or diameter of the radar ring. This item had intrigued hurricane workers for years.

Hurricane Helene was typical of what we may refer to as a large or extensive hurricane. Aside from the fact that the eye was relatively large and the maximum winds high, the wind distribution evidenced rather small anticyclonic shear so that strong winds extended far away from the center. This picture can be contrasted to that recorded in some small (in area) hurricanes that have been recorded in recent years, like Daisy (1958) and Ione (1955).

In the study of the Helene data we noticed once more the complexity of the inter-relationships between the small-scale variations in wind speed, temperature, humidity, etc. The close association of these variations with the cloud formations at flight level was indicated. Various instances were illustrated pointing to large degree of transitoriness in some features of the wind and temperature fields. There were important short-time variations in the characteristics of the wind, thermal, and moisture distributions, evidence of the unsteady character of the hurricane system. On the other hand there was also evidence of remarkable space continuity downstream around the circulation of features of the wind and thermal fields, apparently associated with quasi-circular precipitation bands.

Evidence was presented of limitations of the vortex thermometer in measuring realistically in regions of extreme gradients. This limitation, however, did not prevent obtaining a representative picture of the thermal properties of the hurricane at various stages of its life cycle.

This Helene report continues a series of NHRP reports, including reports on hurricane Carrie (Staff, NHRP [15]), hurricane Daisy (Colón [1]), and hurricane Cleo (LaSeur and Hawkins [11]), which have attempted to illustrate the major characteristics of a large spectrum of hurricanes in various stages of intensity. This collection constitutes a useful source of data on hurricane behavior which should assist hurricane workers in carrying out research in the mechanisms of hurricane formation and evolution.

REFERENCES

1. J. A. Colón and Staff NHRP, "On the Structure of Hurricane Daisy (1958)," National Hurricane Research Project Report No. 48, U. S. Weather Bureau Oct. 1961, 102 pp.

2. J. A. Colón, "Changes in the Eye Properties During the Life Cycle of Tropical Hurricanes," National Hurricane Research Project Report No. 50, March 1962, U. S. Weather Bureau, pp. 341-354.

3. J. A. Colón, "On the Evolution of the Wind Field During the Life Cycle of Tropical Cyclones," National Hurricane Research Project Report No. 65, U. S. Weather Bureau, Nov. 1963, 36 pp.

4. R. C. Gentry, "A Study of Hurricane Rainbands," National Hurricane Research Project Report No. 69, U. S. Weather Bureau, Mar. 1964, 85 pp.

5. H. F. Hawkins, F. E. Christensen, and S. C. Pearce, "Inventory, Use and Availability of NHRP Meteorological Data Gathered by Aircraft," National Hurricane Research Project Report No. 52, U. S. Weather Bureau, Apr. 1962.

6. H. F. Hawkins, "Vertical Wind Profiles in Hurricanes," National Hurricane Research Project Report No. 55, U. S. Weather Bureau, June 1962, 16 pp.

7. D. T. Hilleary and F. E. Christensen, "Instrumentation of National Hurricane Research Project Aircraft," National Hurricane Research Project Report No. 11, U. S. Weather Bureau, Aug. 1957, 61 pp.

8. C. L. Jordan, "A Mean Atmosphere for the West Indies Area," National Hurricane Research Project Report No. 6, U. S. Weather Bureau, Mar. 1957, 17 pp.

9. C. L. Jordan, "Estimating Central Pressure of Tropical Cyclones from Aircraft Data," National Hurricane Research Project Report No. 10, U. S. Weather Bureau, Aug. 1957, 12 pp.

10. T. N. Krishmanurti, "On the Vertical Velocity Fields in Hurricanes," National Hurricane Research Project Report No. 50, U. S. Weather Bureau, Mar. 1962, pp. 355-367.

11. N. E. LaSeur and H. F. Hawkins, "An Analysis of Hurricane Cleo (1958) Based on Data from Research Reconnaissance Aircraft," Monthly Weather Review, vol. 91, Nos. 10-12, Oct.-Dec. 1963, pp. 694-709.

12. B. I. Miller, "On the Momentum and Energy Balance of Hurricane Helene," National Hurricane Research Project Report No. 53, U. S. Weather Bureau, Apr. 1962, 19 pp.

13. H. Riehl and J. S. Malkus, "Some Aspects of Hurricane Daisy (1958)," Tellus, vol. 13, 1961, pp. 181-213.

14. C. E. Schauss, "Reconstruction of the Surface Pressure and Wind Fields of Hurricane Helene," National Hurricane Research Project Report No. 59, U. S. Weather Bureau, Oct. 1962, 45 pp.

15. Staff, NHRP, "Details of Circulation in the High Energy Core of Hurricane Carrie," National Hurricane Research Project Report No. 24, U. S. Weather Bureau, Nov. 1958, 15 pp.

16. Staff, Weather Bureau Office, Miami, Fla., "Hurricanes of 1958," Monthly Weather Review, vol. 86, No. 12, Dec. 1958, pp. 477-485.

(Continued from back of title page)

No. 66. On the filling of tropical cyclones over land, with particular reference to hurricane Donna of 1960. December 1963.
No. 67. On the thermal structure of developing tropical cyclones. January 1964.
No. 68. Criteria for a standard project northeaster for New England north of Cape Cod. March 1964.
No. 69. A study of hurricane rainbands. March 1964.
No. 70. Some theoretical results which pertain to the upper-tropospheric vortex trains of the Tropics. April 1964.
No. 71. Energy generation and flux processes associated with a weakening depression over the Gulf of Mexico. June 1964.

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