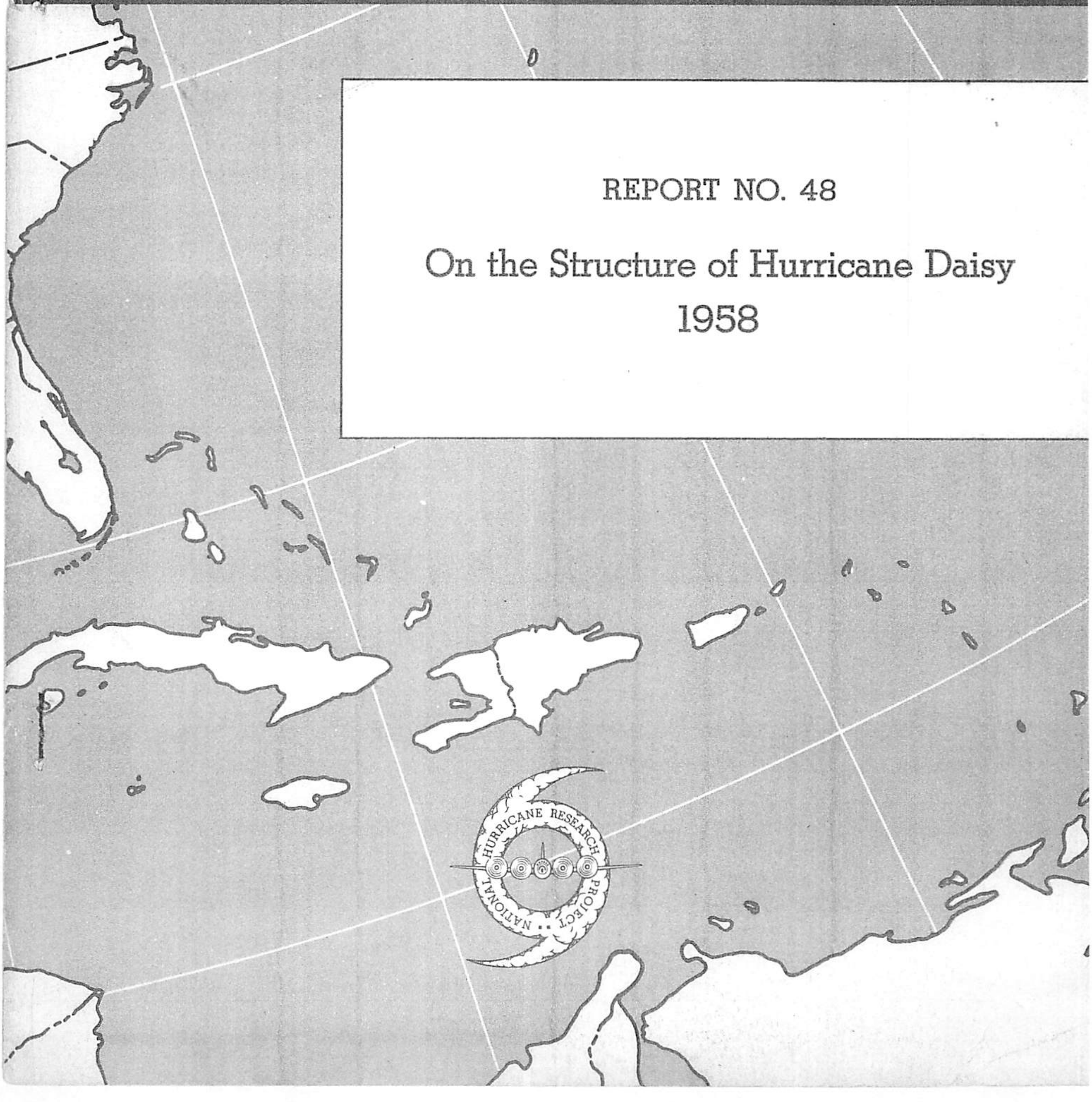
NATIONAL HURRICANE RESEARCH PROJECT



REPORT NO. 48

On the Structure of Hurricane Daisy
1958

U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

NATIONAL HURRICANE RESEARCH PROJECT

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On the Structure of Hurricane Daisy (1958)

by
José A. Colón and Staff
National Hurricane Research Project, Miami, Fla.

Washington, D. C.
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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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ON THE STRUCTURE OF HURRICANE DAISY (1958)

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ABSTRACT

During the 4-day period August 25 to August 28, 1958, the aircraft of the National Hurricane Research Project flew a total of eight research missions into hurricane Daisy at levels ranging from 960 to 240 mb. Hurricane Daisy developed in the vicinity of the Bahamas Islands during August 24, 1958 and had barely attained hurricane intensity at the time of the first NHRP mission on August 25. Fairly complete data showing the 3-dimensional structure of the hurricane at two stages in its life cycle were obtained. The structure of hurricane Daisy is described in this report and the data are amply illustrated in the form of profiles. The general characteristics of the winds, temperature, dew point, and cloud and precipitation fields are discussed, including the nature of the fluctuations of these parameters in the hurricane area and how the temperature and wind observations are affected by cloud formation and precipitation along the path of the aircraft.

The changes that took place during the process of development are analyzed by means of space cross sections perpendicular to the direction of motion on the weak and intense days. It is found that most of the changes took place inside the 20-mile radius. There was an increase in wind speed of around 50 kt. in the eye-wall, and a warming of around 6°C. over most of the tropospheric sections of the eye which was associated with a surface pressure deepening of 50 mb. The relative contribution of different layers of the troposphere to the surface pressure drop is discussed briefly. Some of the changes observed in the transition to a weaker stage are also discussed.

The radial distribution of winds is compared with that observed in other hurricanes. Selected wind profiles from hurricane Helene of 1958 are used to illustrate a type of intensification process different from that observed in Daisy illustrating essential differences in the structure and size of the high-kinetic-energy core.

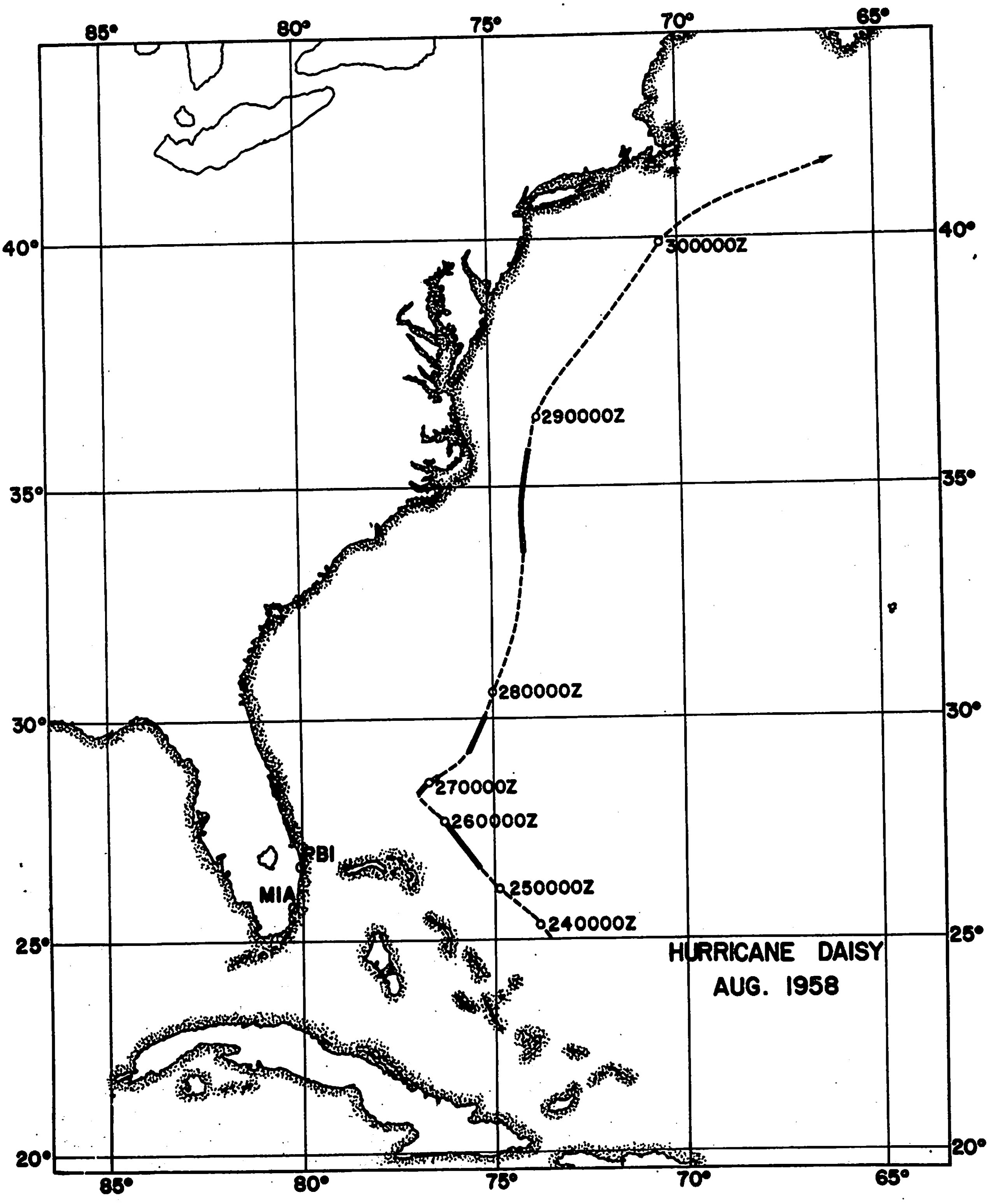

Figure 1. - Track of hurricane Daisy, August 24 to 30, 1958. Solid lines show when NHRP aircraft investigated the storm.

1. INTRODUCTION

For the last few years the National Hurricane Research Project has been engaged in an investigation of hurricanes, which in one of its aspects involves the use of specially instrumented aircraft for detailed study of the hurricane core. A discussion of the characteristics of the instruments aboard the aircraft is contained in a report by Hilleary and Christensen [6]. Additional information on instruments and data processing methods, as well as a listing of the various reconnaissance missions and type and amount of data collected by the Project to date, is given in a report by Hawkins et al.[5]. Analyses of some of the aircraft data gathered by the Project have appeared in the NHRP Report series and in various scientific publications (Riehl and Gentry, [20]; Staff, NHRP [25]; Gangopadhyaya and Riehl, [3]; Malkus et al.[15] and others).

One of the most successful investigations carried out so far was that of hurricane Daisy during August 25 to 28, 1958. The staging of reconnaissance missions into a hurricane involves complex operational planning. The number of missions in a given hurricane and the time available for study depends to a great extent on its location with respect to the home base of the aircraft. One very good opportunity for study was afforded by the formation of hurricane Daisy in a position near the Bahamas Islands on August 24, 1958. Thereafter hurricane Daisy moved slowly northward in a recurving path (fig. 1) and remained fairly close to the Florida coast and the Operations Base of NHRP at West Palm Beach, Fla. As a result, several successful and rather lengthy research missions were flown into Daisy on four consecutive days. These consisted of a 3-plane study on August 25 at levels between 1,600 and 35,000 ft.[1] over a period of 12-14 hours; two missions (low and high levels) on August 26; two missions (middle and high levels) on August 27; and a 1-plane mission at middle levels on August 28. Hurricane Daisy presented at all times a well-defined wind and radar configuration that simplified considerably the detection and investigation of the core. During the period of study there were significant variations in the intensity of the circulation, and it was, therefore, possible to obtain data at different stages in the development.

The main purpose of this report is to describe the structure of hurricane Daisy, and, at the same time, to illustrate the type, amount, and nature of the available data. Considerable analysis of certain aspects of Daisy, other than that discussed here, has already been completed or is in progress. Malkus et al. [15] made a study of the cloud distribution and discussed it in terms of thermodynamic processes. Jordan et al. [10] discussed the three-dimensional structure of the eye of Daisy on August 27, 1958, and presented some interesting radar observations concerning the vertical extent of the eye-wall. Gray [4] attempted to evaluate the balance of forces in this storm. Riehl and Malkus [22] have computed the heat, moisture, kinetic energy, and momentum budgets for Daisy on August 25 and 27, 1958. Additional work on other aspects of the Daisy circulation is being conducted by members of the NHRP staff.

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[1] Unless otherwise specified, all altitudes referred to in this report are pressure altitudes in the U. S. Standard Atmosphere.

Since one of the main objectives of this report is to illustrate the general characteristics of the hurricane data gathered by NHRP, the discussions and illustrations are generally more detailed than is strictly needed for a description of the structure of hurricane Daisy. In the final section, the properties of the Daisy circulation will be summarized and compared with other hurricanes. Some of the major changes in the parameters that accompanied the process of development will also be discussed. No strong attempt will be made to delve deeply into the dynamical and thermodynamical processes. Some work along these lines is already available in the reports on Daisy referred to above.

2. DATA AND METHOD OF ANALYSIS

The present discussion will be based on analyses of the wind, temperature, pressure, radar, and cloud fields. Analyses and interpretation were carried out almost exclusively on radial profiles. Horizontal analyses at levels for which data were plentiful were also attempted and a few selected charts are discussed. To produce these charts it is necessary to combine data taken over several hours and time variations that occur during the course of the mission must be ignored. In spite of this, fairly accurate patterns of the distribution of the meteorological variables around the center can be obtained. Nearly all of the radial passes made through the center during the 4-day period are illustrated; these include the observations of actual winds, temperatures, "D" values,[2] and humidity. Where possible, the positions of the radar bands and cloud formations along the path of the aircraft are also included. In all cases, attempts were made to illustrate details of the data to the extent deemed reasonable in view of the limitations imposed by drafting and reproduction of charts.

One of the most important features of the observational system installed in the NHRP aircraft was its high degree of automation, both in the recording of the observations aboard and in the processing of data after completion of the mission. All parameters, except the radar altitude, were digitalized and punched on cards aboard the aircraft. Readings of the various instruments were taken at intervals varying from 2 to 20 seconds; inside the hurricane circulation the 2-second interval was used most frequently. Positions of the aircraft and the winds were obtained with the aid of a Doppler navigational system; temperatures were measured with a vortex thermometer, and the humidities with an infrared hygrometer. (For a more complete description of these instruments see [6].) In addition to the above data, fairly continuous films of the photopanel display, radar scope, and of the cloud camera installed in the front of the aircraft were also available. The analysis of the radar and cloud data required time synchronization between the respective timing mechanisms and the master clock of the digital system.

The pressure variations were obtained by means of the so-called "D" values; that is, the difference between the radar altitude and the pressure altitude. In the processing of these "D" values, complete automation could not

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[2] As used here the "D" value is defined as the deviation of the height of a pressure level from its value in the U. S. Standard Atmosphere. It can also be defined in reference to any other standard.

be obtained. The radar altitude was not digitalized and had to be read from the photopanel display (see Hawkins et al.[5]). This particular display was not the most convenient for easy determination and, in general, the readings of radar altitude could not be obtained with as much accuracy and precision as was desirable. The processing of the "D" values involved a reading and smoothing process that eliminated minor variations which undoubtedly exist in the pressure field. As a result the "D" value data illustrate only the large-scale features of the pressure field around the hurricane.

The humidity readings were digitalized, and were available as often as the other parameters, but, owing to the limitations of the instruments, the results at times fell short of expectations. As is well recognized, humidity measurements are very difficult to obtain accurately, even at a stationary site on the ground.

During the course of the research missions, attempts were usually made to maintain the aircraft at a specified constant pressure level. However, deviations from this flight level, which in extreme cases reached to over 1,000 feet, inevitably occurred. For the interpretation of variations in the horizontal along a constant pressure surface it was necessary to eliminate the vertical variations and this was done by adjusting the data to a reference level. The parameters adjusted in this manner were temperatures, dew points, and "D" values; an average temperature lapse rate based on mean conditions was used in this procedure. No vertical corrections were introduced for winds.

For purposes of analysis all observations were positioned relative to the center of the system. In most of the work carried on at the National Hurricane Research Project (Staff, NHRP, [25]), including that on Daisy described here, the so-called "radar center" - i.e. the geometric center of the inner radar band, or eye-wall - was selected as the center for positioning of the data. Two other possible choices are the pressure center and the circulation or wind center. It has been found that these three centers do not generally coincide; in fact there are some cogent reasons why they should not do so. The choice of the radar center has the advantage that it is possible to determine its position with respect to the aircraft, even when the observer is located some distance away; in the case of the pressure or wind center a penetration into the eye is required. The method is not absolutely accurate; there are always human errors in determining the precise center of the radar eye; the configuration and size of the eye opening may change with time - especially in developing storms - so that there is at times some uncertainty as to whether one is following a conservative point. In spite of these shortcomings this method has been found to be the most meaningful and convenient. The compositing in the case of Daisy was greatly simplified by the fact that it had at all times a well-developed and clear-cut doughnut-shaped inner radar band with a small eye diameter. On a few occasions in which a good radar picture was not available the circulation center as given by the relative winds was used as an aid in positioning the data. On occasions in which the aircraft went through the eye on a diameter pass, care was taken to see that, in the absence of clear evidence to the contrary, the point of maximum wind speed was at approximately the same distance from the center on both sides. The reality of this observational feature has been amply verified by NHRP data. Due to the uncertainties and the assumptions adopted in the analyses, it is not possible to determine unquestionably any relationships that may have existed between the positions of the circulation, pressure, and radar centers.

3. FORMATION AND SYNOPTIC HISTORY

Hurricane Daisy developed quite rapidly during August 23-24, 1958, in an easterly wave that moved westward from the eastern Atlantic Ocean (Staff, WBO, Miami [26]). At 0000 GMT August 23 (fig. 2), the wave was located near the Windward Passage, was of only normal amplitude, and gave no particular signs of development. Twelve hours later (fig. 3) early signs of intensification began to appear with the formation of a weak, low pressure center some distance north of Haiti. As 0000 GMT August 24 (fig. 4) a weak circulation with a minimum pressure of 1009-1010 mb. was in evidence. Cyclonic development continued rapidly and late that afternoon a U. S. Navy reconnaissance aircraft located an eye formation with maximum winds of 55 m.p.h. and a minimum pressure of 1002 mb.

During August 25 and early on the 26th the hurricane moved northwestward at a speed of 7-8 kt. Recurvature toward the north and northeast occurred around noon on August 26; the forward motion at this time decreased to a slow pace of 2-3 kt. Later on August 27 and 28 the motion of the center increased steadily as the hurricane moved into extratropical latitudes. At the same time there were significant changes in the circulation characterized by a steady increase in intensity (decrease in the central pressure) to a maximum recorded late on August 27 (fig. 5). The central pressure decreased steadily from a value of 1002 mb. on August 24 to a minimum of 948 mb. on August 27. At the time of the last research mission, on August 28, filling of the central pressure had already begun. The hurricane was then located near latitude 35° N. and was moving very rapidly northeastward into middle latitudes.

The NHRP aircraft entered the hurricane circulation for the first time around 1200 GMT on August 25, only 18 hours after storm development had started. Thus, the data gathered during August 25 depict the hurricane in its early stages of development, when it was just attaining hurricane intensity. The flights on August 26 showed a circulation with a minimum pressure of 972 mb. and maximum winds of about 90 kt. The missions on August 27 were made close to the time of maximum intensity (central pressure around 948 mb.); while that of August 28 investigated the storm in the early phase of the dissipative stage.

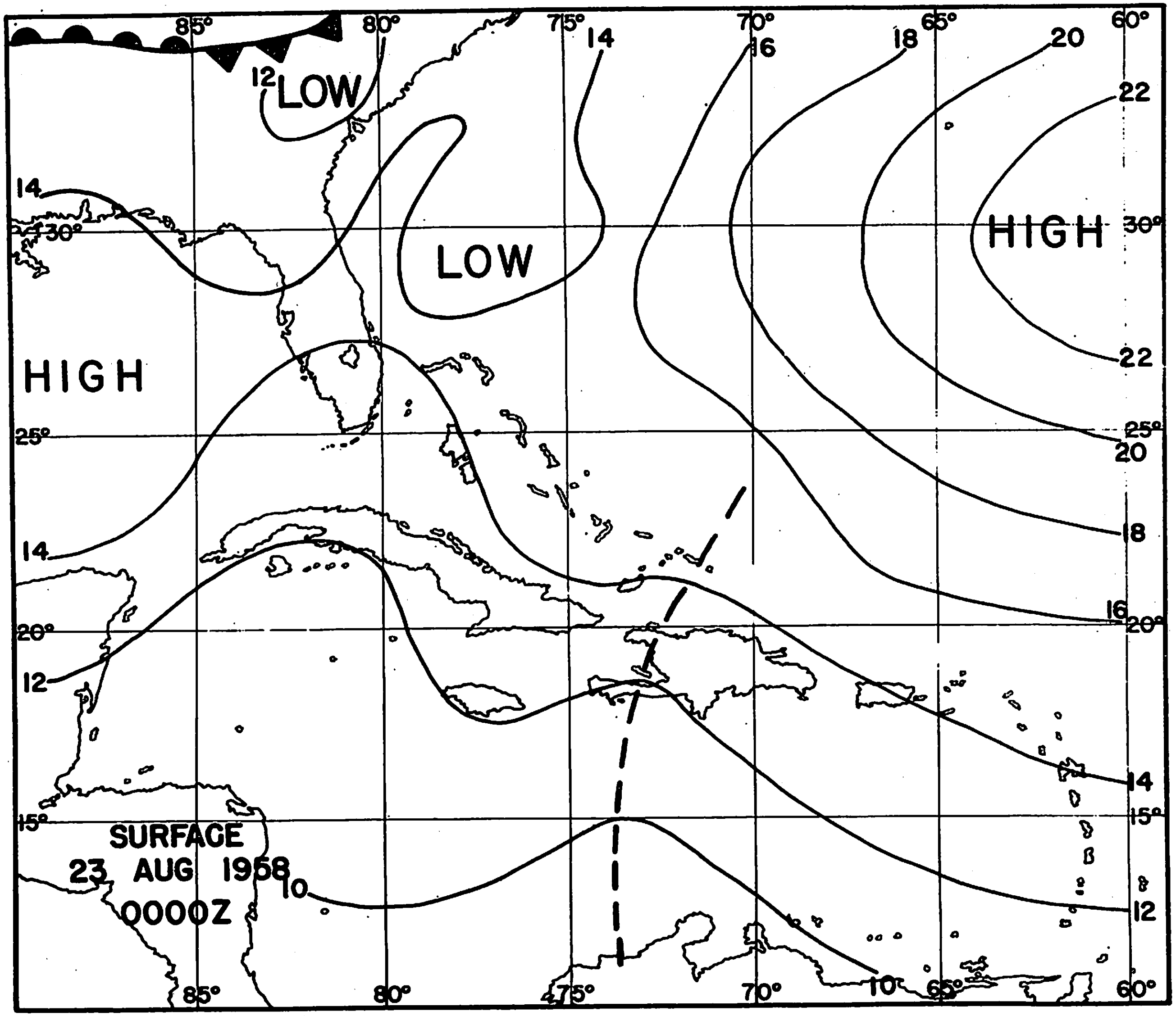

Figure 2. - Sea level isobars, labeled in mb. over 1,000, for 0000 GMT, August 23, 1958. Dashed heavy lines show the easterly wave that eventually intensified into hurricane Daisy.

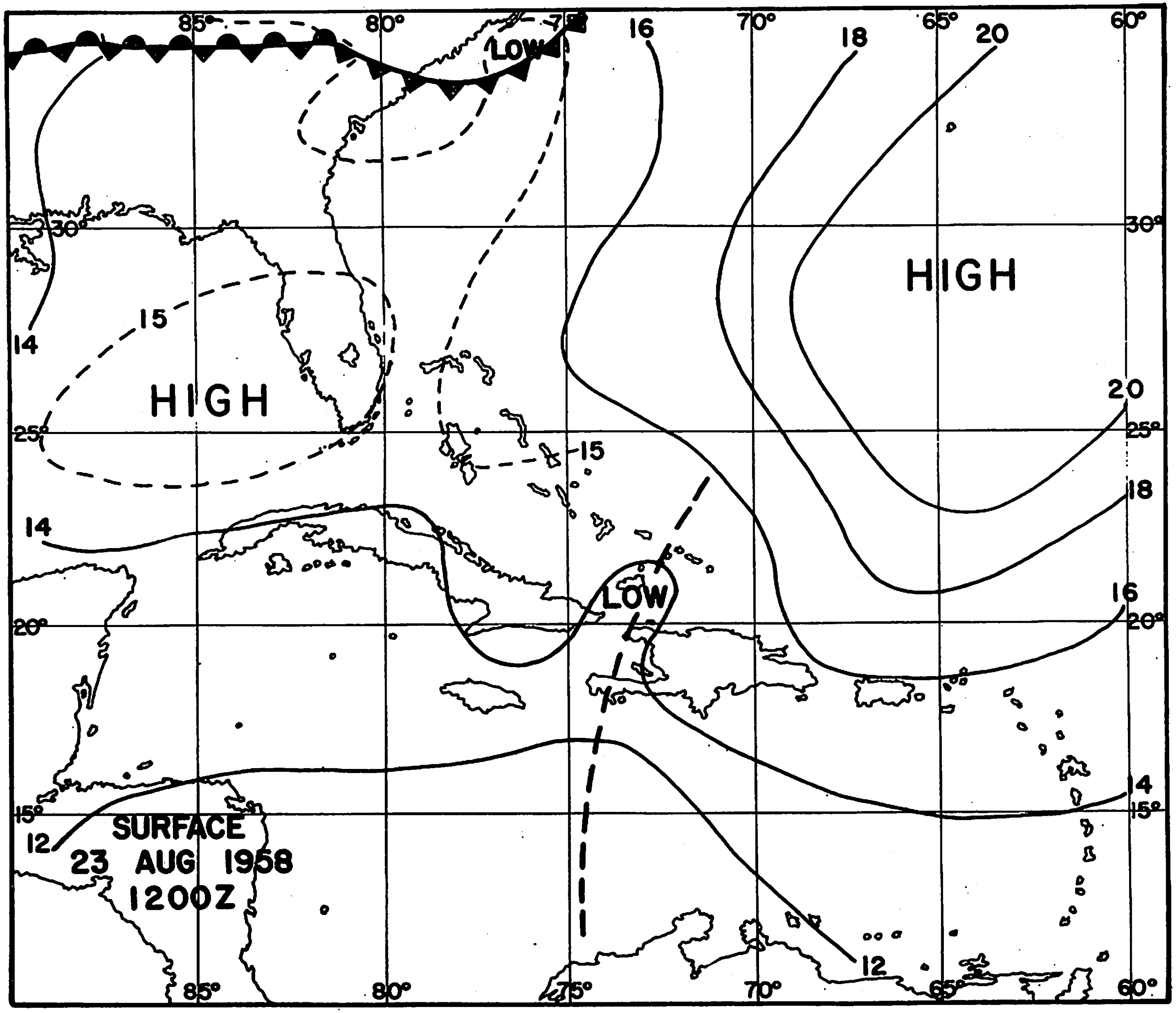

Figure 3. - Sea level isobars for 1200 GMT, August 23, 1958.

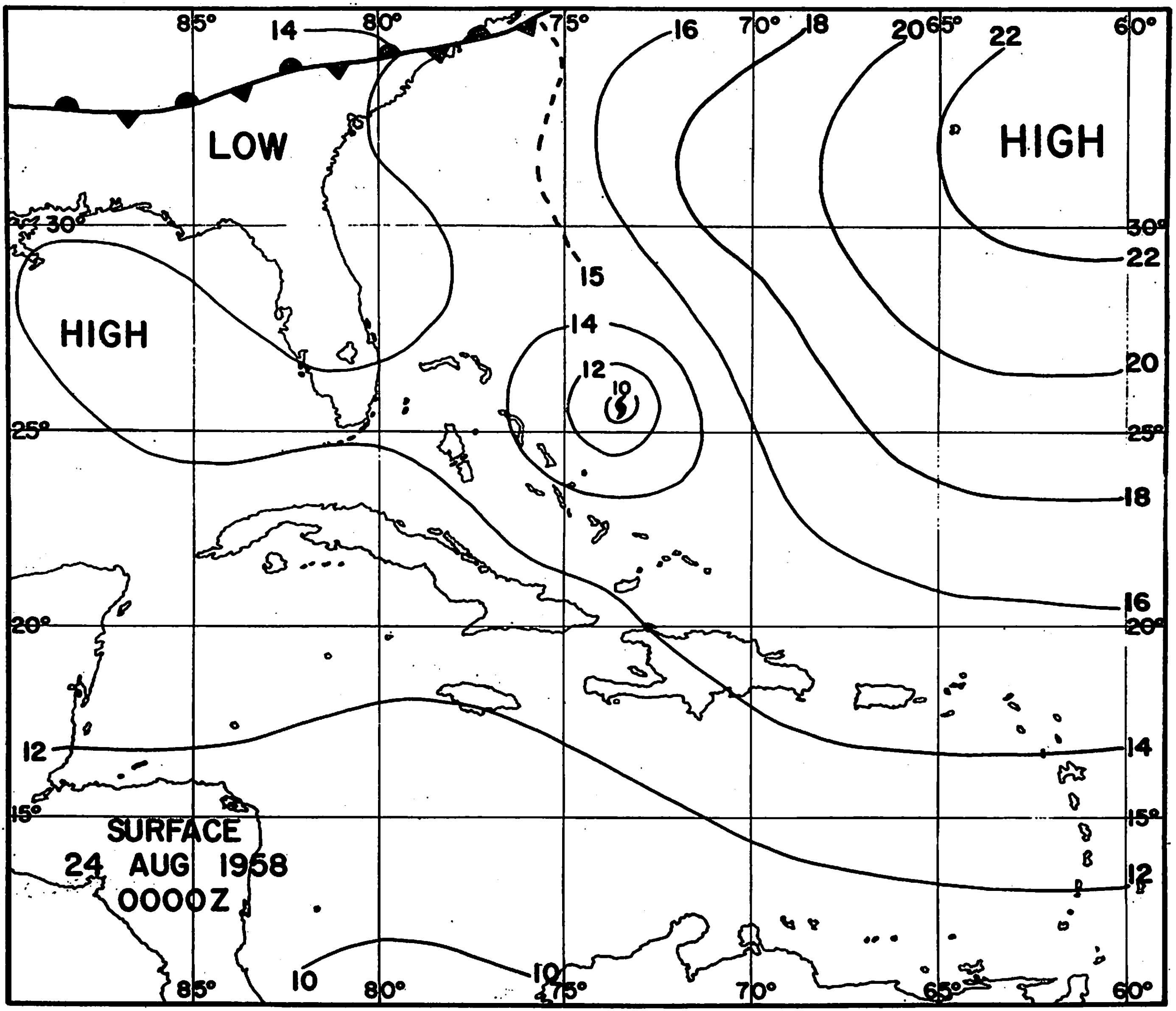

Figure 4. - Sea level isobars for 0000 GMT, August 24, 1958.

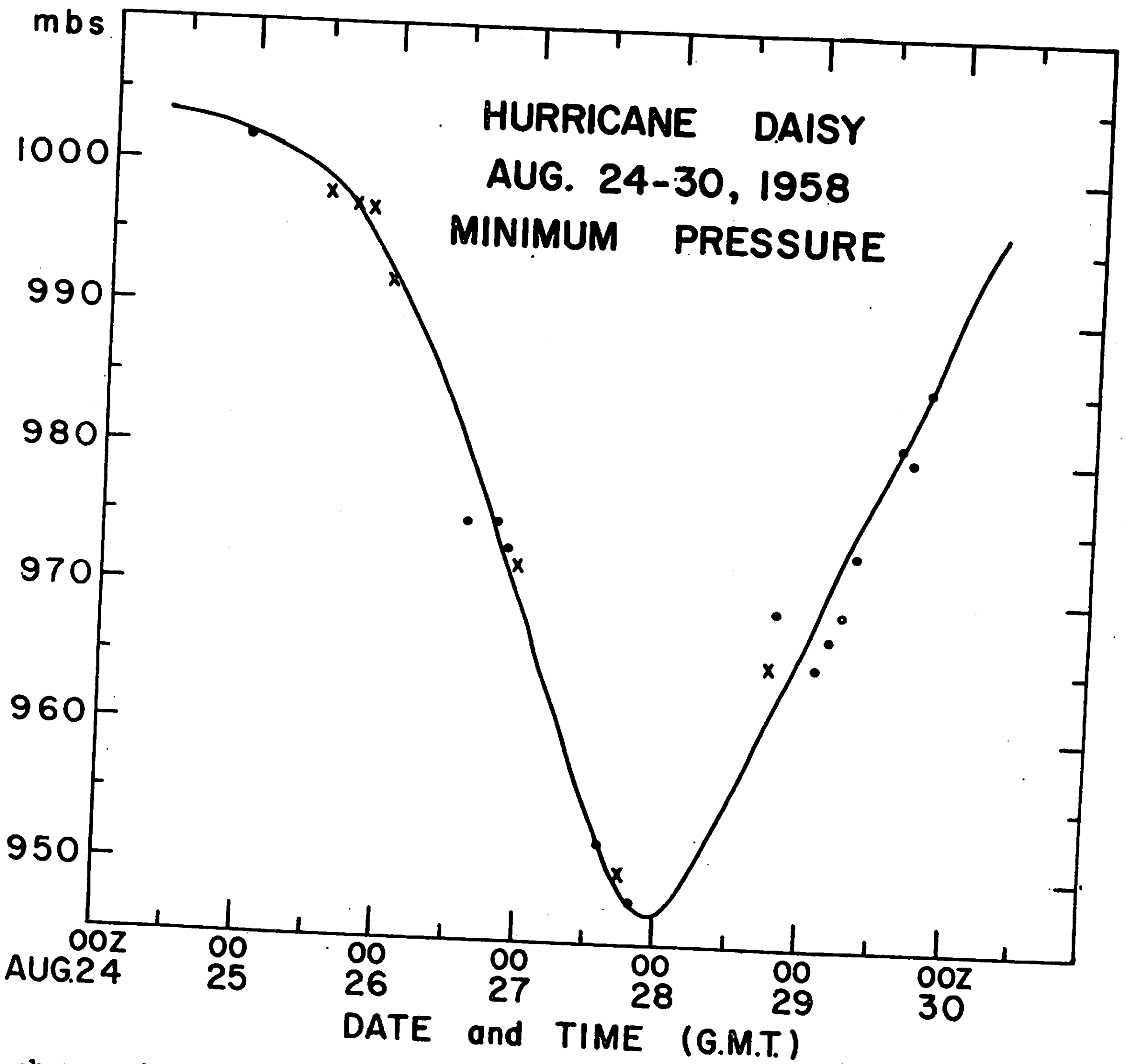

Figure 5. - Time changes in the central pressure of hurricane Daisy. The x's indicate values estimated from NHRP data; the dots show values obtained from dropsonde soundings by the military reconnaissance aircraft.

4. HURRICANE STRUCTURE, AUGUST 25

On August 25, data in varying quantities were obtained at five different levels over a period of about 14 hours. The "A" aircraft[3] flew a west to east pass at 1,600 ft., starting at about 1200 GMT; this was followed by a more extensive investigation in various sectors of the storm at 5,500 ft. Toward the end of the mission the aircraft descended to 2,800 ft. and flew an east to west traverse through the center of the eye. The "B" plane flew a 6-1/2 hour mission at an altitude of 15,600 ft. from 2000 GMT August 25 to 0230 GMT August 26. The "C" aircraft gathered data from 1800 to 2300 GMT at a level of 35,000 ft. The tracks flown by each plane with respect to the storm center are indicated in the appropriate horizontal charts and profile illustrations.

a. Radar structure.

Usually the best radar pictures were obtained by the planes flying at high levels, since they integrated the precipitation echoes over a deeper layer. The radar data illustrated in figures 6 and 7 were obtained by the "C" plane at 35,000 ft. Because of the location of the hurricane with respect to the Operations Base, and the track followed by the aircraft, fairly complete coverage of the bands on the west side of the circulation was obtained. The southernmost echoes (not shown in fig. 7 because of size limitation of the drafted chart) were observed about 190 mi.[4] south of the latitude of the eye in the extension of the two bands located 75 and 180 mi. east of the center. Some echoes were observed about 190 mi. north of the eye center; while in the east side a well defined band was observed about 180 mi. from the center with some isolated echoes located as far away as 260 mi. Other echoes associated with the storm circulation probably existed beyond the limits of the data.

Perhaps the most striking feature in figures 6 and 7 is the well organized pattern of bands around the eye and the clear definition of the eye-wall. At this time the storm was less than 24 hours old; therefore, a quite rapid development and organization of the precipitation bands had taken place. Figure 6 shows a well-defined inner band around a small eye about 12 mi. in diameter. A zone of weaker echoes, almost an opening, was present on the west side and at times gave to the wall cloud the appearance of a spiraling structure rather than a closed ring. This feature persisted and was observed in essentially the same position two days later.

To the west and southwest of the eye (fig. 7), all precipitation bands ceased at the 30- to 40-mi. radius; to the south there was a big gap between the 40- and 70-mi. radii, with a series of bands between the 70- and 100-mi. radii that came out of the east side and extended southwestward. On the east side the inner bands extended to about the 70-mi. radius with two significantly wide gaps between the 15- and 25-mi. and the 40- to 55-mi. radii. Outside the 70-mi. radius to the east, there was a band of scattered isolated echoes at about 180-mi., which

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[3] The aircraft were identified by the letters A, B, and C. Ordinarily the "A" plane flew at low levels, the "B" at middle levels, and the "C" (the jet) at levels close to 35,000 ft.

[4] All references to "miles" in this report are to nautical miles.

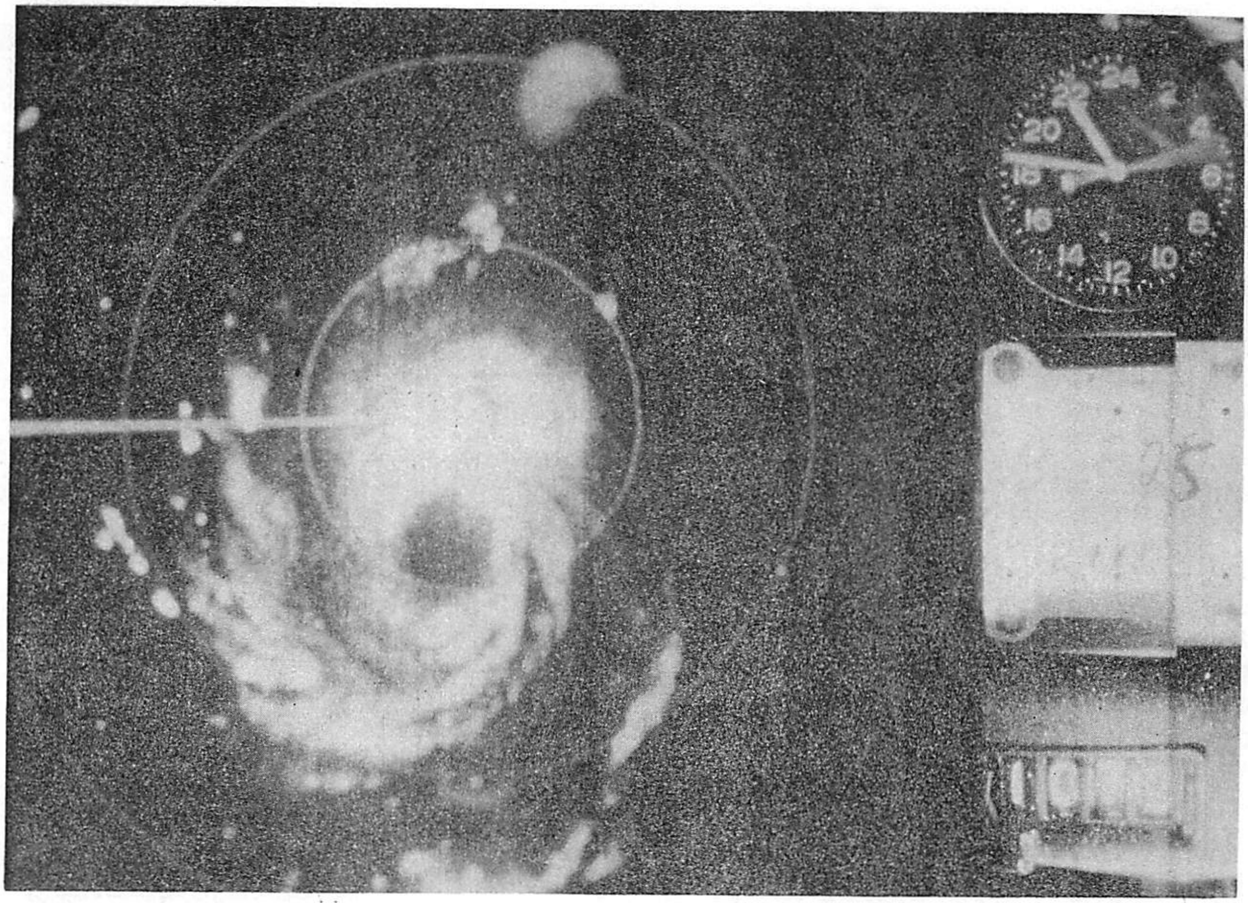

Figure 6. - Photograph of the radar scope from the NHRP B-47 jet aircraft taken at 2146 GMT, August 25, 1958, showing the eye of hurricane Daisy. Range markers are at 20 n. mi. intervals; the top of the photograph is North. The path of the aircraft with respect to the center is shown in figure 22.

spiraled around the north side and appeared to make a connection with one of the bands located on the 70- and 100-mi. radii directly ahead (northwest) of the eye. There was a distinct asymmetry in the distribution of echoes and bands in the right and left semicircles of the circulation. The inner system of bands extended about 60 mi. to the right and 30 mi. to the left of the direction of motion, with considerably longer extensions ahead of and behind the moving storm. The band located about 80-90 mi. to the south of the eye was associated with some of the most prominent and highest cumulonimbus towers observed in the cloud film studied by Malkus et al. [15].

b. <u>Circulation at low levels (1,600 to 5,500 ft.)</u>.

Data on the left front quadrant and in a direction about 90° to the right of the motion were obtained at the 1,600-ft. (957-mb.) level (fig. 8); at 2,800 ft. (915 mb.) there was a pass directly through the center of the eye in a direction perpendicular to the motion (fig. 9). At the 5,500-ft.(827-mb.) level there were three diameter profiles, two in directions not far from

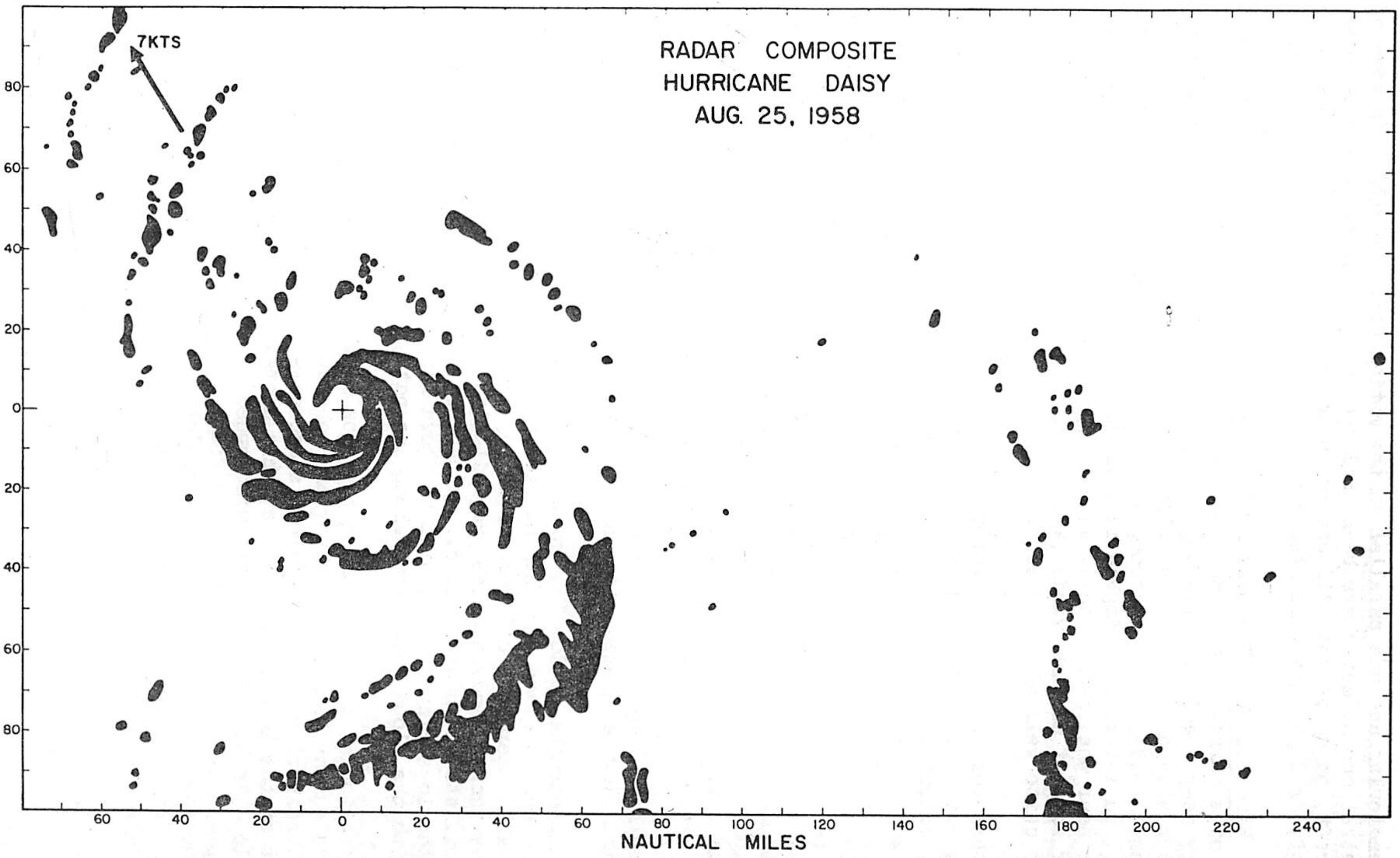

Figure 7. - Composite distribution of radar bands of hurricane Daisy as obtained from the film made by the NHRP jet aircraft on August 25, 1958. Additional echoes were observed beyond the limits of the figure to the north and south of the latitude of the center. In this and other horizontal charts in this paper the top of the figure is north.

the perpendicular and one parallel to the motion (figs. 10-13). In some of the illustrations no data have been included in the central region because the aircraft, on occasions, did not go in an exact radial path on the penetration of, or departure from, the eye.

(1) Wind field. - The most noticeable feature of the wind field was the presence of a narrow zone of maximum winds, located in all profiles (figs. 8-13) at or very near the 10-mi. radius. In some cases there was a marked peak, as in the left side of figure 9 and right side of figure 10; in others there was a somewhat broader zone of strong winds. In the left side of figure 8, at 1,600 ft., an interesting double maximum was observed, one at the 8-mi. and the other near the 21-mi. radii, with a higher speed at the larger radius. The inner zone of maximum winds (where more than one was present) in all cases coincided quite well with the inner radar band surrounding the eye.

Another very striking property of the wind field was the large asymmetry in the extent of the strong winds in the right and left semicircles. In all profiles, except figure 11, winds of over 30 kt. extended to the limits of the data (in some cases over 100 mi.) on the right side, but only to about the 30-mi. radius on the left side. In the eye core the maximum winds in the right side were close to 60 kt.; on the left side they were 40 to 45 kt. The forward speed of motion on August 25 was 7 kt., so that the maximum strength of the relative winds (observed wind vector minus the storm motion vector) was about the same on both sides. This was not the case at all times or in all sections of the hurricane. In the traverse at 2,800 ft. (fig. 9), the actual winds were equally strong on both sides of the eye; as a result the relative winds were about 14 kt. higher on the left side. This effect was not present at 5,500 ft. (see fig. 10) and may have been a transitory feature that did not persist long. Outside the 30-mi. radius the asymmetry observed in the actual wind flow persisted also in the relative wind field.

The appearance of double, and sometimes triple, peaks in the speed profiles has been observed in other hurricane data gathered by NHRP. Except for the eye-wall, there did not seem to be any well defined relation between these zones of stronger winds and the precipitation bands. The profiles show other minor oscillations in wind speed, which were more pronounced at the higher than at the lower levels. As will be shown later, some of these were associated with the cloud formations along the path of the aircraft.

Inspection of the strength of the flow in the three levels in figures 8-12 revealed the lack of any clear and consistent variation of speed with height. Ordinarily one would expect a decrease of wind speed with elevation, but at the levels shown above, this decrease was not particularly noticeable. In some sections the wind speed appeared to increase upward. For example, note in the left side of figures 9 and 10 (both profiles along nearly the same radial direction) the relative constancy of the wind flow outside the 40-mi. radius. However, the speeds at the upper elevation were about 10 kt. higher than those at the lower. Furthermore, the data at the higher level, figure 10, were obtained about 5-6 hr. earlier than at the lower one; therefore, the difference cannot be explained on the basis of changes in intensity, since the over-all circulation was intensifying with time.

The wind profile along the direction of the storm motion (fig. 11) shows properties different from those observed in other directions. On the forward side there was not much concentration of wind strength at the eye-wall and the flow was weaker than on the rear side. Outside the 30-mi. radius the winds were equally strong on both sides.

In the analysis of the horizontal field at 5,500 ft. (fig. 14); some of the minor variations shown in the profiles were smoothed out. For detailed evaluation of the horizontal gradient, particularly in the vicinity of the eye, one should refer to the individual profiles rather than to the horizontal analysis. The streamline field reflected to a large extent the typical lower-level flow in hurricanes. There was a bulge in the streamlines toward the northwest, the significance of which is difficult to evaluate, but nearly circular streamlines were obtained in the core. The isotach field showed a crescent-like region of speeds over 50 kt. around the right semicircle of the eye. There was a small zone of winds of over 60 kt. on the right side, while ahead and to the left of the storm motion the speeds were around 40 kt. Winds of over 30 kt. extended outward to about 90 mi. on the right side and covered essentially the right-rear and half of the right-front quadrants. There was a rather large zone of winds of over 40 kt. located about 60 mi. out on the right side, while on the left side at the same distance the speeds were less than 20 kt.

The relation between the streamlines and isotachs in figure 14 indicated an increase in wind speed downstream from left rear to right rear quadrants and decrease downstream from right front to left front quadrants. The distribution of the streamline and pressure fields (not illustrated) was such that the flow was generally toward lower pressure (acceleration) in the rear and toward higher pressure (deceleration) in the forward side of the circulation, in agreement with the observed wind speed variation.

(2) Temperature and moisture properties. - The temperatures in the eye at 1,600 ft. (fig. 8), and also at the 2,800-ft. level (fig. 9), were not much warmer than those outside of the storm. The maximum temperature recorded at the 1,600-ft. level was 23.8°C., mean normal for August at that level; while at 2,800 ft. the maximum was 22°C., only 0.7°C. warmer than normal. At the higher elevation, the maximum temperature in the eye was 20°C., or about 3.5° C. warmer than normal. The small difference between the temperature of the surface air in the eye and that of the outside low-level air is well known; its significance with regard to the thermodynamic aspect of the air spiraling in toward the center near the surface has been amply discussed in the hurricane literature (Riehl [18]).

One of the most surprising features of the thermal field was the appearance of a region of relatively cool air just outside the eye-wall. In figure 8 it was located in the 20- to 30-mi. radius on the left and in the 30- to 40-mi. radius on the right; in figure 9 it was very prominent near the 20-mi. radius on both sides of the circulation; while at the 5,500-ft. level it appeared at about the same radius on all sides of the storm. In some cases there were other zones of cool air located farther away from the center with relatively warmer air in between. These cold temperatures in the rain area have been discussed extensively among researchers who have worked with the

NHRP data. The same effect has been noted also in other hurricanes. The problem of instrumental errors in the vortex thermometer has been raised, but to date it has not been possible to clarify the issue conclusively. This subject will be discussed further, later on in this report; it may be of interest to mention here that Bergeron [1] hypothesized the existence of cool regions in the rain area near the core, due to the cooling effect of evaporation from falling rain.

The dew point profiles showed, in general higher values near the center. Radial variations were in some cases in phase with the temperatures, as observed in the left side of figure 8 near the center and on the right side of figures 9, 10, and 11. However, out of phase variations were just as prominent in certain sections of the storm; for example, the region outside the 65-mi. radius on the right of figure 8, the outer regions on the left side of figure 9, and also certain sections of figures 10 and 12.

The variations in temperature and dew point observed in figures 8 and 12, as well as in the other profiles shown in this report, can be shown to be closely associated with the crossing of radar bands in the flight path and with the cloud formations along the path. The radar information included in all of the profiles was obtained from the films obtained by the particular aircraft at the time of the radial passes, and the exact details need not coincide with those observed at other levels or with what one can determine from figures 6 and 7. The accuracy of the positioning of the radar bands (and the same is true for the cloud data) involves a time synchronization between the radar (or cloud) and data clocks. It depends also to a great extent on the degree of sharpness of the particular echoes, which in turn is a function of multiple factors, such as the intensity of the rainfall gradient, the characteristics of the instrument, the altitude of the aircraft, the setting on the control console in the aircraft at the time of the photographs, and the quality of the photographic reproduction. All possible care was taken in the determinations illustrated in this report, but some minor leeway must be allowed with regard to the positions of the band edges. The same is true for the cloud data.

In spite of these shortcomings, there were some interesting well-documented relationships evident between the variations in temperature and dew point and the cloud and radar fields. For example, on the left side of figure 9 one can notice drops in dewpoint as the plane exited from the bands at the 13- and 23-mi. radii; a drop in the temperature also occurred at the exit from the outer band. On the other hand, outside the 30-mi. radius, there were variations in temperature and dew point of somewhat similar characteristics that have no relation to precipitation bands. Figures 7 and 8 show no radar bands outside the 30-mi. radius on the southwest side of the storm.

Some of the relationships with the cloud distribution can be observed in those profiles that include cloud data. For the flights at 1,600 and 2,800 ft. the cloud data were either not available or unsatisfactory. It could be established, however, that at 1,600 ft. the aircraft flew - for the most part - just below the cloud bases; only in certain sections near the eye-wall did it penetrate the clouds. There was also a reliable indication that the sudden drop in temperature and rise in moisture observed at the 85-mi. radius on the right of figure 8 was produced when the aircraft went through precipitation just below the cloud base.

Other significant and interesting variations in temperature and dew point with cloud distribution are illustrated in figures 10 and 13. Figure 13 shows part of the data of figure 10, plus the wind direction, plotted against time on an expanded scale. Starting on the north side, the aircraft went into clouds at about 1415 GMT (radial distance of 65 mi.) and emerged at 1416 GMT (radius of 61 mi.). Precipitation was falling from the cloud and appeared distinctly on the radar scope (see fig. 10). The dew point increased as the plane entered the cloud, while the temperature first decreased, then increased to a minor maximum at a radius of 63 mi. (1415.6 GMT). This was followed by a sharp drop of almost 2° to a minimum near the inner edge of the cloud. The drop in temperature and dew point apparently started within the cloud and continued beyond the cloud edge. Shortly after the plane arrived in the clear, the temperature recovered and increased again, while the dew point continued to decrease. Oscillations in temperature and dew point of about 2°C. in magnitude, characterized by a rise on entering cloud and a drop on emerging, were produced by two active clouds (and associated precipitation bands) in the period from 1420 to 1423 GMT (radii of 47 to 40 mi.). The temperature again recovered after the plane emerged from the second cloud, while the dew point continued decreasing slowly - the same effect noted before. The oscillations in wind direction and speed were practically negligible; if anything, there was a slight tendency for speed decrease within clouds and increase on breaking out.

Between 1422.4 and 1427.5 GMT (radial range of 40 to 22 mi.) the aircraft was in the clear, between cloud decks, except for a minor thin cloud crossed between 1425 and 1426 GMT, which did not cause noticeable changes in the parameters. The sudden increase in dew point between 1425 and 1426 GMT (radial distance of 30 mi.) is spurious and caused by the instrument going into reference for calibration. Similar effects may be noticed occasionally in some of the other profiles but usually all such records have been deleted. At the 22-mi. radius the plane entered the cloud system of the eye-wall, and the break-out into the clear eye occurred at about 1435 GMT near the 3-mi. radius. The radar film showed no significant bands between those in the 47- to 40-mi. zone and the wide inner band around the eye.

On the south side of the eye the cloud system extended from about the 9- to the 20-mi. radii (1438 to 1441 GMT). There were two main radar bands on this side (see fig. 10), one on the inner edge and the other on the outer edge of the wall-cloud mass.

One of the most interesting features of the cloud distribution is that during penetration into the eye from the north side the aircraft remained in clouds until it was very close to the geometric center the "radar-doughnut." This may have been due to a layer of clouds protruding from the eye-wall into the center. In this respect it can be mentioned that one of the eye traverses made on the same day by another plane at an altitude of 15,600 ft. was made completely in cloud.

There were significant variations in temperature and dew point across the eye-wall cloud system; on the north side the temperature decreased in the outer section of the cloud to a minimum at about 1429 to 1430 GMT (radial distance of 17 to 14 mi.); this cold section was located near the outer edge of the precipitation band. Both the temperature and dew point then increased toward the center of the eye, but both the dew point and the temperature showed a momentary decrease near the inner edge of the hard precipitation echoes at the 10-mi. radius (1431 to 1432 GMT). A quite sudden increase in temperature and decrease in dew point occurred as the plane emerged into the clear section in the eye at 1435 GMT. As the plane continued along the flight track, the temperature reached a peak near the south edge of the eye, then dropped rapidly to a minimum in cloud near the outer edge of the inner radar band at the 12-mi. radius (1438-1439 GMT). There was some additional cooling inside the clouds to a minimum at the immediate outer edge, followed by rapid warming beyond the cloud edge. The dew point decreased in the clear section of the eye to a minimum near the south edge, increased inside the cloud system, and apparently decreased near the outer cloud edge, but part of the data are missing. From the 20-mi.radius outward the aircraft was in the clear. The temperature reached a maximum near the 35-mi. radius (1445 GMT); from there on, the variations in temperature and dew point were relatively minor until the crossing of a precipitation cell at the 106-mi. radius which produced some rapid and large fluctuations (see fig. 10).

The fluctuations in wind speed were generally small and did not have a very clear connection to the cloud and precipitation fields - at least in this section of the data. This is not true at some of the upper levels, as will be shown later. The variations in wind direction were rather minor and could not be easily associated with the cloud or precipitation distribution.

The above discussion indicates that the small-scale fluctuations in temperature and humidity are for the most part associated with the clouds and precipitation distribution at flight level. Interestingly enough, the data showed both a trend for warming in cloud and cooling on breaking out, as in the section from 1415 to 1423 GMT in figure 13, and for cooling in cloud and warming on breaking out, as observed in the passage through the eye wall. This might be due to differences in the age or stage of development of the clouds. For example, warming in clouds suggests a young, developing, and vigorous convective current; while cooling might reflect cold downdrafts in precipitating clouds that have reached the mature stage. There is also a question of possible instrumental error due to water and condensation processes in the immediate vicinity of the probe; this question will be discussed in a later section.

The data of figures 10 and 13 indicate that the convectively inactive zone outside the 30-mi. radius on the south side was about 2°C. warmer than the corresponding, but more convectively active, zone on the north side. These relationships between the temperature field and the convective systems have been discussed also by Malkus et al. [15] who emphasize the pronounced asymmetry in the convective development on different sides of the storm (shown clearly in fig. 7) and the tendency for larger temperature fluctuations and colder temperatures to be associated with more active convection.

One interesting feature of the temperature data was the tendency for the peaks and valleys in the radial profiles to be located at about the same radius along different directions. As a result the horizontal distribution (fig. 15) showed alternating zones of relatively cool and warm air arranged in quasi-circular fashion around the center. Since the temperature fluctuations have been shown to be closely related to the convective cloud system,

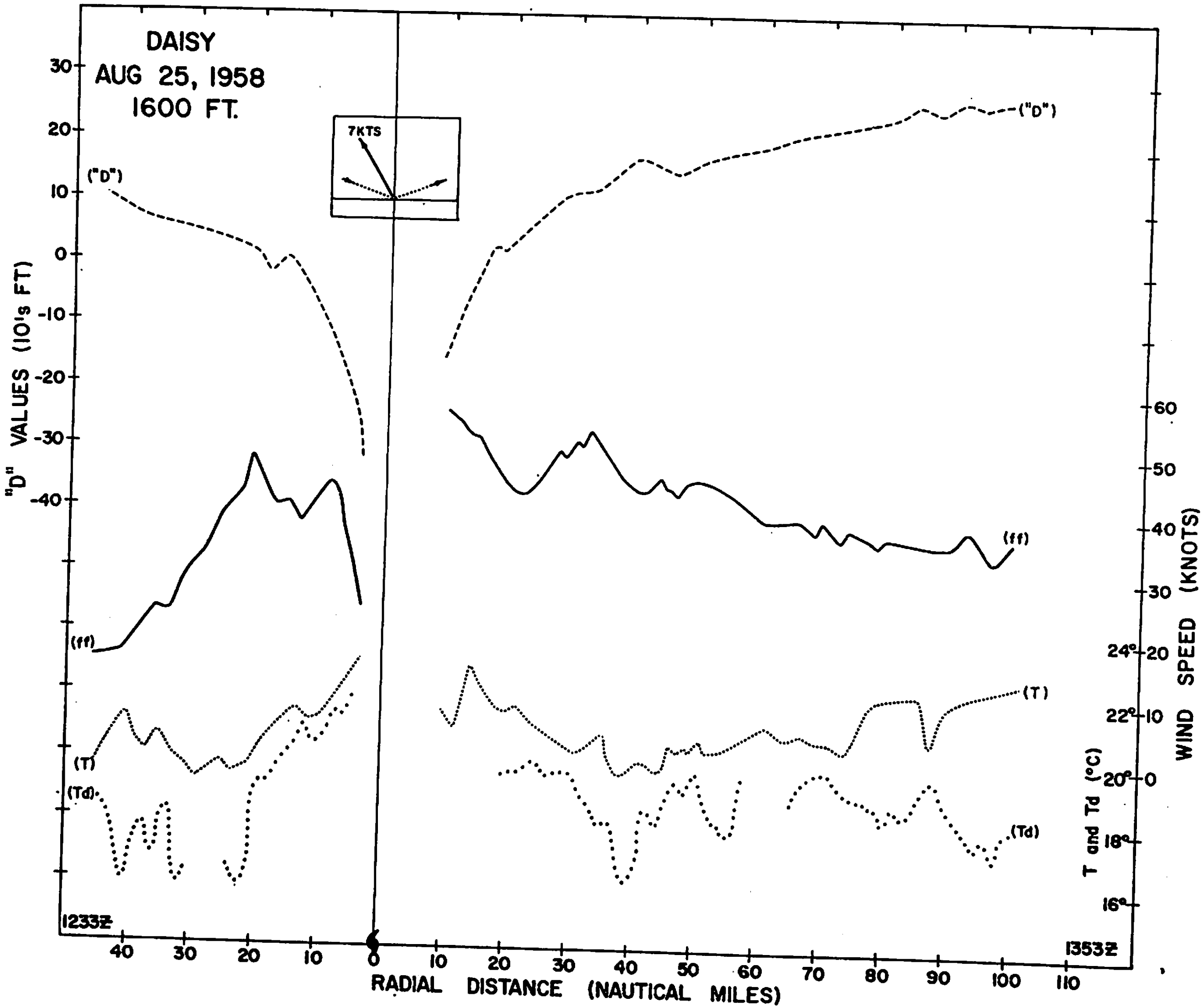

Figure 8. - Data profile ("D" values, wind speed, temperature, and dew point) at 1,600 ft. (pressure altitude, U. S. Standard Atmosphere), 957 mb., August 25, 1958. Small insert at the top is a horizontal diagram which shows the approximate path of the aircraft (dashed) and the storm motion (solid). This same format is followed in all profiles shown in this report. No cloud or radar data included here.

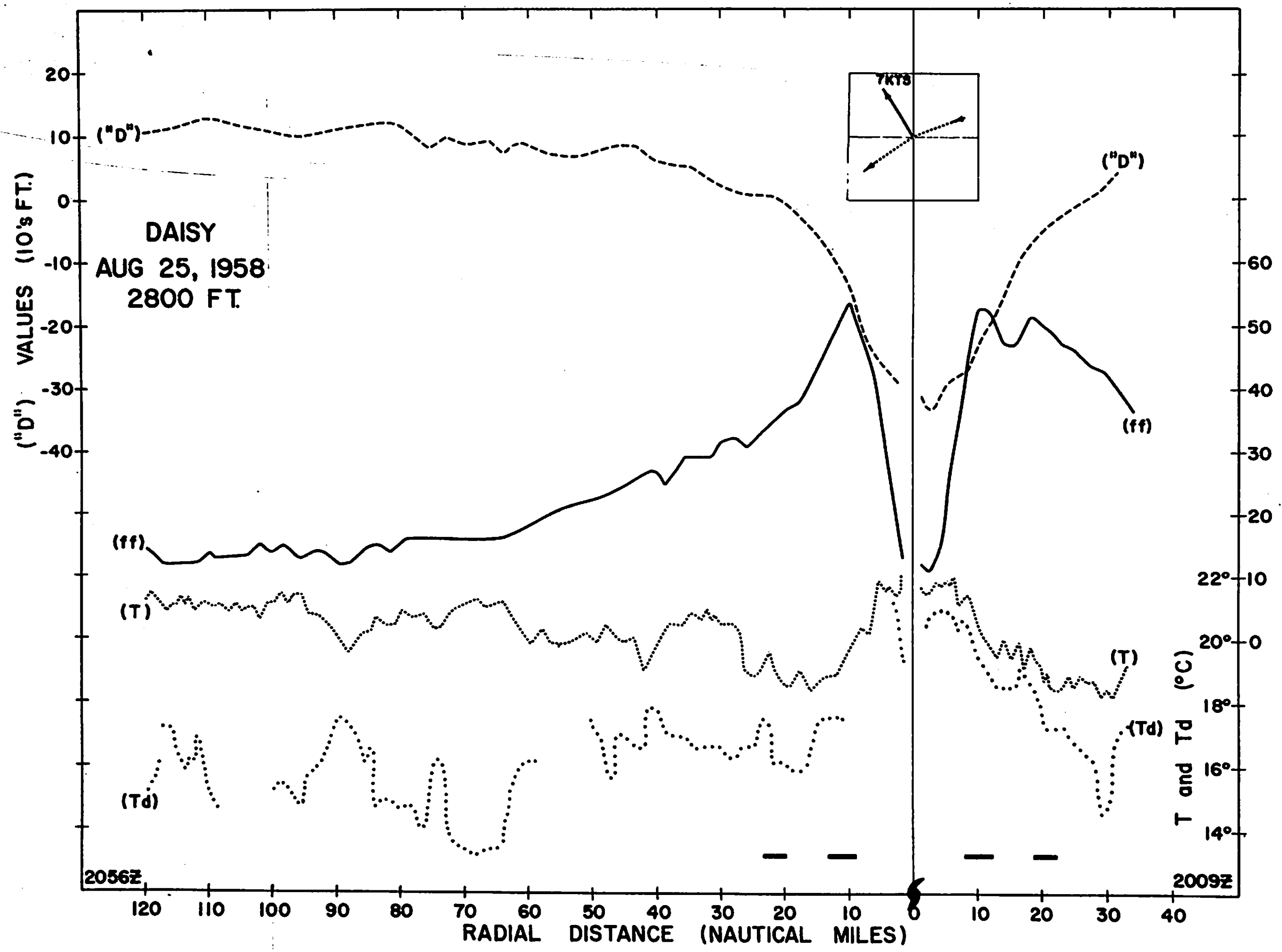

Figure 9. - Data profile at 2,800 ft., 915 mb., August 25, 1958. The black horizontal line segments in the bottom represent the position and extent of radar bands observed by the aircraft. No cloud data included.

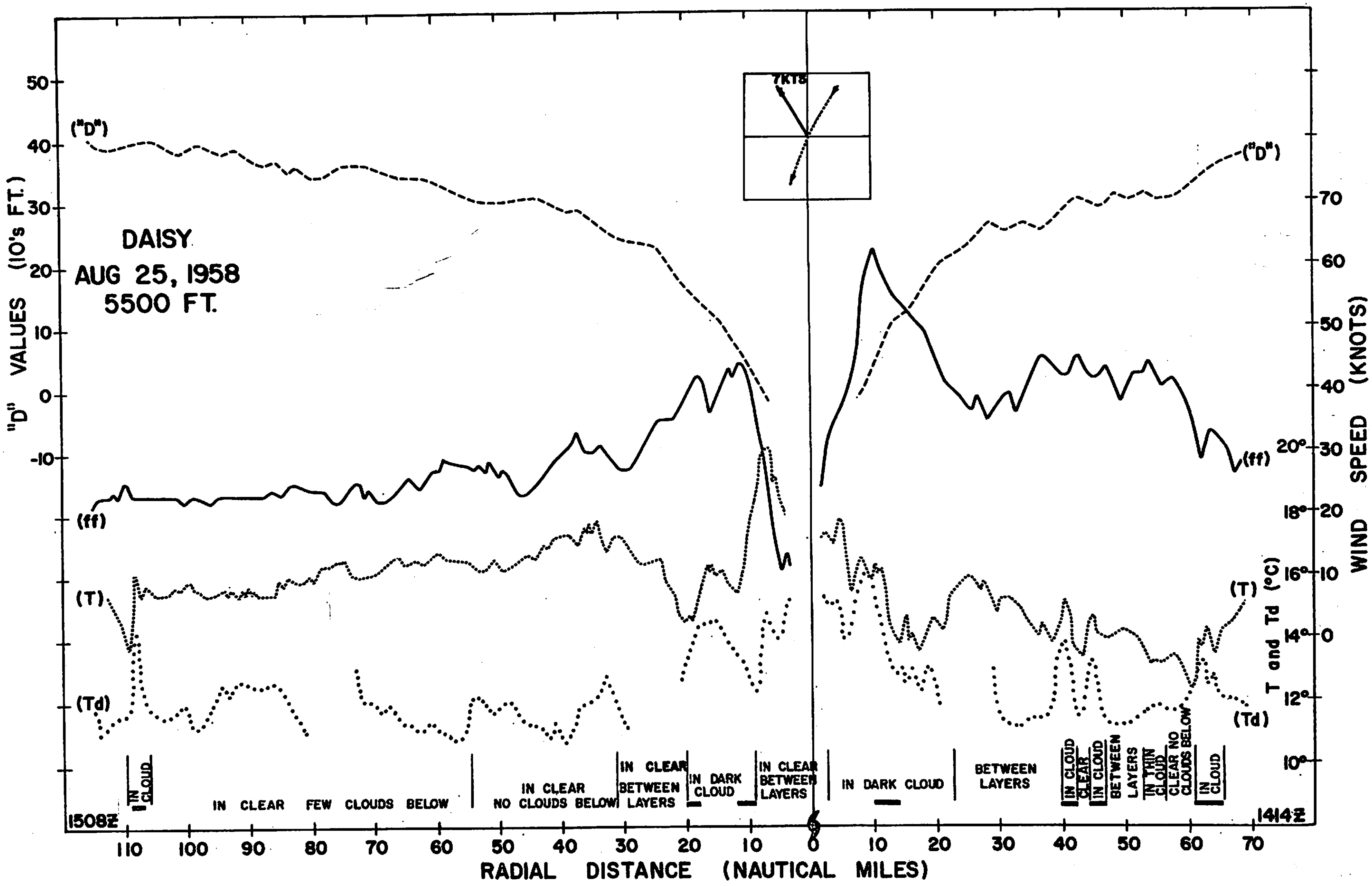

Figure 10. - Data profile at 5,500 ft., 827 mb., August 25, 1958. This diagram includes the radar bands and also brief remarks on the cloud distribution at flight-level as obtained from the nose-camera film. The cloud remarks apply to the sections included between the vertical lines. The same format in regard to clouds and radar is followed in all profiles.

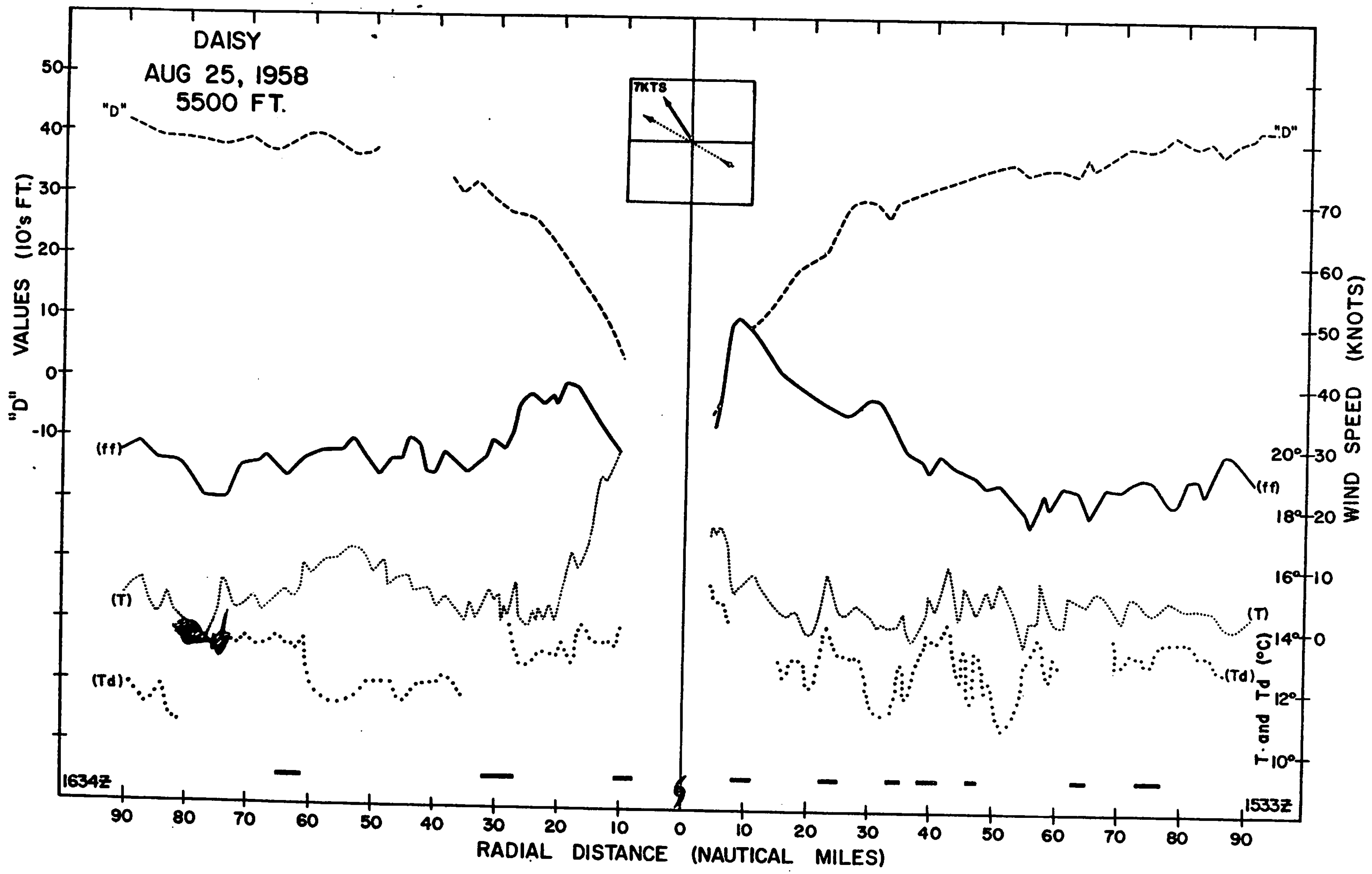

Figure 11. - Data profile at 5,500 ft., 827 mb., August 25, 1958.

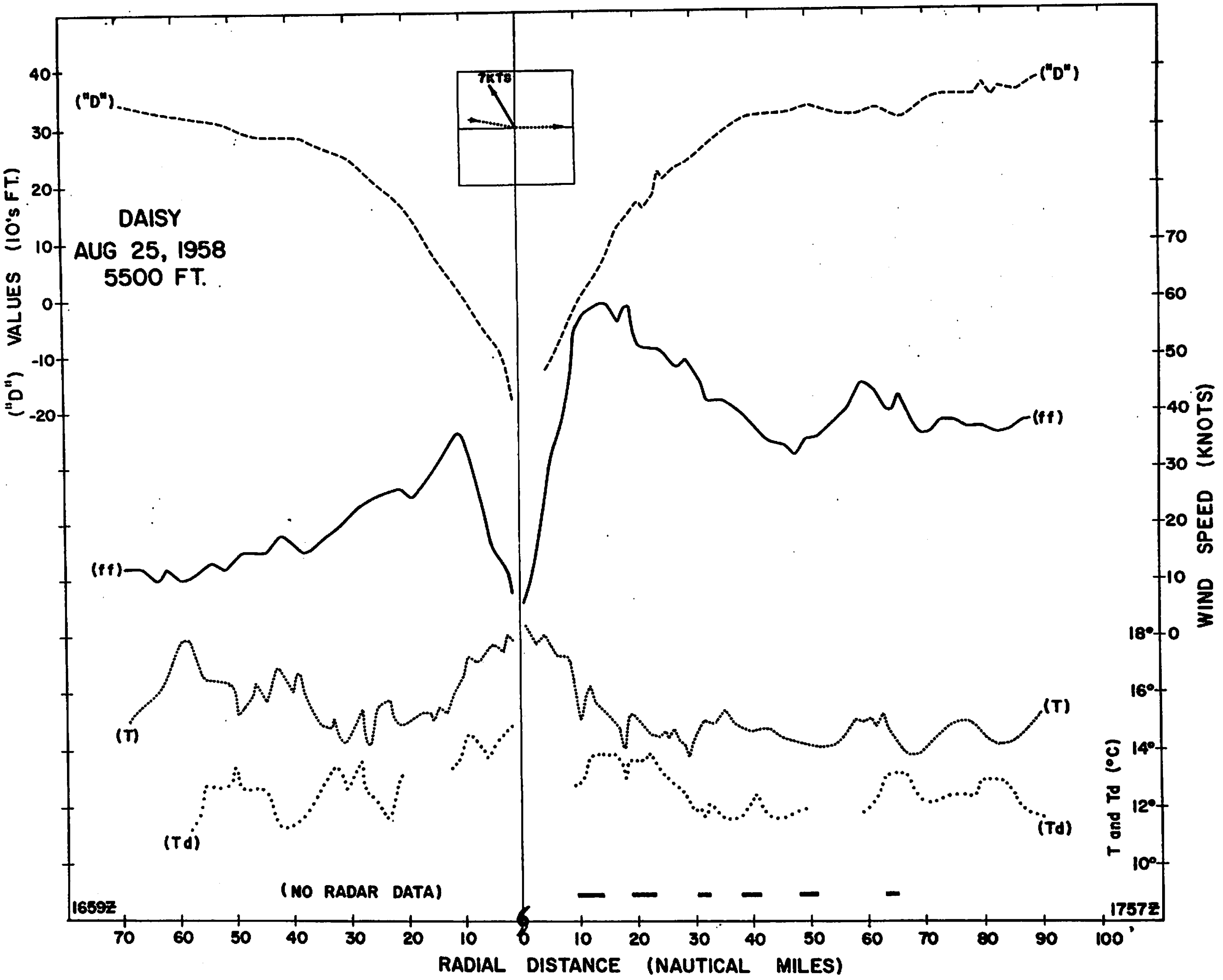

Figure 12. - Data profile at 5,500 ft., 827 mb., August 25, 1958.

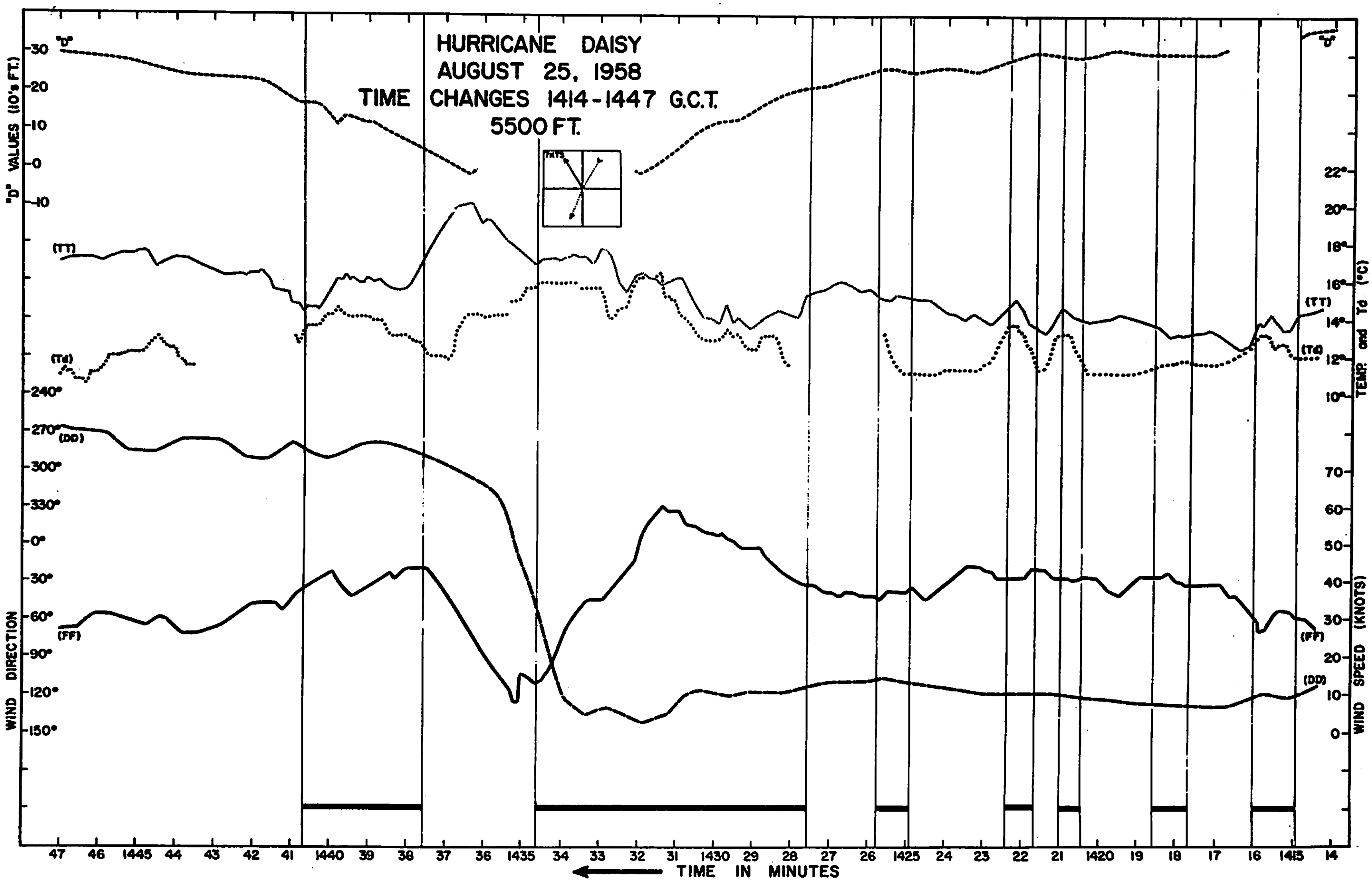

Figure 13. - Time variations of "D" value, temperature, dew point, wind speed, and wind direction for section between 1414 and 1447 GMT. These same data are plotted in a space scale in figure 10. The horizontal line-segments show the intervals when the aircraft was in cloud.

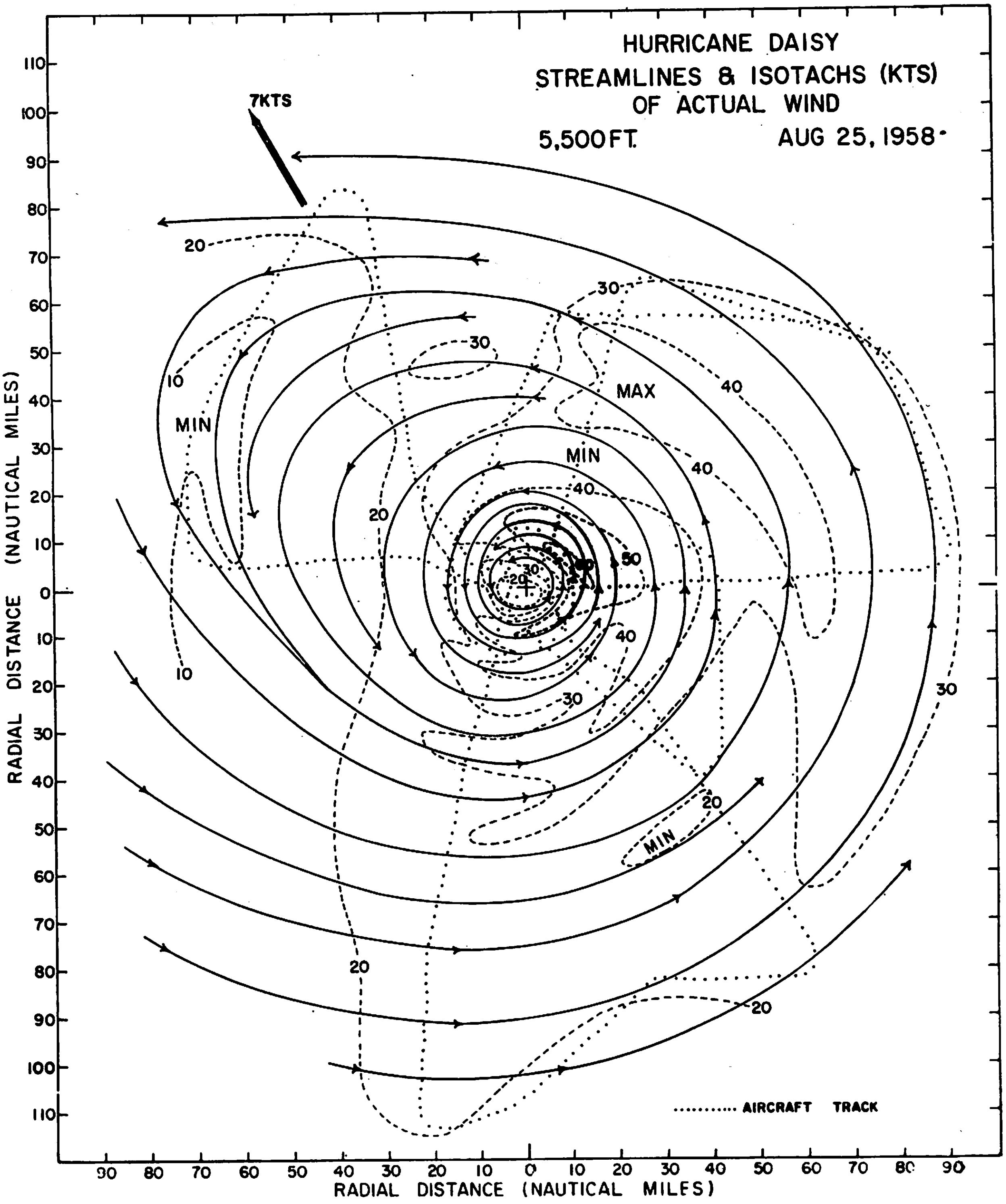

Figure 14. - Horizontal wind field at 5,500 ft., 827 mb., August 25, 1958. Streamlines in solid, isotachs (kt.) in short dashed lines. Dotted path shows the track of the aircraft relative to the storm center. Heavy arrow at top indicates the storm motion.

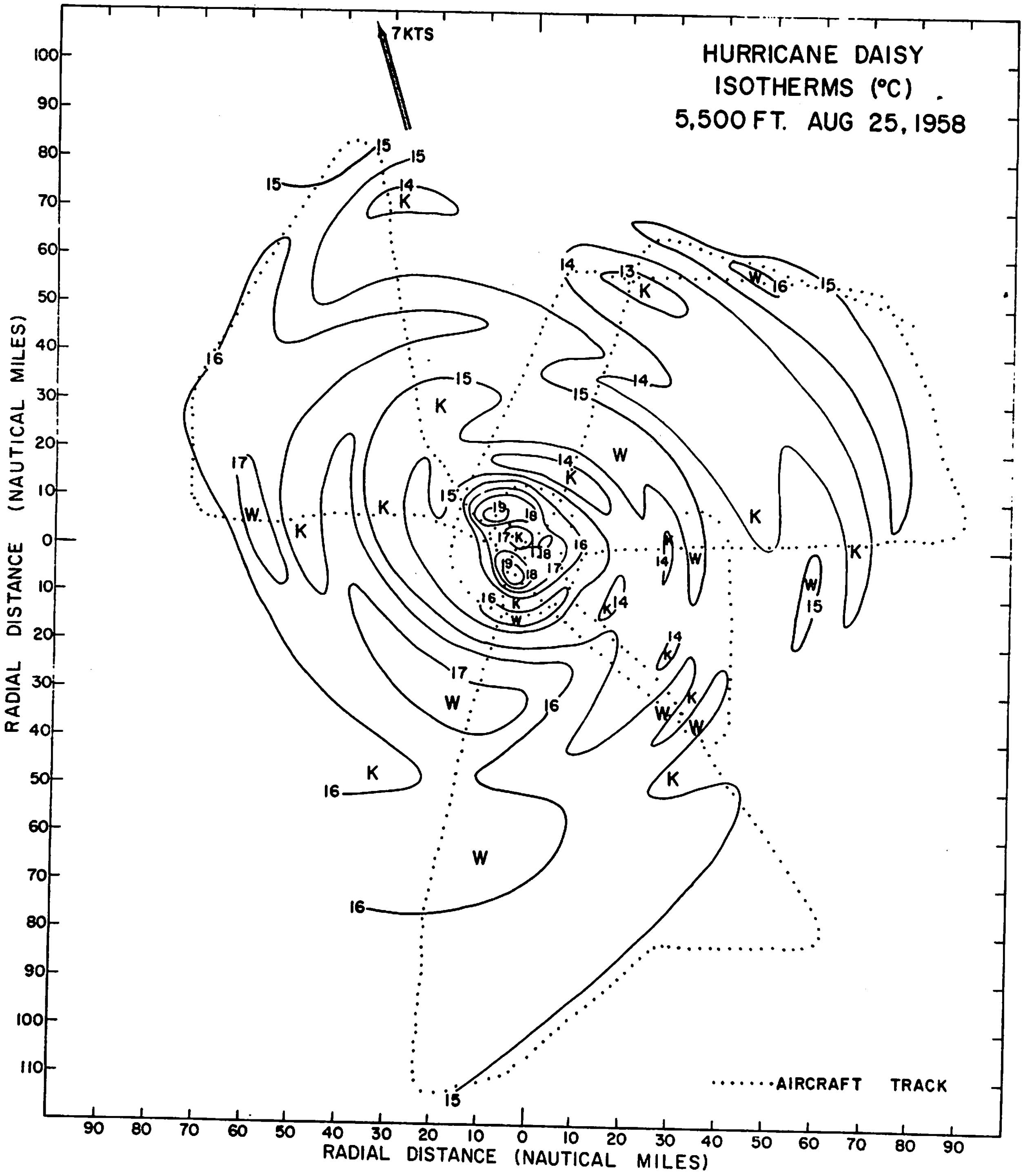

Figure 15. - Temperature field at 5,500 ft., 827 mb., August 25, 1958. W stands for warmer, and K for colder. Dotted path shows the path of the aircraft. Heavy solid arrow at the top indicates the storm motion.

this circular trend was a reflection of the fact that the major convective clouds were also arranged in a quasi-circular orientation around the center. Of particular interest is the cool region near the 15- to 20-mi. radius. The maximum temperatures in the eye were not located in the exact geometric center, but toward the periphery. One of the centers of temperatures above 19°C. was displaced quite significantly toward the forward side of the eye. The asymmetry in the magnitude of the temperatures between the two semicircles of the hurricane appears clearly in figure 15; temperatures above 16°C. were observed only in the eye and in the left side, while temperatures below 14°C. were present only in the right semicircle.

(3) Pressure field. - The "D" value profiles showed the typical variations of tropical cyclones. The horizontal gradients were practically negligible outside the 30-mi. radius and increased rapidly inward toward the center. A horizontal analysis has not been illustrated, since it shows nearly circular isopleths with strong gradient near the eye. The minimum value observed on the 25th at the 1,600-ft. level was -340 ft. which corresponds to a central pressure of about 998 mb. (Jordan [8]). At the 2,800-ft. level the minimum value was -330 ft. for a central pressure of 997 mb., while at the 5,500-ft. level the minimum was -170 ft., or a central pressure of 997 mb. The profile across the eye in figure 9 shows the center of minimum pressure displaced slightly to the right of the radar and wind centers. In view of the uncertainties in the measurement of "D" values and of the radar center, this observation may be beyond the limits of accuracy of the data. However, previous studies indicate that such a displacement is to be expected (Myers [17]).

c. Hurricane circulation at middle levels - 15,600 ft.

(1) Wind field. - The wind field at the 15,600-ft. (560 mb.) level (figs. 16-20) was characterized by a distribution somewhat similar to that observed at lower levels; there was a zone of maximum winds, with speeds of 50-55 kt., located near the 10-mi. radius. The maximum wind speeds were only slightly lower than those at low levels. Since some intensification had taken place - the central pressure at the time of the "B" flight was around 992 mb. - it is quite possible that the general strength of the flow was greater than at the time the lower-level data were recorded. However, even allowing for this effect, no appreciable weakening of the hurricane circulation with elevation could be detected at this level. Figure 16, a profile on the right front quadrant, showed a maximum of 50-55 kt. near the center, with indications of a secondary maximum at about 35-40 mi. radius. This was somewhat similar to the picture observed on the same side of the system at low levels (figs. 8-10), although the minor features were not the same. On the left side of the circulation (left sides of figs. 18 and 19) the maximum winds were about 35 kt. in the profile shown in figure 18 and about 50 kt. in the profile of figure 19. Interestingly enough, these two profiles were taken at about the same azimuth, but were made about 2 hours apart. They illustrate some of the variation of the parameters with time. The greatest difference between the two was observed inside the 30-mi. radius, where the winds on the later pass (fig. 19) were about 10 kt. higher than those on the earlier one. The small-scale oscillations were also different on the two passes, but some of the gross features in the outer sections were not too dissimilar.

Other fluctuations in time can be observed in the two profiles of the right front quadrant, figure 16 and the right side of figure 19. Both were at about the same azimuth, but the one in figure 19 was recorded about 4-1/2 hours later. There was a slight similarity in the wind profiles in that both showed a tendency for a secondary maximum zone in the 30- to 40-mi. radius, but the details were different. The wind speeds in figure 16 (the earlier pass) were generally higher, contrary to variations observed on the southwest side. Striking differences in the two profiles were noticed in the temperature field and in the distribution of the radar bands.

It is interesting to notice in figure 19 that the difference in the maximum winds on either side of the eye was so small that the relative winds were higher on the left side; the same effect was observed in figure 9, on the same side of the storm.

The wind flow in the direction parallel to the motion (fig. 17) showed some significant differences from the other profiles. First, there was no wind speed concentration near the eye; instead, there was a broad zone of relatively constant speeds on both sides. Comparison with figure 11, with data in about the same direction at lower levels, shows some differences and similarities. At the lower level there was a wind speed concentration near the eye on the rear side; on the forward side the character of the wind was about the same at both levels. The strength of the wind in the forward side was greater at the upper level; this may have been partly due to the changes in storm intensity in the time interval.

The above discussion gives a good idea of the complexity of the circulation in the hurricane area and the large degree of variation, both in time and space, that seems to take place in the hurricane core. This points to the difficulty of makinggeneralizations on the basis of individual profiles; it is very difficult at times to decide which observations pertain to transitory details and which reflect more permanent properties of the various fields.

A fairly close correspondence between the position of the inner radar bands and the maximum winds in the eye-wall was also present at this middle level. Outside of the eye the relationship between the radar bands and variations in wind speed and temperatures did not follow a definite pattern. There was a tendency, much more pronounced than in the lower levels, for the wind speed to drop significantly within some of the radar bands. Clear occurrences of this were present at the 32-mi. radius on the left side and at the 13-mi. radius on the right side of figure 18; also in figure 19 at the 25-mi. radius on the right and the 52-mi. radius on the left. One can also notice in figures 16-19 greater variability in the wind speed than was observed in the profiles at 5,500 ft.; even less variability was present at 2,800 and at 1,600 ft. Also, the frequency and amplitude of the oscillations seem to be greater in regions of more active convection; for example, the inner area in figures 16 and 17, and the right side of figure 18. This feature of the wind field poses some intriguing questions. For instance, was this a characteristic feature of the flow at middle levels only? The fact that the variability was larger at the middle levels and in the precipitation areas suggests a close association with the vertical currents in the convective cells. If this is true, then it should not be unexpected to see a greater oscillatory trend at the 500- to 600-mb. levels, close to the level of non-divergence, where the vertical motion is generally at a maximum. From the point of view of momentum transfer in the vertical, one would expect the horizontal wind to be greater in regions of ascent and weaker in regions of descent. One can also look at it from the point of view of the thermal effect of the vertical currents on the pressure field. If one assumes that the temperatures are warmer than the surroundings in the ascending currents, then the vertical currents would create horizontal temperature gradients which would result in the isobaric surfaces bulging upward in the warm regions so that horizontal contour-height gradients would be created and produce an increase in wind speed on the radially-inward side of the warm updraft and a decrease on the radially-outward side. Similarly, in the cold descending currents, the isobaric levels would be closer together and horizontal gradients would be created such that the wind speed increased on the radially-outward side and decreased on the radially-inward side. It has not yet been possible to verify these ideas; for one thing the data gathered to date do not define the pressure field or the field of vertical motions adequately. It can be said, however, that there exist some reasonably sound arguments, which suggest that the greater degree of variability of the horizontal wind at the middle levels in hurricanes is a real effect, probably associated with the field of vertical motion on the convective scale.

The horizontal distribution of the wind field (fig. 20) shows a picture similar to that recorded in figure 14. There was a small zone of winds over 50 kt. to the right of the eye in about the same position and shape as at the 5,500-ft. level. Weaker flow was present in the northwestern and southwestern sides of the eye ring. There was also asymmetry in the extent of the strong winds similar to that observed at low levels, but the difference in wind speed between corresponding sections of the right and left semicircles was not as large.

(2) Temperature and humidity fields. The temperature profiles at the middle level showed the same type of oscillations present in the lower levels; there was a cool zone surrounding the eye shown in nearly all the profiles. At 15,600 ft. the maximum temperature recorded in the eye, was 2.5°C., about 4.5°C. warmer than the normal, a larger anomaly than was recorded at any of the lower levels.

The relationship between the temperature oscillations and the cloud and precipitation fields, as at the lower level, did not follow a definite pattern. Instances of rising temperatures within radar bands were noticed in the 20-mi. and 32-mi. radii on the left side of figure 19, while cooling was observed at the 40-mi. radius on the right. However, it was also apparent that some of the temperature variations were not directly related to the presence of precipitation or clouds. Some evidence for this is offered in figure 16, where some prominent temperature oscillations are observed between the 32- and 52-mi. radii and outside of the 57-mi. radius, where the aircraft was in the clear. Another instance of temperature variations in the absence of precipitation bands was observed between the 42- and 80-mi. radii on the right of figure 18; cloud data were not available on this pass.

A comparison of figure 16 with the right side of figure 19, and between the left sides of figures 18 and 19, gives some idea of the time variations in

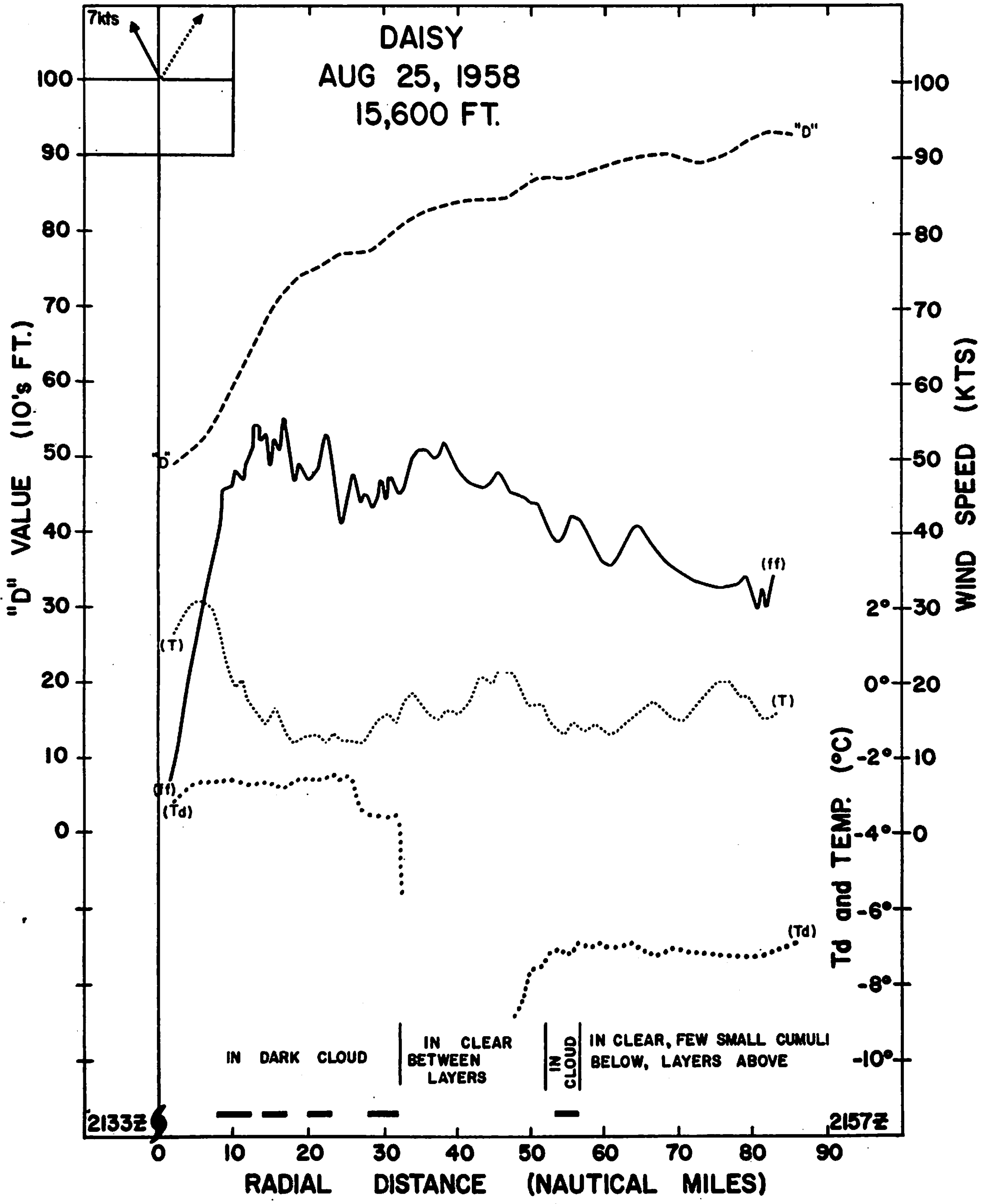

Figure 16. - Data profile at 15,600 ft., 557 mb., August 25, 1958.

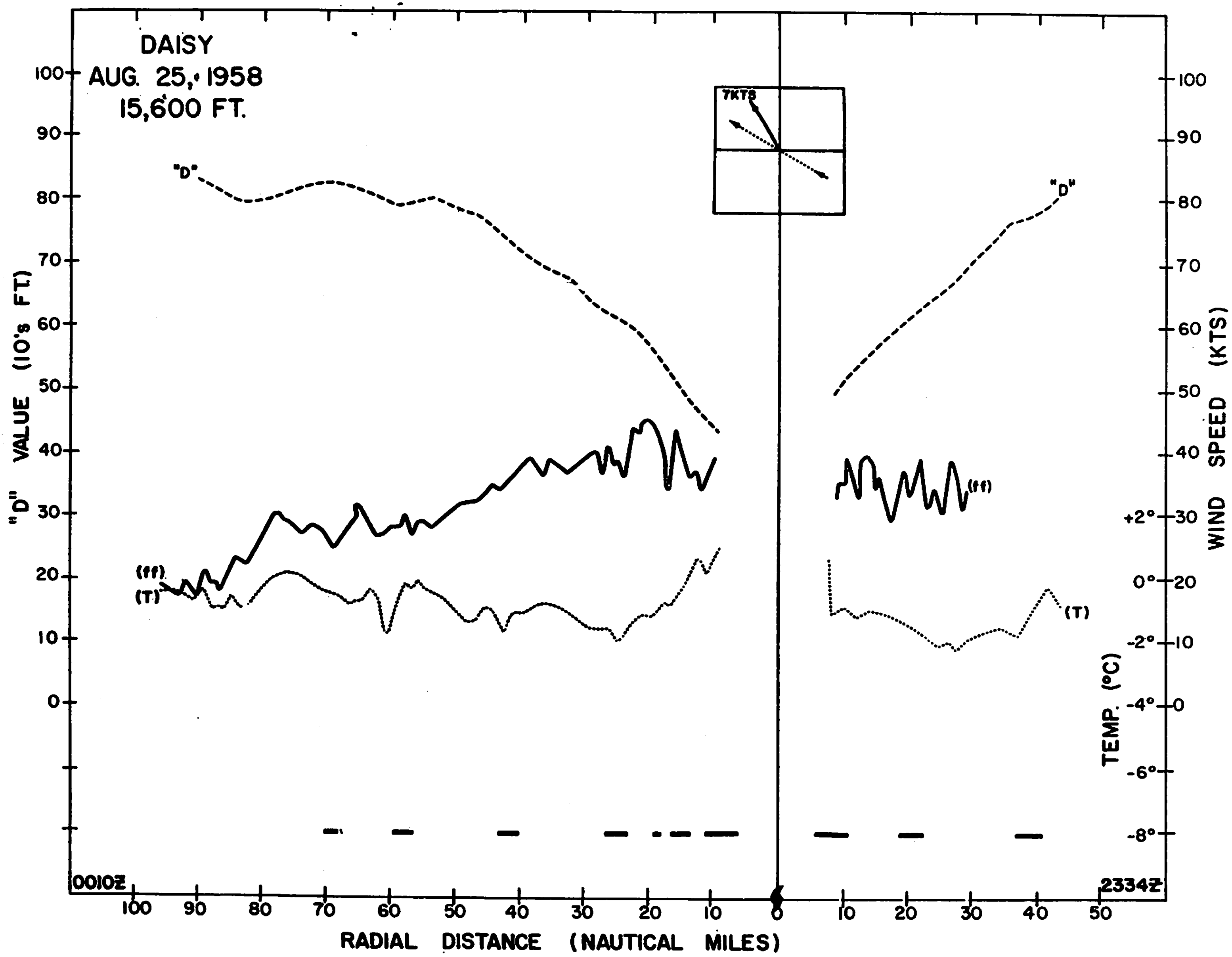

Figure 17. - Data profile at 15,600 ft., 557 mb., August 25, 1958.

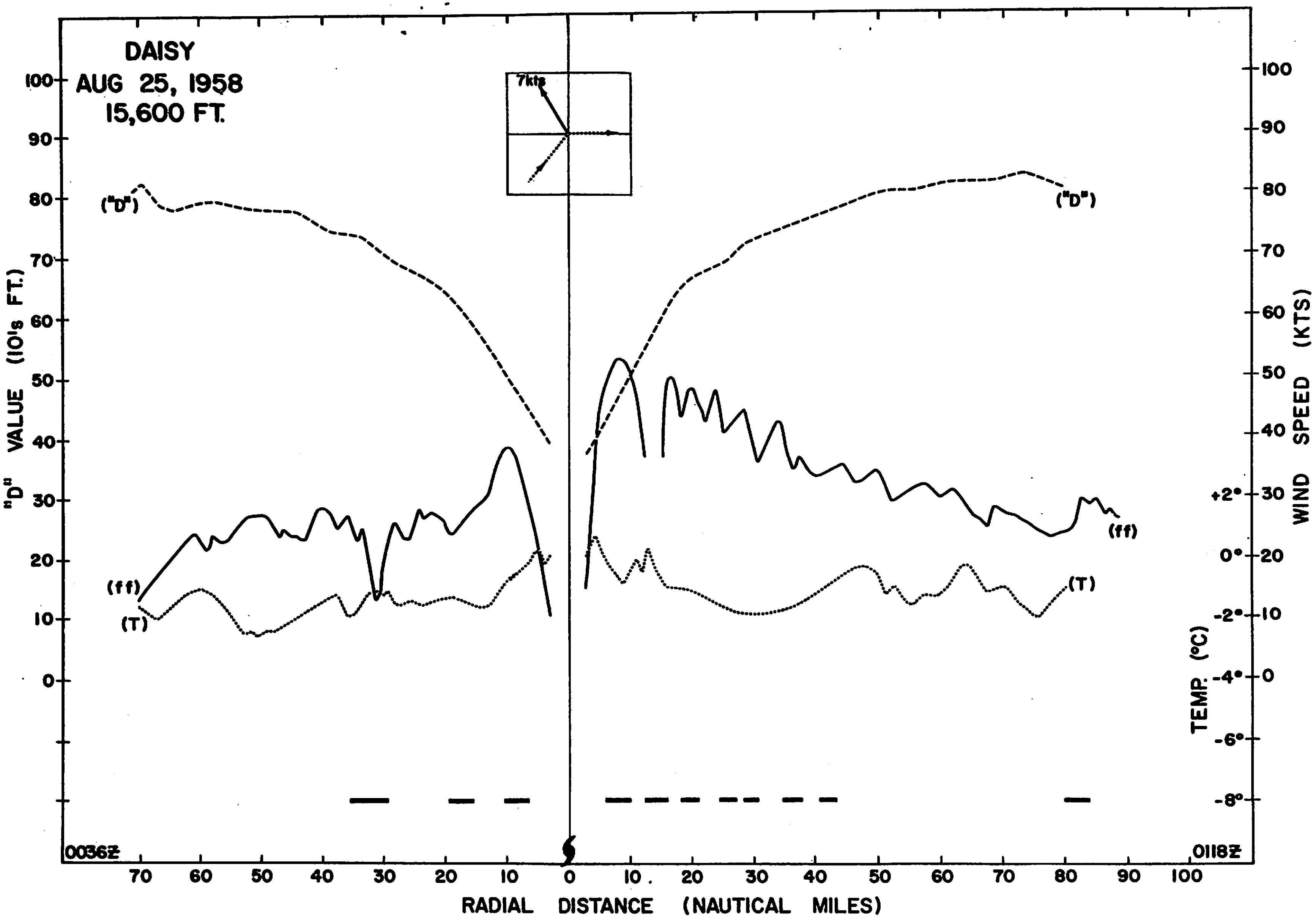

Figure 18. - Data profile at 15,600 ft., 557 mb., August 25, 1958.

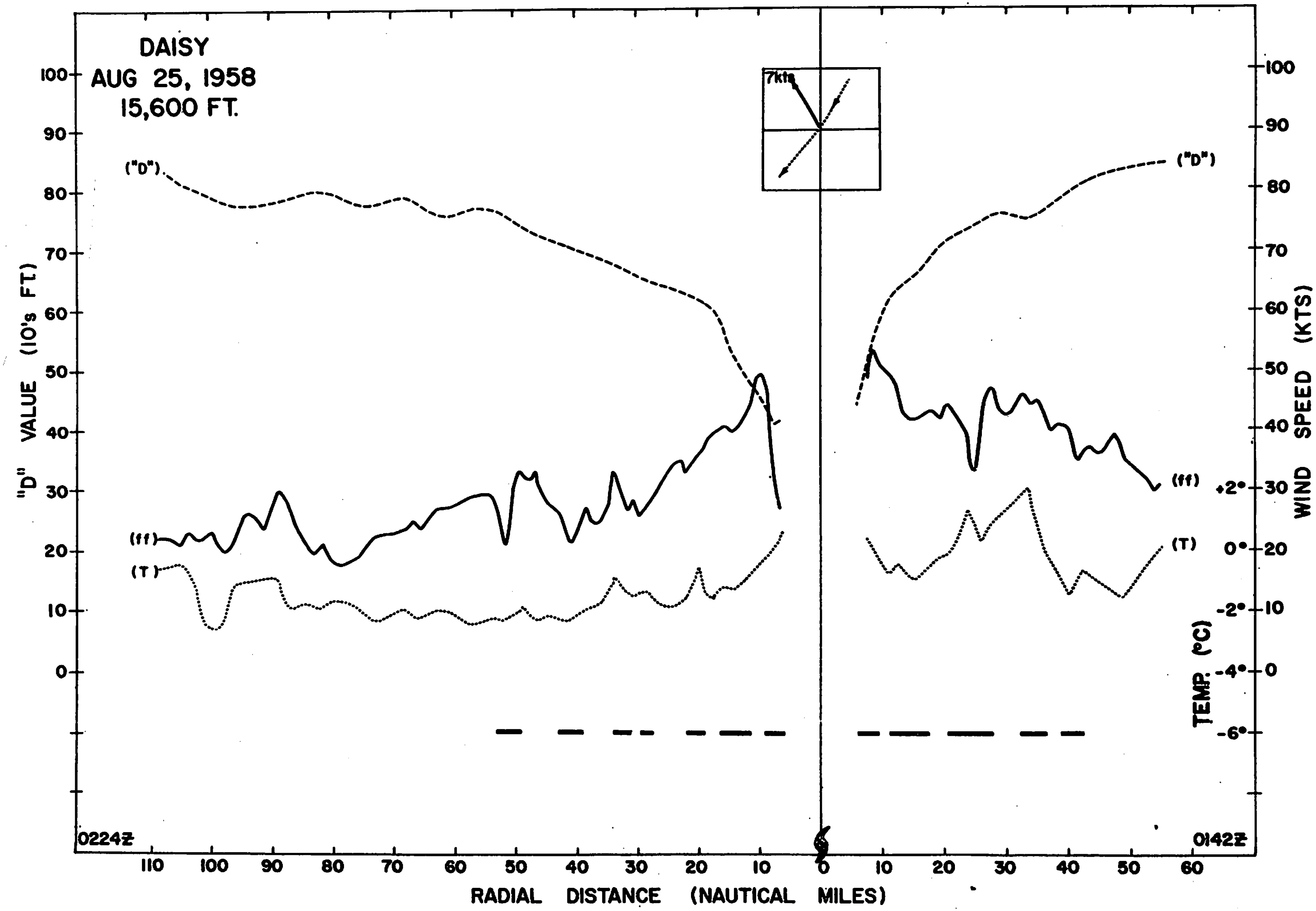

Figure 19. - Data profile at 15,600 ft., 557 mb., August 25, 1958.

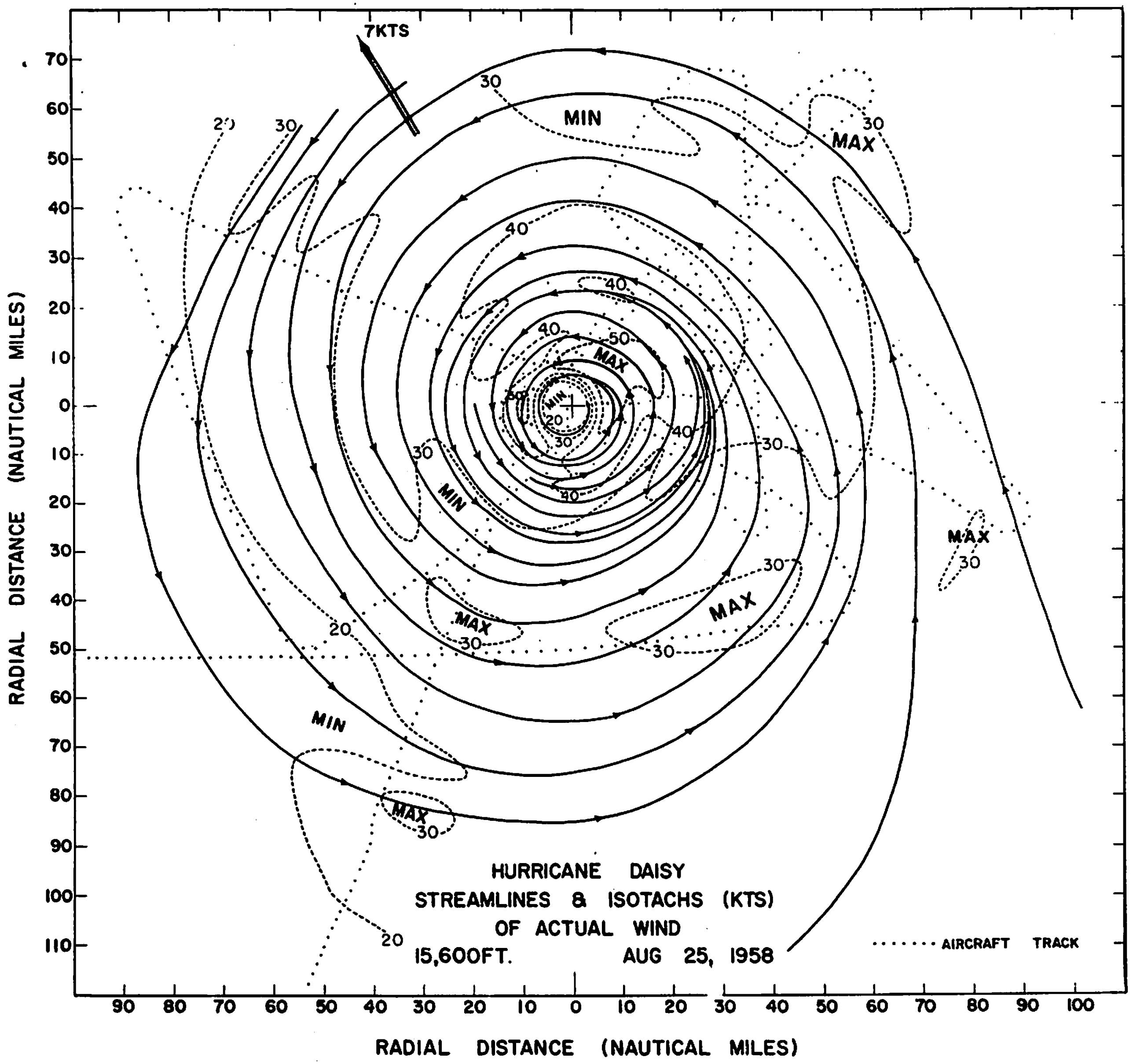

Figure 20. - Horizontal wind field at 15,600 ft., 557 mb., August 25, 1958.

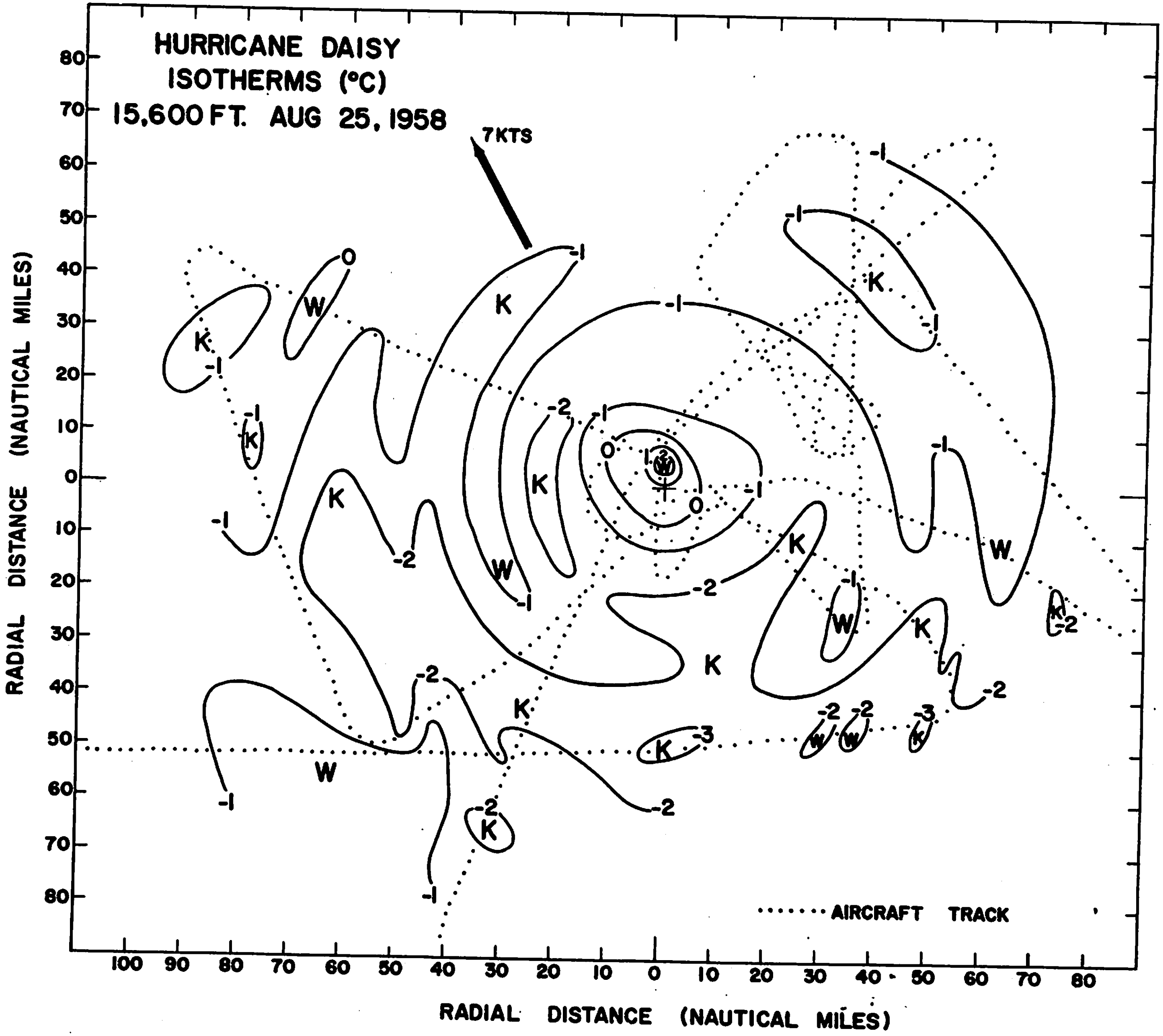

Figure 21. - Horizontal temperature field at 15,600 ft., 557 mb., August 25, 1958.

the temperature field along the same radial direction. Some striking differences with time were observed along the northeast direction. Figure 19 shows a pronounced warming near the 30- to 35-mi. radius and a cooling at the 45-mi. radius, which were almost out of phase with the oscillations recorded 4-1/2 hours earlier. Some significant differences were noticed also along the southwest direction. However, certain time variations in the distribution of the radar bands appeared to have taken place also.

The horizontal temperature field (fig. 21) showed a distribution, which, at first sight, looks similar to that observed at the lower levels. Areas of relatively cool and warm air alternated from the center outward; some of them could be followed in quasi-circular fashion around the center. A ring of cold air surrounded the eye at a radius of 20-25 mi.; another cold ring was located in the vicinity of the 50-mi. radius. Asymmetry in the distribution of temperatures was also present at this level, but in the opposite sense to that observed in figure 19; here the temperatures were colder in the left semicircle and to the rear of the motion. A large region of temperatures colder than -2°C. was present on the rear side. Temperatures this cold were not observed anywhere else. The humidity data at this level were generally disappointing and unsatisfactory. The radial profiles did not show as much variability as one would expect. The dew point data have been illustrated in figure 16 where a nearly constant value can be noted from the center to the 30-mi. radius. At this point there was a sudden decrease at the same time that the instrument went into reference. A nearly constant value, but of lower magnitude, was then recorded from the 50-mi. radius outward. The mixing ratio values indicated by these data ranged from 4 to 6 gm. $kg.^{-1}$.

(3) Pressure field. - The minimum "D" values observed at the 15,600-ft. level were about 370 ft., which,,on the basis of Jordan's nomograms [8], indicate a minimum central pressure around 992 mb.; therefore, some intensification of the pressure field had apparently taken place from the time of the penetrations at low levels. The "D" value profiles in figures 16-19 show the main features of the pressure field; a horizontal analysis was attempted, but not illustrated, since it shows the typical picture of near circular isopleths, with relatively weak horizontal gradients outside the 40-mi. radius.

d. Hurricane circulation at 35,000 ft.

The flight track at 35,000 ft. shown in figure 22, was designed essentially to gather data round the periphery of the hurricane. On account of the faster cruising speed and greater overall range of the jet aircraft, the distances travelled were generally greater than those at the lower levels, and data were obtained as much as 250 mi. from the center. Observations on this day were not available any closer than about 15 mi. from the eye on the north side, where easterly flow of about 25-30 kt.was observed. These winds, together with northerly flow observed to the west of the center, indicated a cyclonic circulation around the eye. Cyclonic outflow has been indicated in the streamline flow, but the data are not adequate to tell whether it should be depicted as inflow or outflow. The wind flow at this level was characterized by a series of small cyclonic vortices oriented in a line running from northeast to southwest with northeasterly flow to the west and westerly flow to the east and south of the center. This placed the hurricane in the center of a trough that ran from the region of Bermuda southwestward into the western

Caribbean area in a line nearly perpendicular to the direction of motion of the storm. Centers of maximum wind speed, reaching over 40 kt., were located in the northerly current on the west side of the trough, and in the anticyclonic westerly current to the southeast of the center. At this stage of development the circulation at high levels appeared to be dominated by the large-scale synoptic flow pattern and the influence of the hurricane upon the surrounding circulation was not readily discernible.

The temperature field (fig. 23) showed a warm zone with maximum temperatures warmer than -40°C. near the eye, with other secondary warm pockets located to the west and south of the center. The coldest temperatures, of around -44°C., were observed to the south and east. In drawing the horizontal analysis it was noticed that at nearly all points where different legs of the track crossed each other the temperatures did not exactly agree; generally warmer temperatures were recorded on the later passes. The maximum temperatures at this level were about 5°-6° C. warmer than the August normal. This anomaly was higher than that observed at any of the lower levels. The normal temperature for the level is around -45.5°C., which means that all of the temperatures shown in figure 23 were warmer than normal, even though the data extend over a rather extensive area. This was not true in the observations recorded at the lower levels.

The field of "D" values (not illustrated) showed very weak mesoscale gradients. There was essentially a low pressure trough running from northeast to southwest with higher pressures to the northwest and southeast, very much in accordance with the wind flow illustrated in figure 22. The "D" values were lower in the center of the hurricane; the exact minimum value was not known. However, the difference between the highest and lowest values observed along the whole flight track was only about 140 ft.

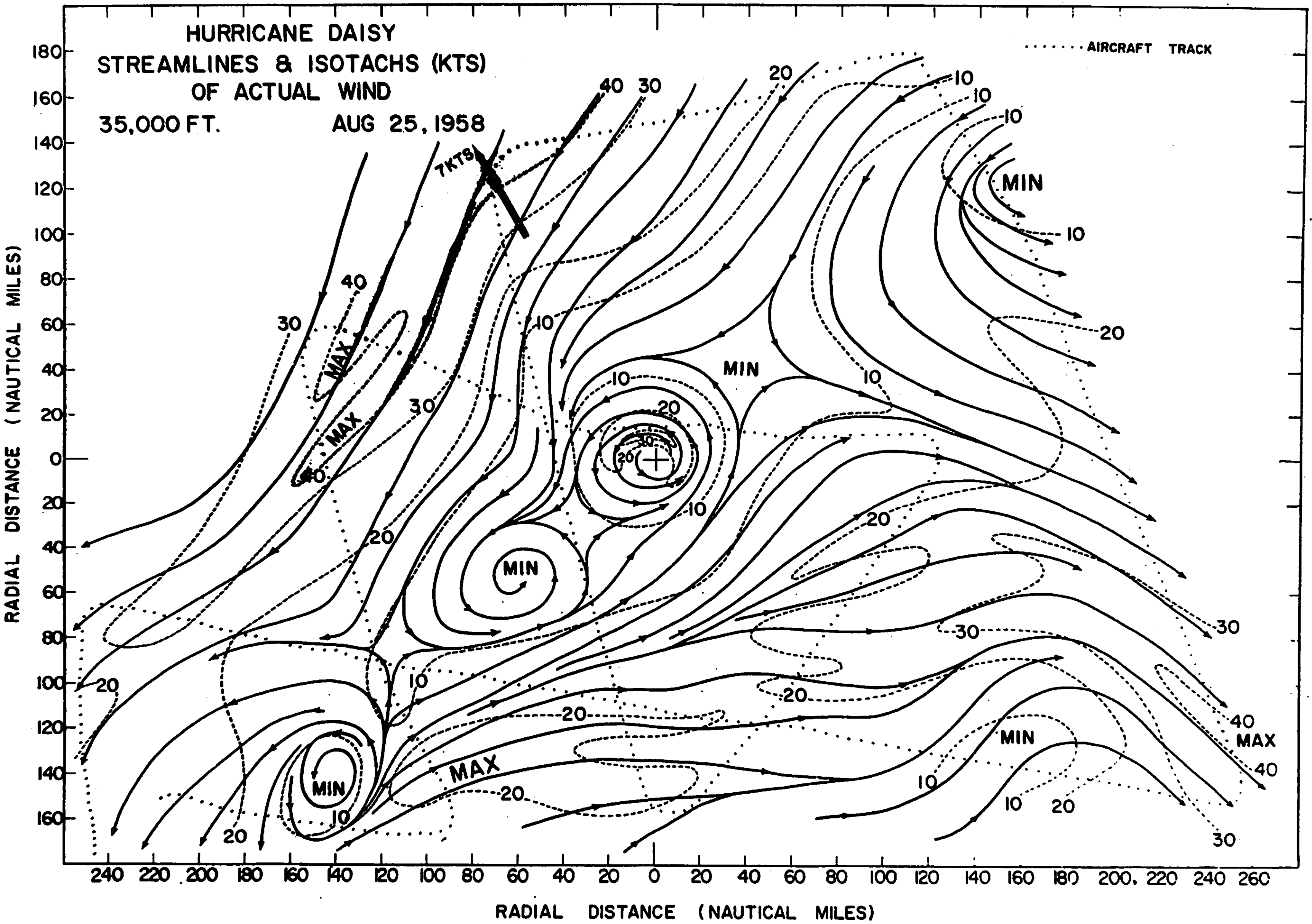

Figure 22. - Horizontal wind field at 35,000 ft., 238 mb., August 25, 1958.

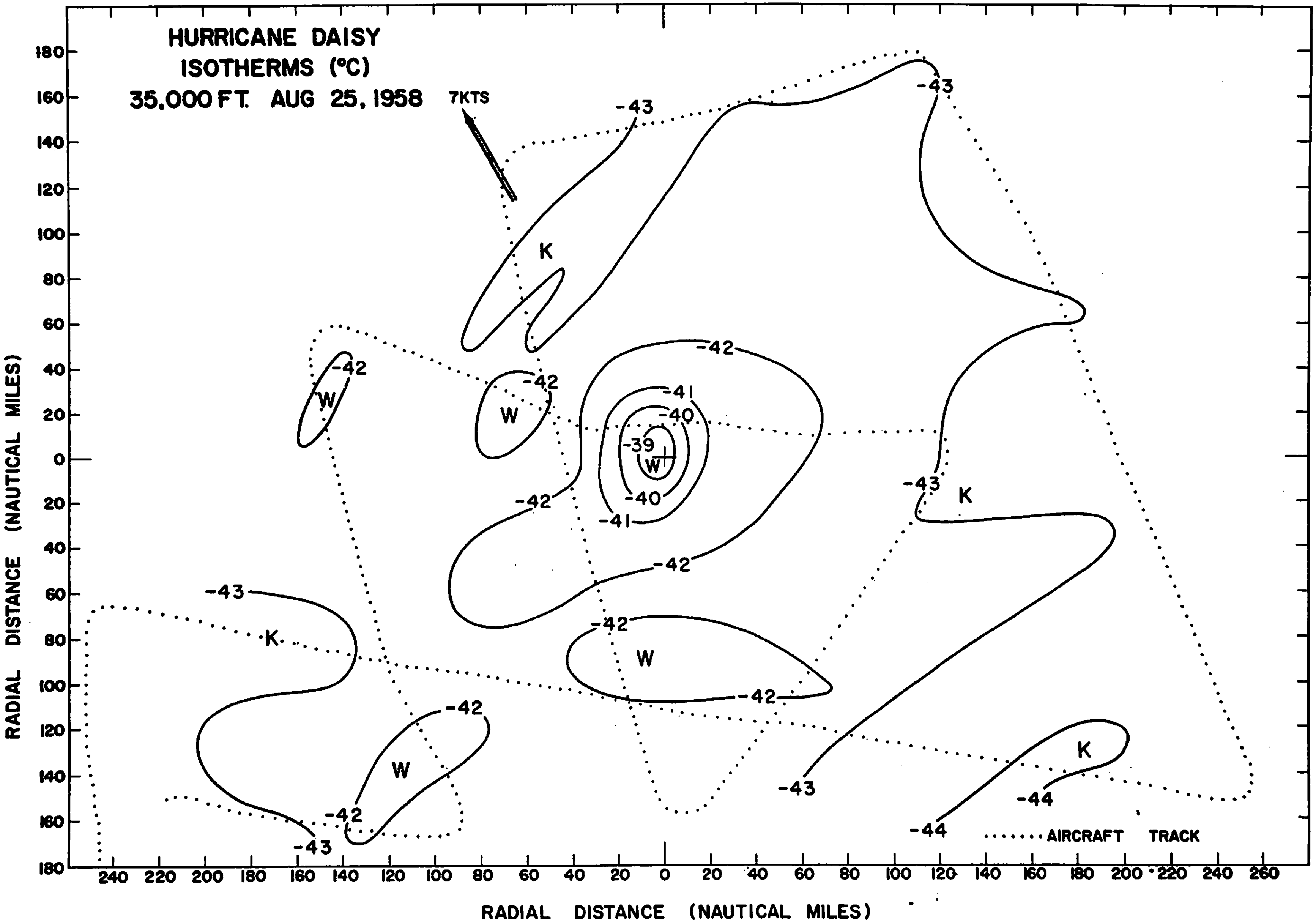

Figure 23. - Horizontal temperature field at 35,000 ft., 238 mb., August 25, 1958.

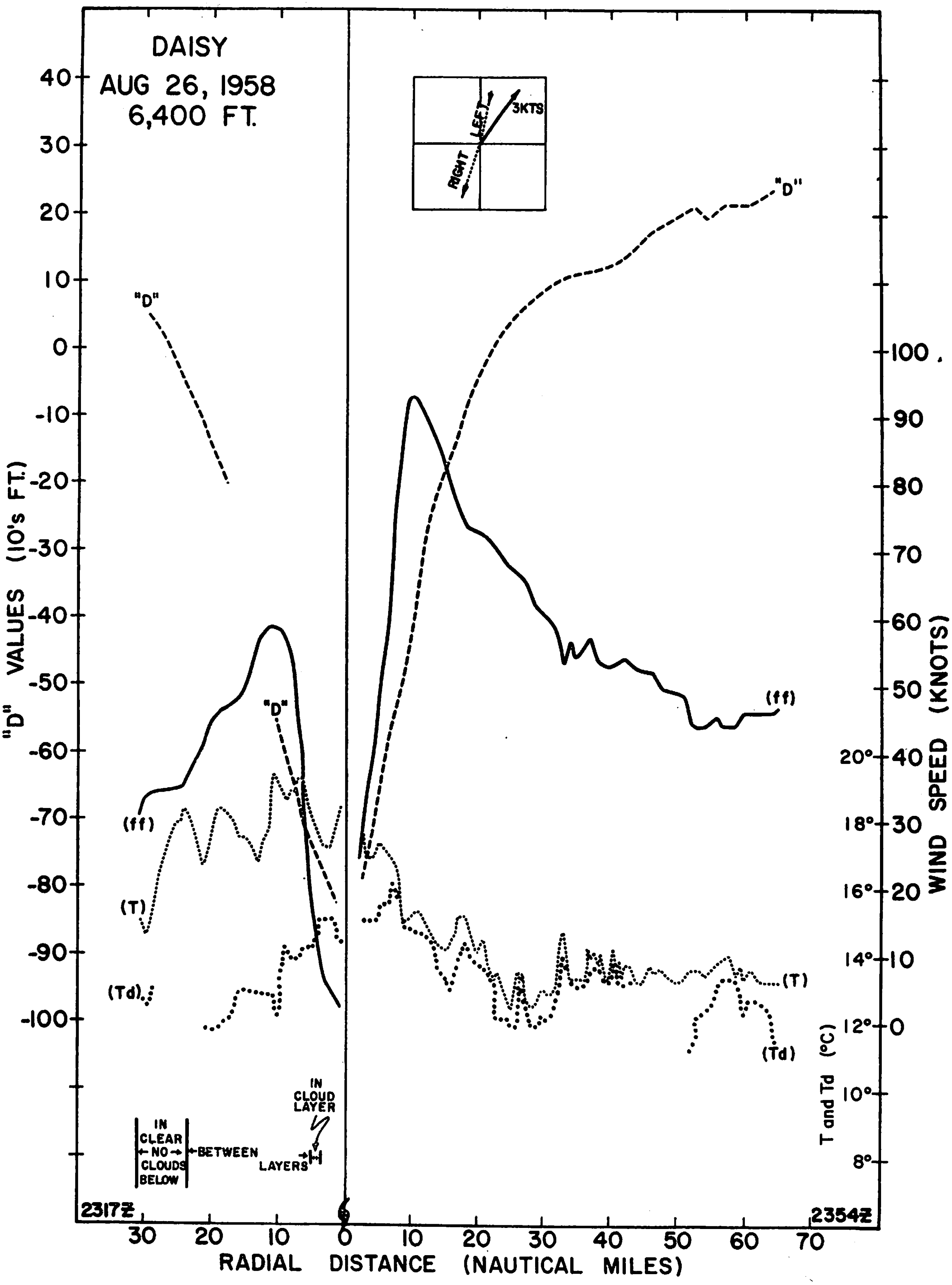

Figure 24. - Data profile at 6,400 ft., 800 mb., August 26, 1958.

5. HURRICANE STRUCTURE - AUGUST 26

Hurricane Daisy recurved to the north and east early on August 26 and by the time of the reconnaissance missions during the afternoon it was already moving northeastward at a very low forward speed of 2-3 kt. A 2-plane mission was carried out on this day. One of the B-50's flew at low levels between the hours of 1730 GMT August 26 and 0200 GMT August 27; while the jet aircraft flew again at about 35,000 feet between 1800 and 2300 GMT, August 26 in a track relative to the center that resembled that of August 25. Most of the observations gathered at low levels were in tracks around the periphery of the storm and do not permit a reasonable analysis of the wind and thermal structure in the inner regions. Only one eye penetration was made, at an altitude of 6,400 ft. The data are illustrated in profile form in figure 24 and show significant changes in the intensity of the circulation.

The radar pictures obtained on this day, both by the NHRP and the U. S. Navy aircraft, (not illustrated), indicated a well developed eye-wall radar band and distribution of spirals similar to those in evidence on the previous day. The radar eye was still 10-12 mi. in diameter.

a. Circulation at 6,400 feet.

The eye penetration was made from the north in a direction about 30° to the left of the motion; the exit was made in a direction almost opposite to the direction of motion. The most striking feature of the profile is given by the wind and "D" value curves. The wind field (fig. 24) showed a large concentration of kinetic energy in a very narrow zone centered about 10 mi. from the center of the eye. Maximum speeds of 93 kt. were recorded on the rear side of the storm. Higher wind speeds may have existed in the right semicircle. The wind speeds dropped rapidly inward toward the center; the cyclonic shear observed on the rear side of the eye was 2.4×10^{-3} sec.$^{-1}$ The anticyclonic shear between the 10- and 30-mi. radii on the right side of figure 24 averaged 3.5×10^{-4} sec.$^{-1}$ The winds on the north side of the eye were considerably weaker, but the stronger speeds were also concentrated in a narrow band.

The temperature field on the south side demonstrated what we have seen to be typical of other profiles; that is, maximum temperatures in the eye dropping off to a cool zone in the rain area 20 to 30 mi. from the center. On the north side, however, the temperatures showed a peculiar structure with relatively warm temperatures observed well outside the eye. The maximum temperatures recorded on this penetration, about 19°C., occurred on the north side of the eye and were about 4°C. warmer than normal.

The distribution of clouds at flight level in the penetration from the north was quite unusual. Between the 30- and 23-mi. radii the aircraft went through a relatively clear sector. The sea was clearly visible and cumuli of small vertical development were observed below; layered clouds were present above. At the 23-mi. radius the aircraft went in between layers, with cloud decks above and below but not much cloudiness at flight level. The rest of the penetration into the eye was practically between layers; there were no thick clouds indicative of large vertical extent or heavy rain as was observed in other penetrations. This may account for the unusual temperature trace, since, as discussed previously, warmer temperatures are generally observed with suppressed convection and little precipitation. The eye was full of clouds, the same as on previous days. Unfortunately no cloud or radar films were available for the pass on the south side; it seems likely that there were heavier cloud formations and precipitation on that side.

The dew points indicated considerably less moisture content on the north side, probably associated with the lack of cloudiness at flight level. The fluctuations were larger on the south side and suggest greater convective activity and more variation in cloudiness.

The "D" value profile illustrated a considerably more intense pressure vortex than on the preceding day; the minimum value recorded in the center was - 820 ft., which equates to a central pressure of about 972 mb. There seemed to be a slight asymmetry in the profile across the eye, with stronger gradients associated with the more intense winds in the right side.

b. Circulation at 35,000 ft.

The track of the jet aircraft with respect to the storm center on this day was about the same as on the previous day, except that it did not penetrate as close to the eye. The overall area covered was about the same, but the wind data showed a much different picture (fig. 25). The cyclonic circulation had grown considerably in size; it extended to about 60-70 mi. on the south and east sides and farther out on the north and west sides. Around the cyclonic center there was a ring of anticyclonic flow, with definite cells shown on the north and southwest sides of the storm. The whole circulation on this day appeared to be dominated more by the hurricane system than by the synoptic-scale pattern, a definite reflection of the deepening process which brought about an increase in the vertical extent of the cyclonic vortex, as well as a greater influence of the hurricane upon the surrounding atmosphere.

No data were obtained near the center and no attempt was made to extend the analysis inward. A cyclonic outflow was suggested by the data available in the periphery of the cyclonic vortex. The isotach field showed a zone with maximum values of over 40 kt. in the outflow region toward the southeast. Aside from this zone the winds over most of the area were of the order of 10-20 kt.; however, wind speeds of 40 kt. or greater may have existed in the ring around the eye.

The temperature field (fig.26)showed a picture not much different from that of the previous day. The warmest temperatures are located near the center and the coldest in the southeastern sections surveyed. No information on the maximum temperatures near the eye was available,but the area immediately outside appeared significantly warmer than on the previous day; the -42°C.and -41°C.isotherms now enclosed a much larger area. Outside of the center there was a ring of cold air on all sides. The normal temperature for this level is about -45.5°C., which means that all of the observations in figure 26 were warmer than normal.

The field of "D" values (not illustrated) did not show much gradient. The observations ranged from a maximum of about 2,030 ft. to a minimum of near 1,850 ft. In general there was a ring of higher values (or high pressure) surrounding the cyclonic center with low pressure near the center of the eye and on the outer periphery of the chart.

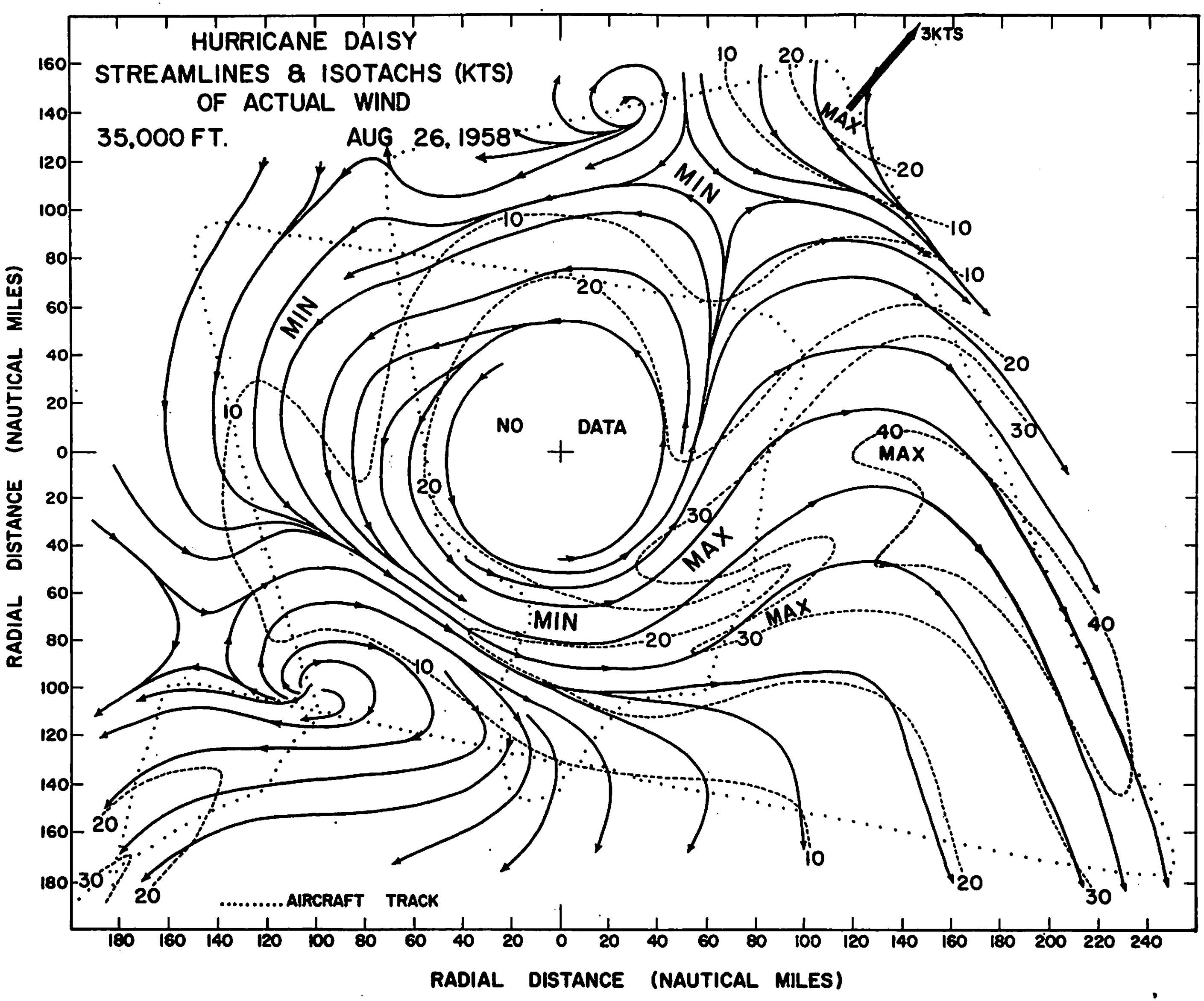

Figure 25. - Horizontal wind field at 35,000 ft., 238 mb., August 26, 1958. No analysis was attempted in the central area due to inadequate data.

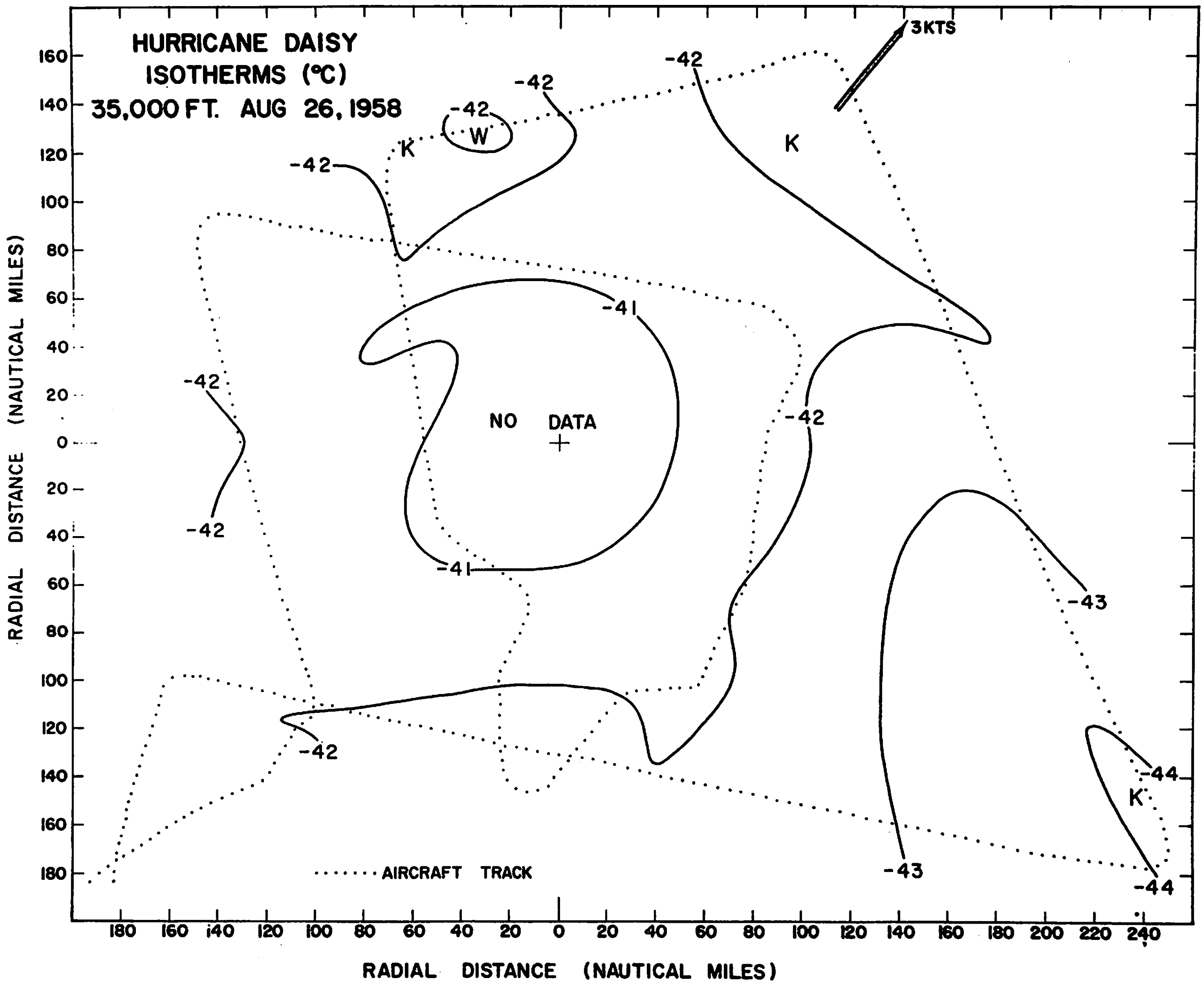

Figure 26. - Horizontal temperature field at 35,000 ft., 238 mb., August 26, 1958.

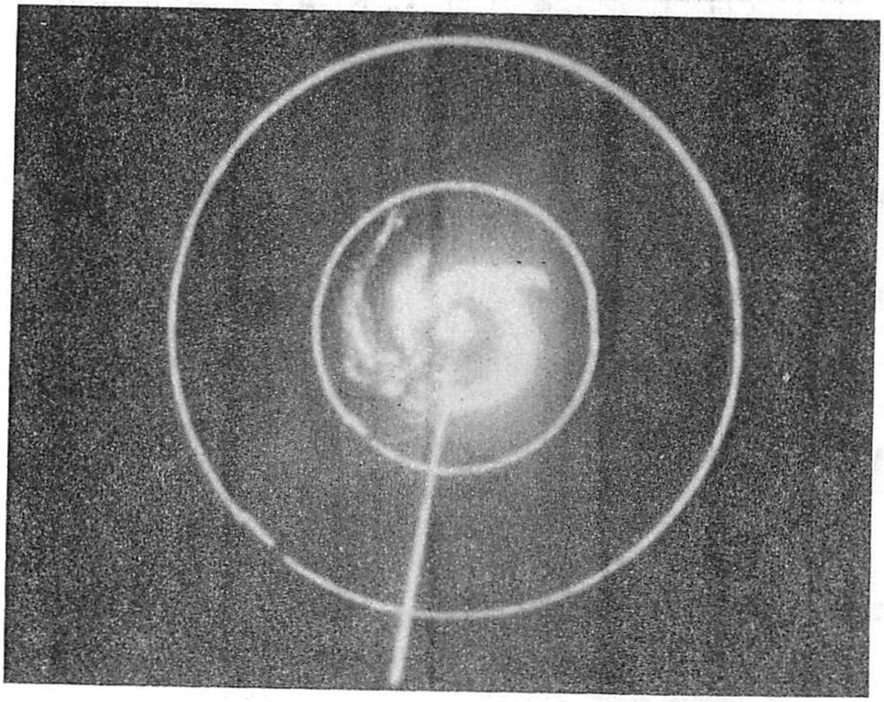

Figure 27. - Photograph of the eye-wall radar band of hurricane Daisy as seen by the NHRP aircraft flying at 13,000 ft. (620 mb.) at 1739 GMT, August 27, 1958. Range markers 20 mi. apart. Top of the photograph is north.

6. HURRICANE STRUCTURE - AUGUST 27

Hurricane Daisy continued moving northward and intensifying during August 26 and 27. At the time of the reconnaissance missions on August 27, the central pressure had dropped to about 950 mb. A 2-plane mission was carried out on the 27th; one plane flew at middle levels, mostly 13,000 ft. between 1500 and 2200 GMT, and another at high levels, mostly 34,200 ft. between 1600 and 2100 GMT. Maximum winds of around 115 kt. were measured in a narrow ring around the eye, giving rise to some of the most striking velocity profiles that have been recorded in tropical hurricanes. According to Jordan et al.[10], the wall cloud on this day extended to altitudes of over 55,000 ft.

a. Radar structure.

Hurricane Daisy retained throughout August 26 and 27 some of the features of the radar distribution observed on August 25, except that there were in general more extensive bands on August 27 than on the 25th. Malkus et al.[15] have discussed some of the similarities, using both radar and cloud data, and pointed out the tendency for certain bands to appear at about the same relative position with respect to the center on both days. Some photographs of the radar structure of Daisy on August 27 have been published by Jordan et al. [10]. One photograph of the eye wall, as seen by the "B"-plane from an altitude of 13,000 ft. is shown in figure 27. Figure 28 is a composite of the radar field as constructed mostly from film obtained by the "B"-plane; as a rule, more of the "soft echoes" were included in this figure than in figure 7.

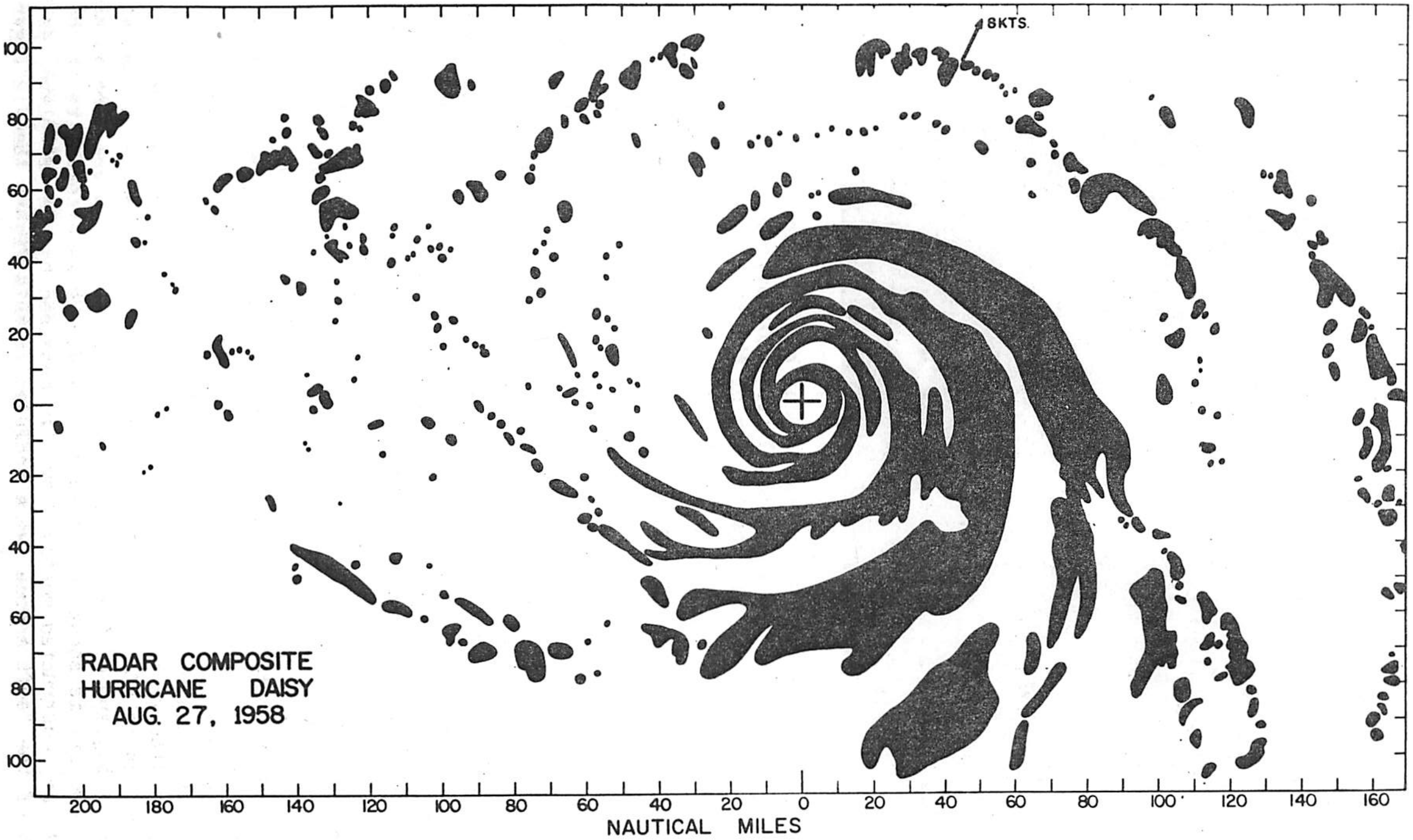

Figure 28. - Composite distribution of radar echoes of hurricane Daisy as obtained from the radar film of the aircraft flying at 13,000 ft. on August 27, 1958. Arrow at the top indicates the motion of the center.

The radar film for the "C"-plane was available only for the latter part of that mission.

The eye was around 12 mi. in diameter, about the same as in figure 6, and presented a well-defined, almost circular ring, with "harder" echoes on the right side. On the left side there was a tendency for the appearance of weaker echoes, in some cases almost an opening similar to that observed on August 25. Occasionally the eye-wall had more of a spiral configuration, as can be seen to some extent on figure 27 (see also fig. 2, 3, 10, and 11 in Jordan et al.[10]). Figure 28 shows that an almost solid mass of echoes extended to about the 60-mi. radius ahead (northeast), to about 80 mi. on the east, and to over 100 mi.on the southeast and south of the center. On the west and northwest sides these echoes extended only to the 30-mi. radius. Farther out there was a widespread zone of scattered cell-type echoes, in some sections arranged in bands, more characteristic of isolated convective cells than the widespread precipitation noted in the the right semicircle. Outside the 90-mi. radius on the east side, there were two separate and well-defined bands located at the 110- and 160-mi. radii. No data were available beyond 100 mi. to the north and south of the center; but probably some of the bands seen on the east side extended well to the south and north.

There were a number of bands on August 27 that appeared to be located in about the same relative position and in about the same location with respect to the eye as corresponding bands observed on August 25. For example, the north-south band located 170-180 mi. east of the eye on August 25 corresponds quite well with the one located north-south about 160 mi. east on the 27th. There were two bands located at the 70- and 110-mi. radii directly northwest of the center on August 25, while in the same direction on the 27th there was one very clear band at the 105-mi. radius and also a tendency for one near the 70-mi. radius. The same was also true for radar bands located near the 40- and 90-mi. radii to the south-southeast on both the 25th and 27th. The band located at the 60-mi. radius east of the center on the 25th was reproduced in about the same position on the 27th but was much more intense. On the other hand the north-south band located at the 110-mi. radius on the 27th, had no analogue on the 25th, at least when considered in this sense. Malkus et al. [15] discussed these features at great length and suggested the possibility that these similarities may exist throughout the life history of other hurricanes as well. However, since the direction of storm motion differed but little on the two days, some of these similarities in the distribution of bands are present also when interpreted relative to the direction of motion. For example, if figures 7 and 28 are superimposed with the direction of motion coinciding,then the band located 110 mi. east of the eye on the 27th offers good continuity for that located 180 mi. east on the 25th, while other bands on the two charts also show fairly good correspondence.

b. Circulation at 13,000 ft.

(1) Wind field. - The most significant feature of the wind field on August 27 was the narrow and concentrated zone of maximum winds at the periphery of the eye, which is strikingly illustrated in figure 31. There was a peak wind speed of about 116 kt. at the 9-mi. radius and extreme values of wind shear both in the cyclonic and anticyclonic sense. The wind equipment failed during the pass through the eye-wall, illustrated in figure 32, but the

data which were available suggested a profile similar to that in figure 31. In the horizontal picture (fig. 33) this zone is pictured as a narrow ring, open on the left side, around the periphery of the eye. The maximum wind speed on the left side was about 85 kt. (see the left side of fig. 30); the difference between the two sides was more than twice the translation speed of the vortex, therefore a slightly higher relative wind was obtained on the right side of the eye. An asymmetry in the extent of the high energy core can also be noticed on this series of charts; for example, figure 30 shows winds of over 40 kt. extended about 100 mi. out on the right side, but to only 30 mi. on the left. There was a secondary center of maximum speeds on the right side of the circulation.

The values of the relative vorticity were computed for the profile in figure 31 under the assumption that the radius of the trajectories was equal to the geometric radius from the eye center (see fig. 60). Magnitudes of about 1×10^{-2} sec.$^{-1}$ were obtained at the 8-mi. radius; these dropped sharply outward from the center on account of the extreme negative values of the shear. Relative vorticity magnitudes approximately equal to these were measured in hurricane Ione of 1955 (LaSeur [11]). Further comments on the vorticity field and its changes with time are included in Section 9.

Some cases of large fluctuations in wind speed associated with the distribution of clouds and precipitation similar to those recorded at the middle level on August 25 are evidenced also in figures 29 to 32. One prominent case was observed between the 110- and 100-mi. radii in the left side of figure 29. Oscillations in temperature and humidity were also quite large. Traveling inward the aircraft went into cloud at the 109-mi. radius. Out-of-phase variations in wind speed and temperature were recorded; the wind speed increased in the clear air before the cloud was entered, then dropped sharply about 15 kt. to a minimum in the center of the cloud, and increased again to nearly its original value, still within the cloud. The temperature first rose inside the cloud, then decreased over 2° to a minimum almost at the exit; at the break-out there was a sharp increase to almost the orginal temperature. The dew point increased as the cloud was entered and decreased as the plane emerged. Because of the rather large fluctuations, all observations in this portion of the flight through the cloud were scrutinized in detail; the changes in altitude, drift angle, indicated air speed, ground speed, aircraft power settings, etc. were investigated. No malfunction in the wind measuring equipment could be detected. It is interesting to see that the wind speeds decreased on the radially outward side and increased on the radially inward side of the warm spots, in accordance with the model suggested in Section 4, c. (1). Occasionally some oscillations, although of smaller magnitude, were observed while the aircraft was in the clear; for example, outside the 40-mi. radius on the left of figure 30 and outside the 60-mi. radius on the right of figure 29.

Figure 29 shows a diameter profile in a direction parallel to the motion; there are some data gaps in the vicinity of the center, but as a whole it shows the same properties as in other directions, contrary to the picture two days before. Discussion of other aspects of the wind field and their changes with time are included in Section 8.

(2) <u>Temperature and humidity fields</u>. - The profiles (figs. 29-32) as well as the horizontal field (fig. 34) indicated a very pronounced increase in tem-

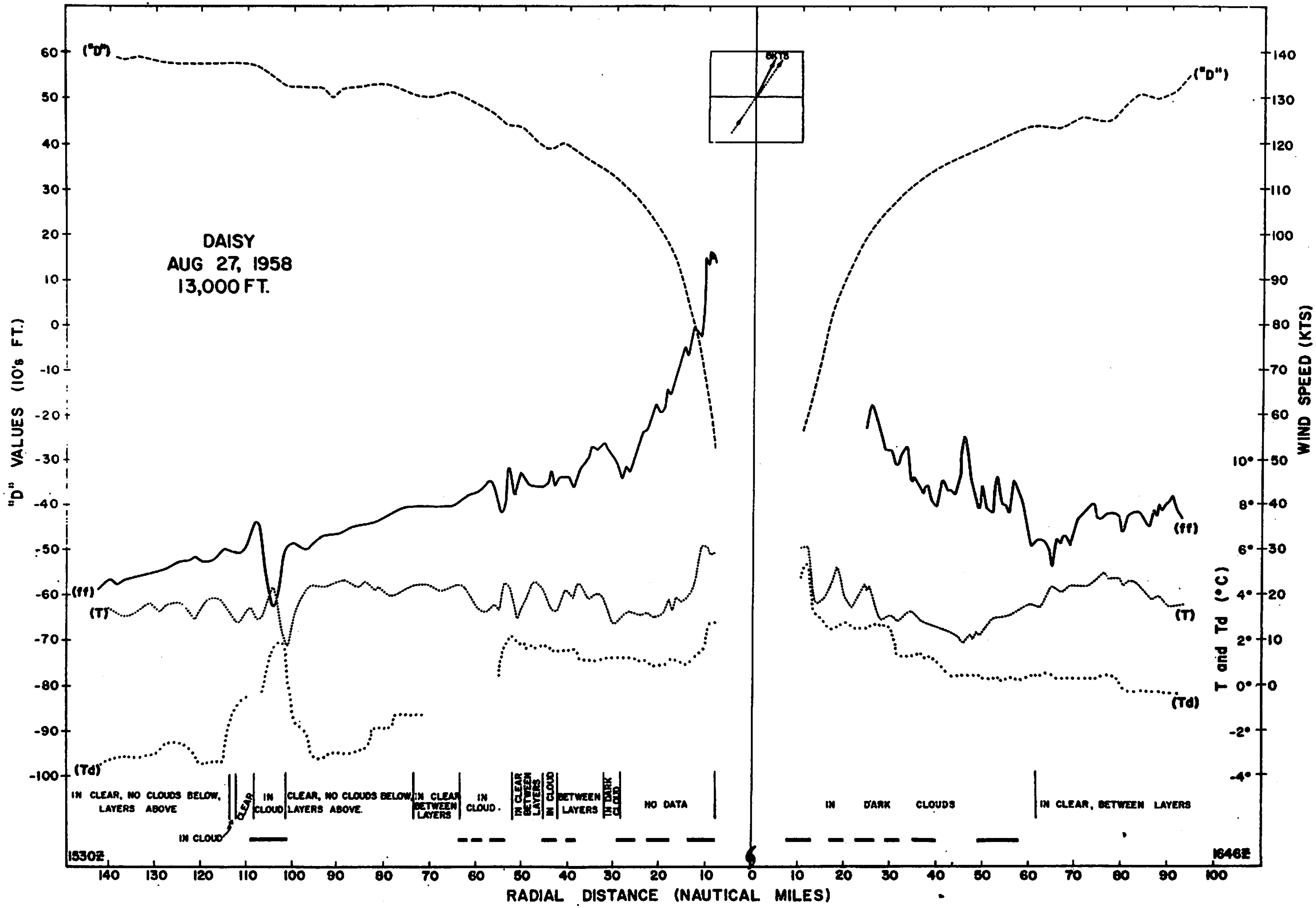

Figure 29. - Data profile at 13,000 ft., 620 mb., August 27, 1958.

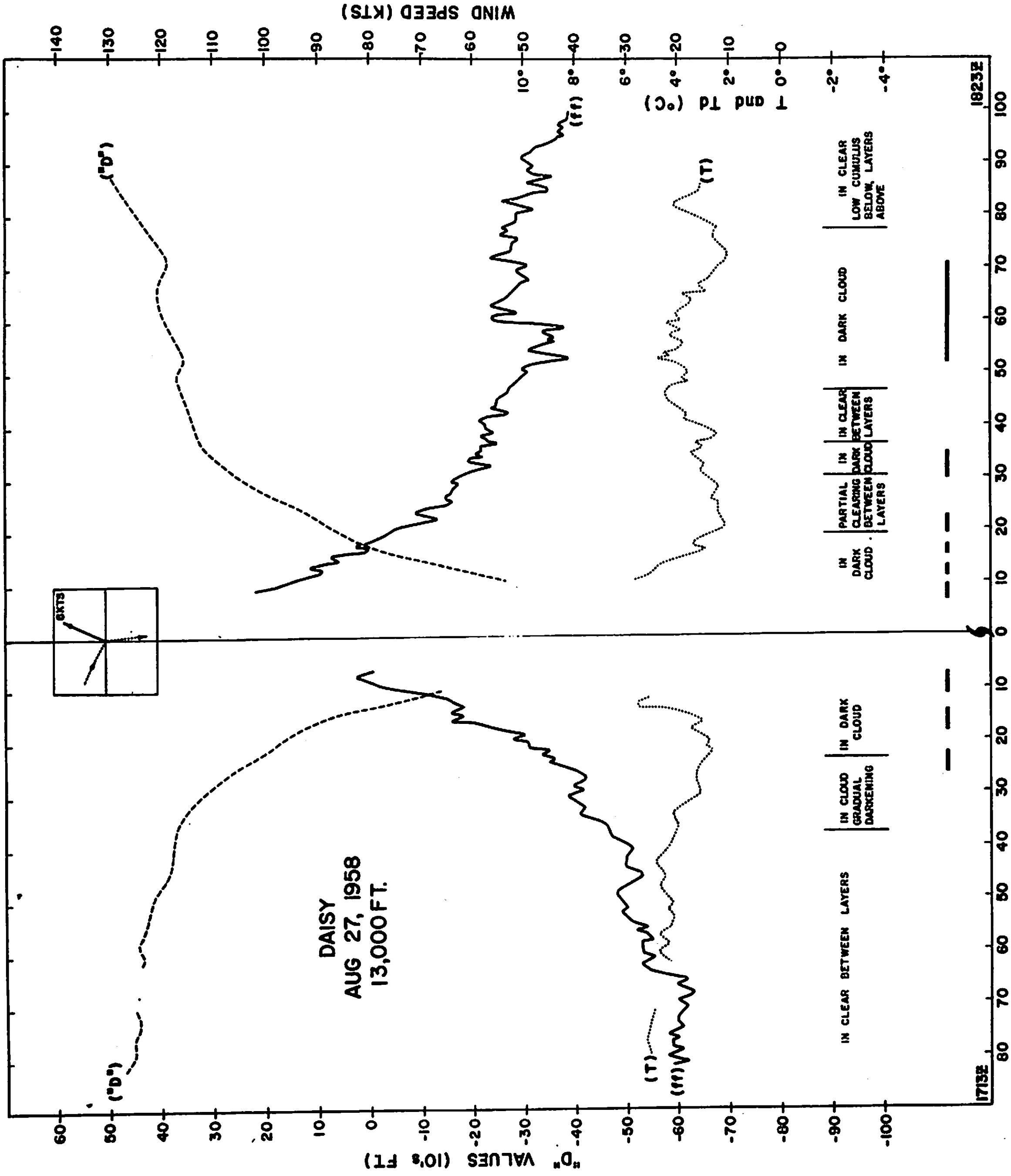

Figure 30. - Data profile at 13,000 ft., 620 mb., August 27, 1958.

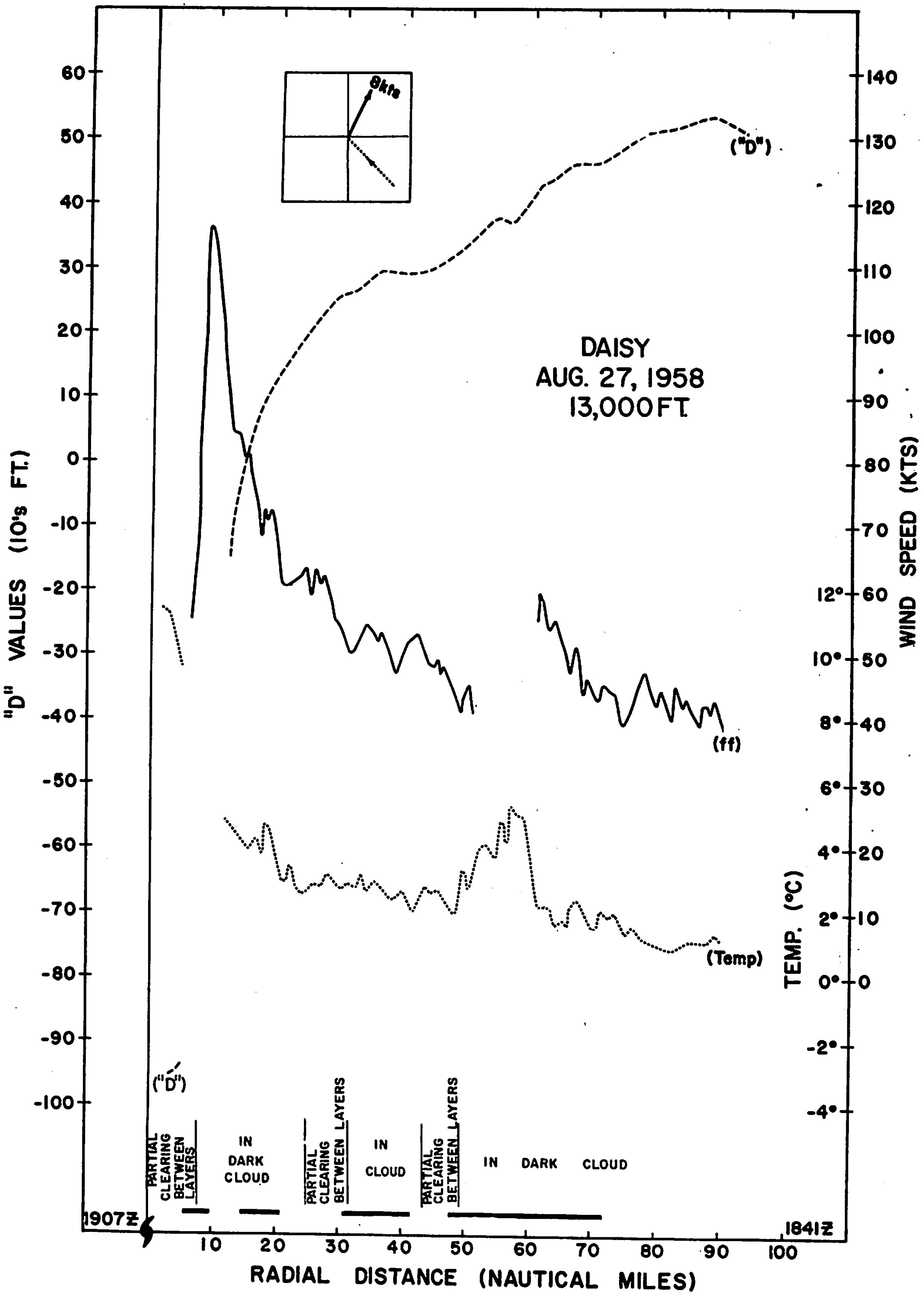

Figure 31. - Data profile at 13,000 ft., 620 mb., August 27, 1958.

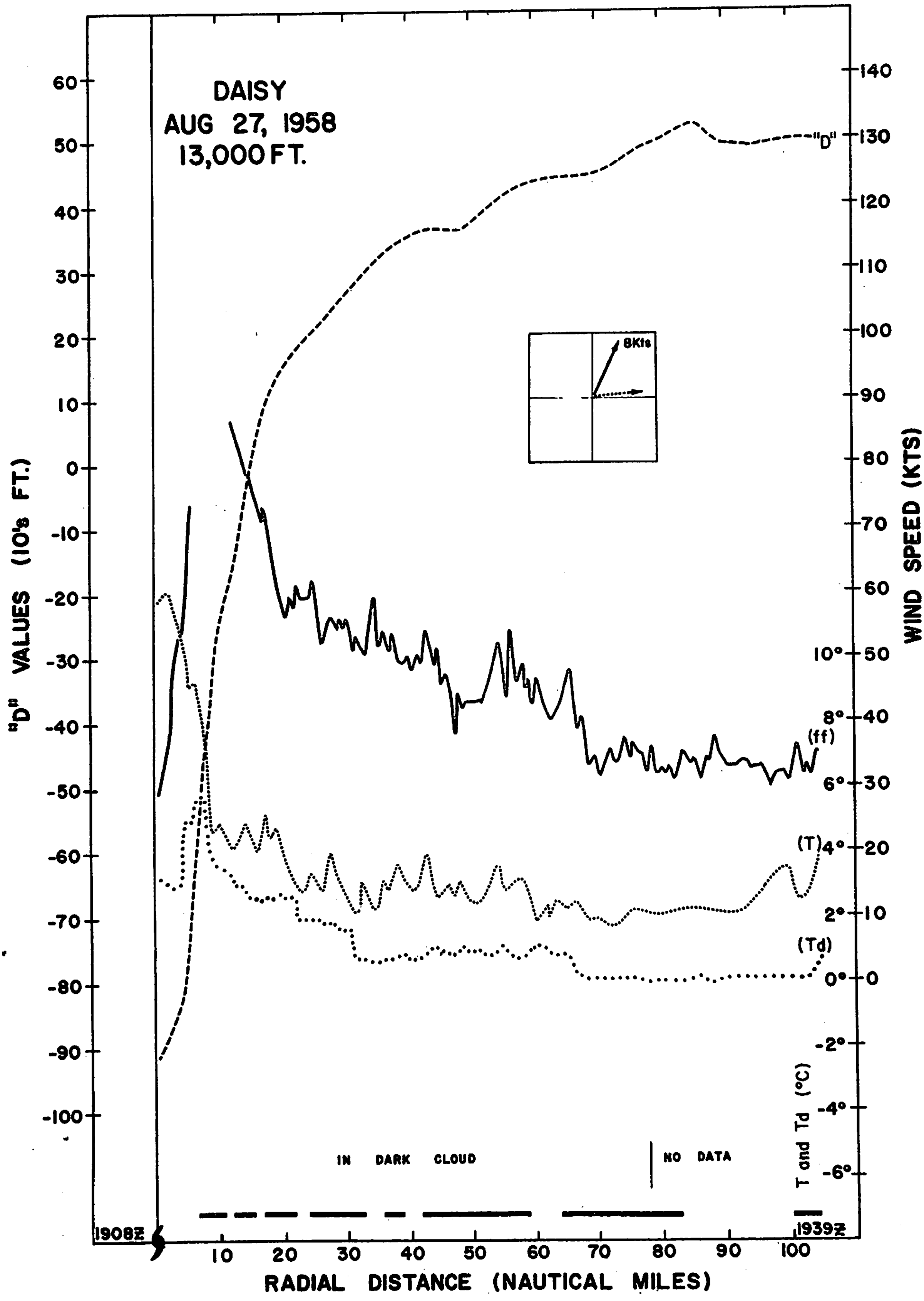

Figure 32. - Data profile at 13,000 ft., 620 mb., August 27, 1958.

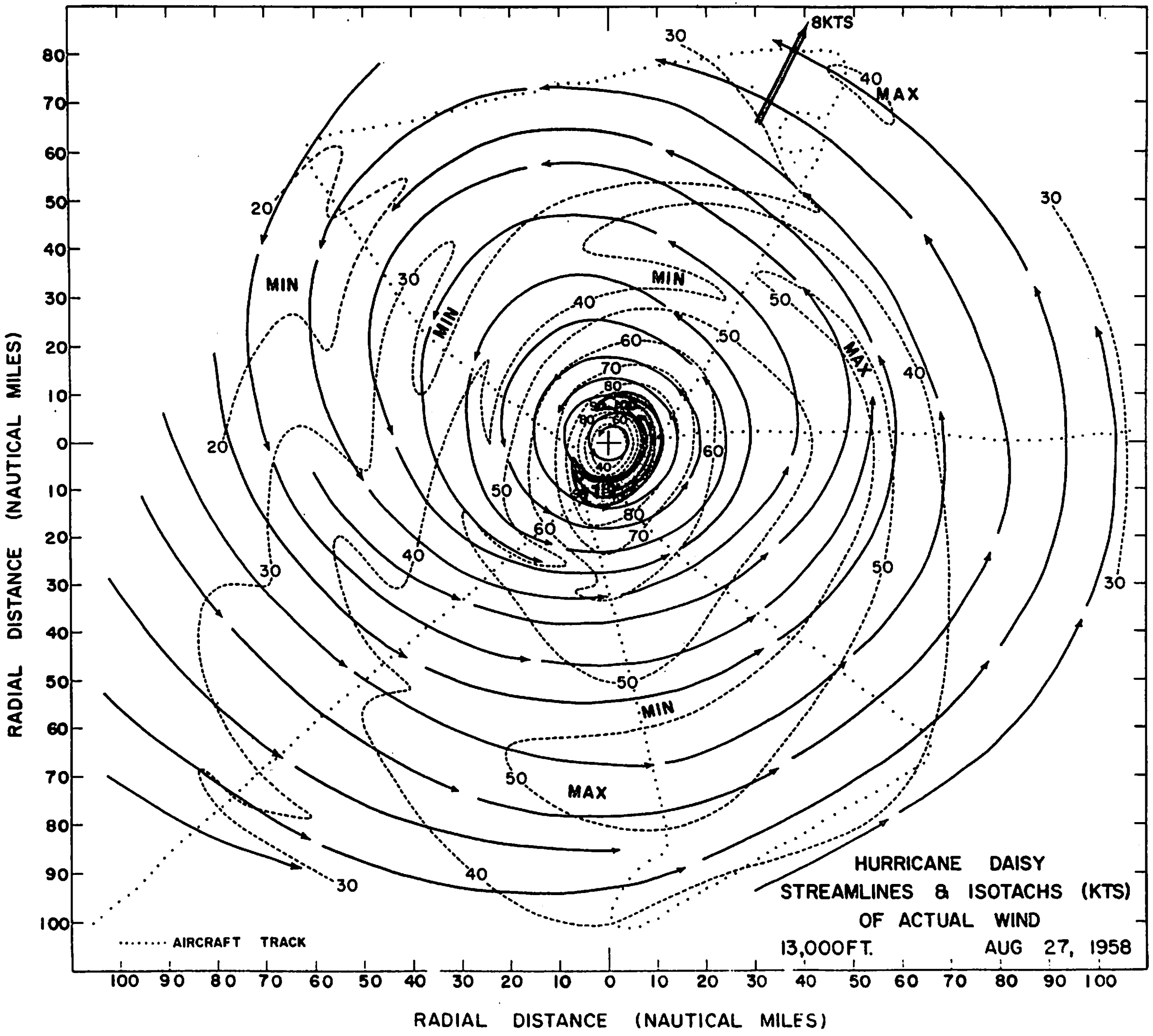

Figure 33. - Horizontal wind field at 13,000 ft., 620 mb., August 27, 1958.

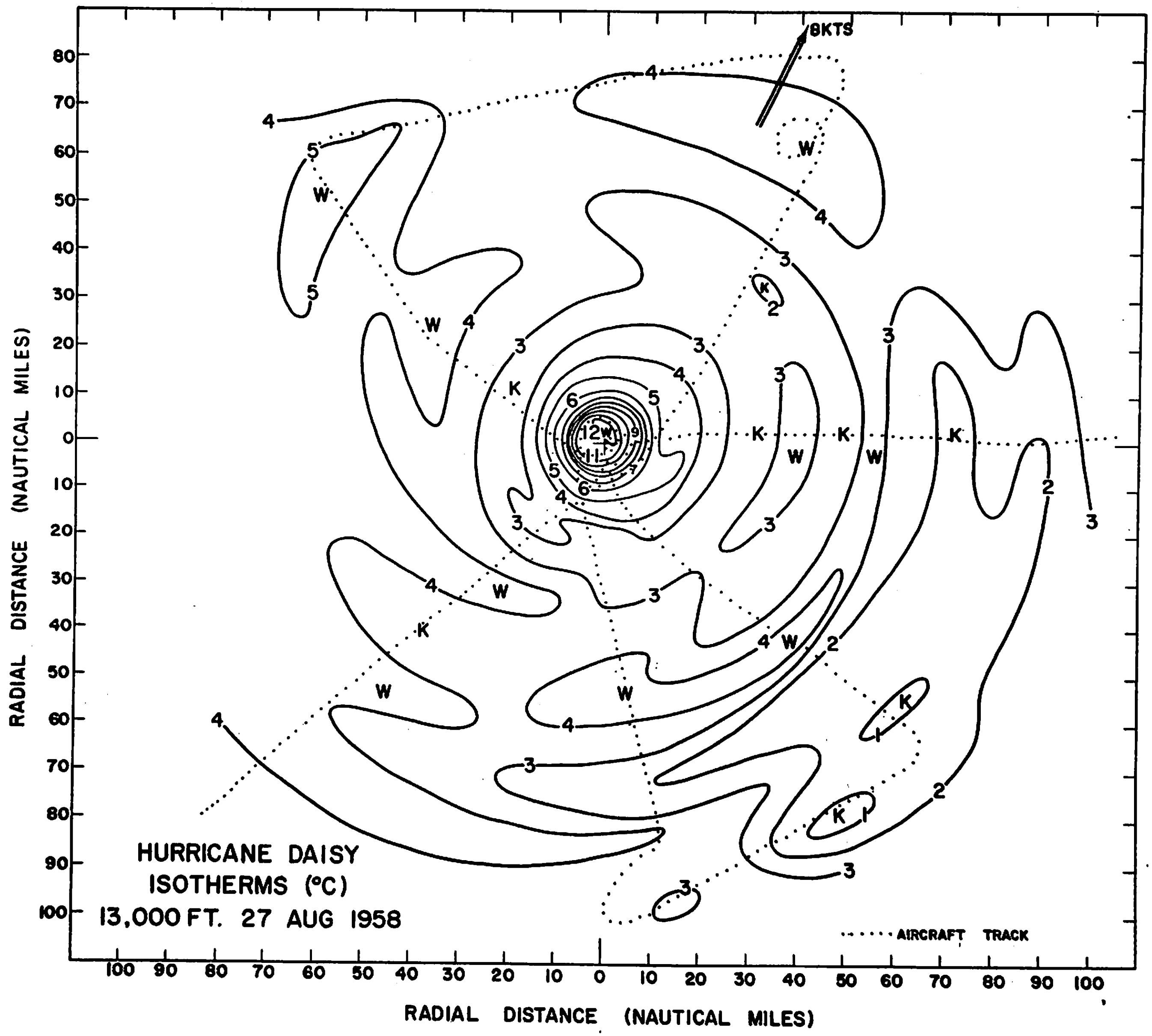

Figure 34. - Horizontal temperature field at 13,000 ft., 620 mb., August 27, 1958.

peratures inside the eye. Figures 31 and 32 illustrate this feature quite clearly. There was a rise from about 5°C. to 12°C. inside the 9-mi. radius. The maximum temperature, 12°C., was about 9°C. warmer than the normal; this anomaly is more than twice that observed at an equivalent level on August 25. These profiles are quite remarkable also in the fact that outside the 10-mi. radius there were practically no horizontal gradients. A cold valley was again present in the rain area outside of the eye; it appeared more prominently in figures 29 and 30. Other zones of cool and warm air were observed in the outer regions in some of the profiles. Of particular interest is the warm zone between the 60- and 50-mi. radii in figure 31, which was quite unique and different from anything recorded on this or other days. The only other occurrence somewhat similar to it was the warm zone in the 35- to 25-mi. zone on the right side of figure 19. At the time of the temperature increase in figure 31, the aircraft was going through an extremely dark cloud, which cleared slightly near the inner edge of the warm zone (see the cloud remarks, fig. 31).

The distribution of clouds at flight level and of radar bands are included in all the profiles presented for this day. Some well-marked and interesting examples of variations in temperature and dew point associated with the cloud and precipitation distribution can be inspected on the left side of figure 29 and the right side of figure 30.

The moisture data have been included for a few of the radial legs. The curves show more variability than those presented for the middle level of August 25, but on the whole not as much as one might expect in view of the variations in cloudiness.

The horizontal temperature field (fig. 34) showed a concentrated gradient in the immediate vicinity of the eye, with nearly circular symmetric isotherms around the center. Outside of this central region the isotherms showed the same type of variations observed on the previous days, with alternating bands of relatively cool and warm air. There appeared to be much greater variability in the temperatures, and also colder temperatures, in the right semicircle than in the left coinciding with a greater amount of convective activity and cloudiness at flight level on that side of the circulation (see also Malkus et al. [15]). Colder temperatures in the right semicircle were also observed in the low levels on August 25 (fig. 15), but not at middle levels (fig. 21).

(3) Pressure field. - The "D" value profiles reflected the large decrease in central pressure that had taken place. The minimum value observed on this day at the 13,000-ft. level was -950 ft. which corresponds to a surface pressure of about 950 mb. This value was confirmed by a dropsonde observation made in the eye at 1945 GMT, August 27, which gave a surface pressure of 948 mb. The horizontal pressure field, as can be ascertained from the different profiles, showed nearly concentric isopleths with maximum gradient in the eye wall.

c. Hurricane circulation, 34,200 ft.

The reconnaissance mission by the "C"-plane on August 27 made two penetrations into the center of the storm (figs. 35 and 36) and supplied very illuminating data on the distribution of wind and temperature across the eye at high levels. The complete track is shown in figure 37; the timing of the penetrations was such that the northwest to south pass at the upper level (fig. 36) was fairly close in time to the northwest to south pass at the middle level (fig. 30).

(1) Wind field. - In the two radial profiles in figures 35 and 36 only the sectors with cyclonic flow have been illustrated. The southwest to northeast pass (fig. 35) was made directly across the center of the eye and shows properties quite similar to those observed at the lower level. The high wind speeds were concentrated in a narrow zone around the eye, particularly on the forward side, with maximum speeds of around 70 kt. The maximum winds were located near the 10-mi. radius, as was the case in the lower level, indicating a nearly vertical slope for the eye-wall zone of maximum speeds. Data obtained by the RHI radar scope aboard a U. S. Navy reconnaissance plane on this day (reported by Jordan et al. [10]) showed this vertical slope quite well.

In the northwest to southeast pass along the perpendicular to the direction of motion, no data were obtained in the eye core. However, speeds of 64 kt. were recorded at the 11-mi. radius on the right side. The strongest anticyclonic shear radially outward from the speed maximum was found quite close to the center; outside of the 40-mi. radius the horizontal speed gradient was relatively small. The winds appeared to be stronger and extended farther out in the right than in the left semicircle.

There were no oscillations in wind speed or in temperature at this level comparable to those observed at the 13,000-ft. level. This may be attributed to the fact that the observations were taken generally at 4-second intervals, and with the faster cruising speed of the aircraft the sampling distribution is different. However, if the small-scale fluctuations were primarily caused by the presence of vertical currents they would not be as pronounced at the upper level. Generally, convective currents do not extend as frequently to this upper level, and if they did, the vertical motion would presumably be small.

The horizontal wind distribution (fig. 37) showed a cyclonic vortex extending to a radius of 50 to 60 mi. There was a ring of maximum winds surrounding the periphery of the eye, open on the left side, that resembled quite well the picture observed at low levels. Outside the 60-mi. radius the flow became anticyclonic; to the left of the motion the winds were generally light with a type of circulation that appeared to be mostly cellular. On the right semicircle there was a strong current flowing anticyclonically toward the southeast. The main outflow from the hurricane core was toward the east and southeast, the same as in previous days; but there was also some outflow toward the north that had not existed previously.

(2) Temperature field. - The temperature profiles showed a warm core extending to the 20-mi. radius; outside of this radius the horizontal gradients were small. The outward extension of the warm core was about twice that observed at the 620-mb. level. The maximum temperature in the eye was -30.7°C., about 13°C. warmer than the normal for this level. There were practically no horizontal small-scale fluctuations, most probably because of the absence of pronounced convective currents at this height. Extensive amounts of cloudiness were noted at flight level. As far as could be determined most of it was of a layer type. In the southwest to northeast pass (fig. 35) the aircraft went

into the cirrus deck at about the 64-mi. radius; the clouds were quite dark and thick inside the 50-mi. radius. Across the eye there was a partial clearing with thinning out of the cirrus layer, so that a bowl-like cloud structure was visible below. However, the aircraft did not break completely into the clear and encountered heavy cirrus again on the forward side of the eye. It subsequently broke out of the cirrus layer at about the 40-mi. radius on the forward side. For the rest of this radial pass it alternated between the top and bottom of the cirrus layer, as indicated by the cloud remarks. In some sections of this leg the aircraft was definitely near the top of the cirrus deck with blue clear sky visible above; the radar altitude indicated the top of the cirrus layer to be near 36,000 ft. The north to south penetration (fig. 36) was made completely in cloud; the aircraft passed just 10 mi. west of the center.

The horizontal temperature field (fig. 38) showed a core of warm temperatures with near circular isotherms perfectly centered on the eye. All the temperatures observed were warmer than normal, as was the case on previous days. No asymmetry in the distribution of temperatures on different sides of the circulation was evident at this level.

(3) Pressure field. - The profiles of "D" values were incomplete but a combination of the two fragmentary profiles gives a fairly reliable picture of the horizontal pressure variations. A quite pronounced pressure vortex was present, with most of the gradient occurring inside the 30-mi. radius. The minimum "D" value recorded was 1,420 ft. The horizontal field showed nearly circular contours near the eye, much like those at the lower level. In the outer region it was somewhat difficult to delineate the field of contours, since the gradients outside the eye were very small.

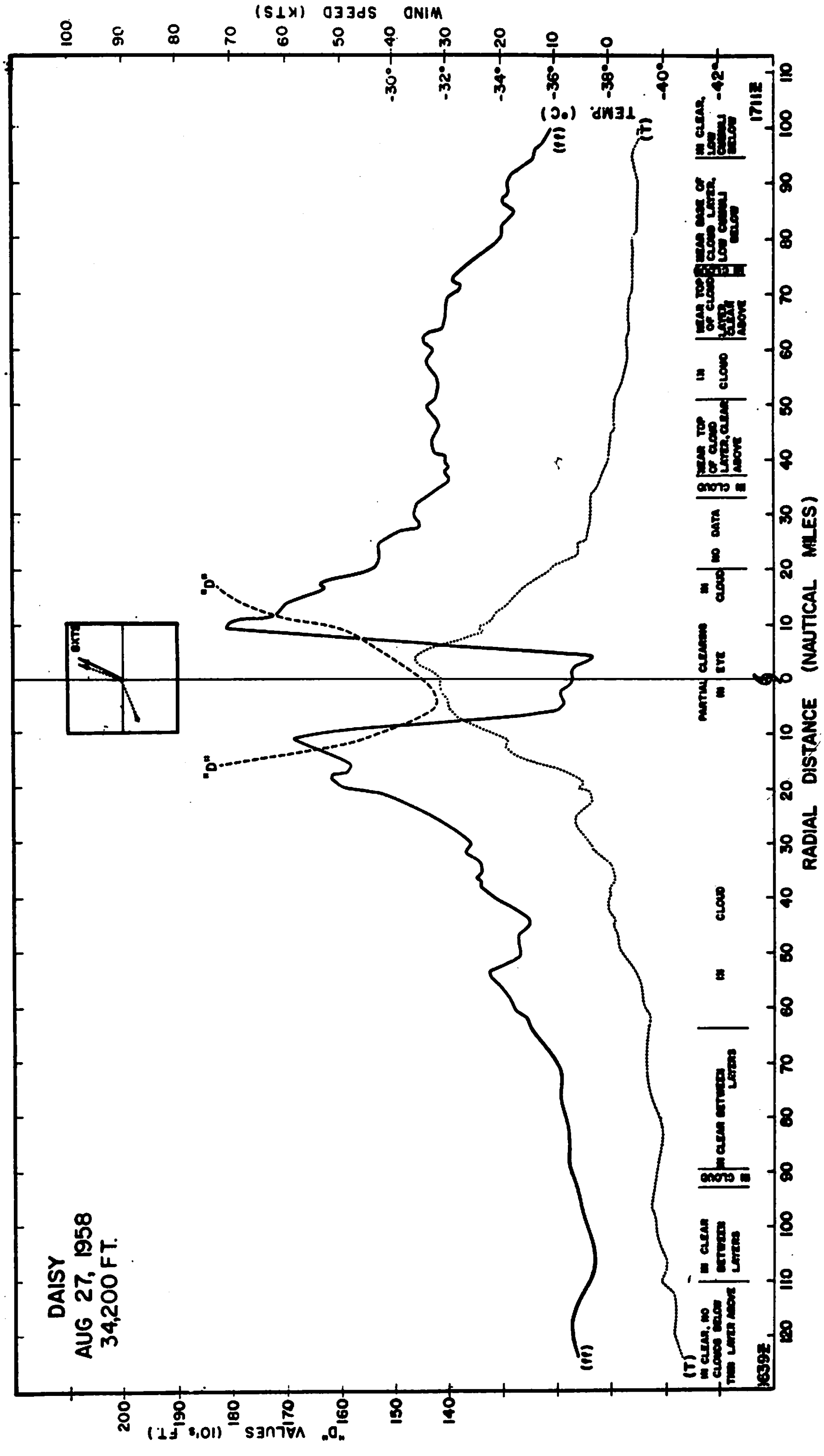

Figure 35. - Data profile at 34,200 ft., 248 mb., August 27, 1958.

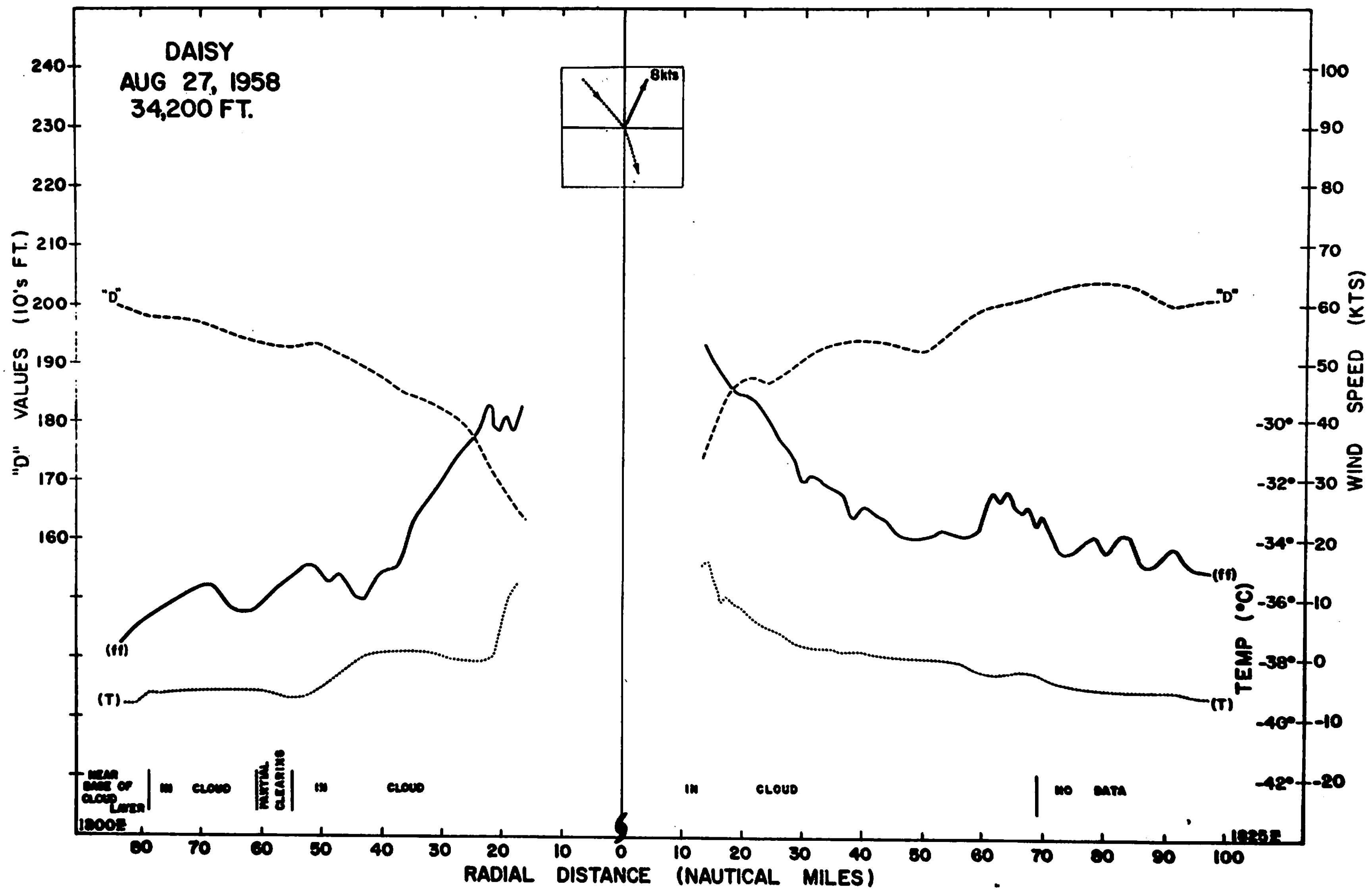

Figure 36. - Data profile at 34,200 ft., 248 mb., August 27, 1958.

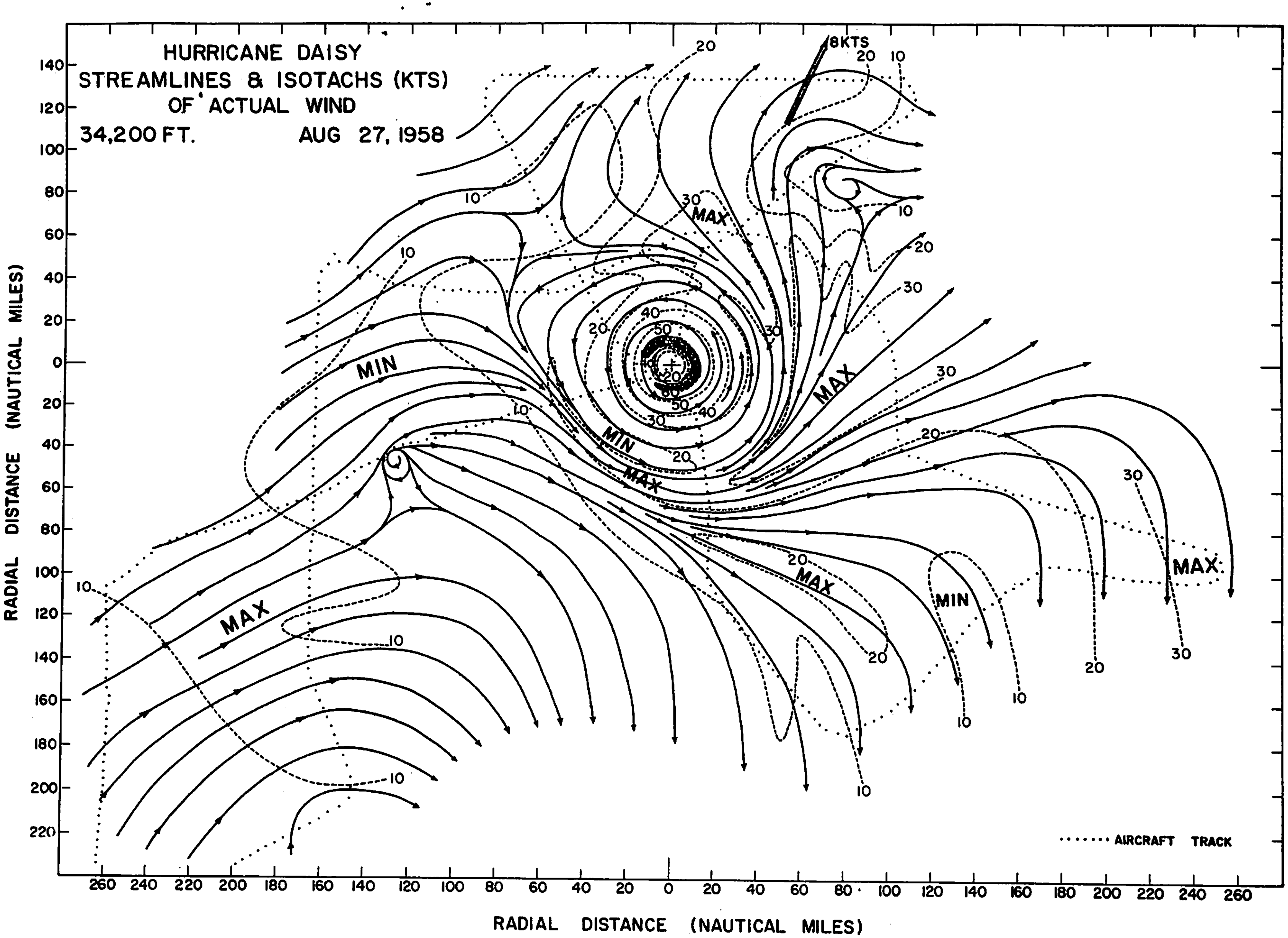

Figure 37. - Horizontal wind field at 34,200 ft., 248 mb., August 27, 1958.

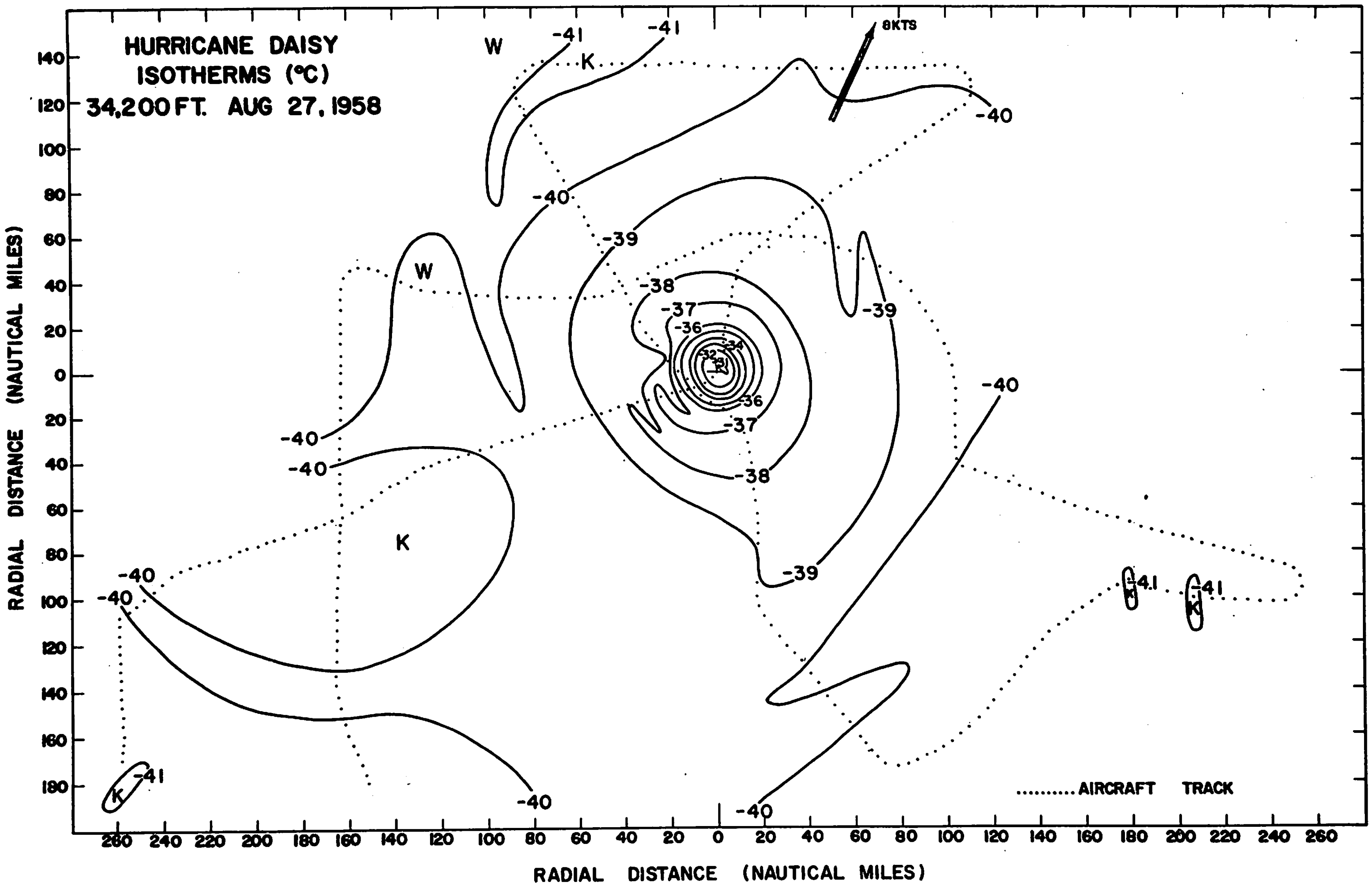

Figure 38. - Horizontal temperature field at 34,200 ft., 248 mb., August 27, 1958.

7. HURRICANE STRUCTURE - AUGUST 28

At the time of the research mission on August 28, hurricane Daisy was located near latitude 35°N. (fig. 1) moving rapidly northward at a speed of about 18 kt. There was only a 1-plane mission on this day; the "A" aircraft flew a track as shown in figure 44 between the hours of 1600 and 2200 GMT, at an altitude of 13,000 ft. The estimated central pressure was near 966 mb., so that filling of about 16 mb. had taken place since the observations on the previous day. A comparison of the data with those taken at the same level on the 27th shows the changes in the circulation and thermal fields during the early phase of the dissipation stage.

a. Wind field.

One of the main characteristics of the wind circulation was the absence of the extreme concentration in a narrow peak that had been observed on August 27. The wind field showed the same general characteristics on all sides (figs. 39-43). The intensity of the maximum winds, over 100 kt. in the right side. was only slightly lower but the zone of strong winds in the eye wall covered a rather large and broad zone. This contrasted sharply with the narrow peak observed in figure 31. In the left side of the storm (figs. 41 and 43) the flow was considerably weaker; there was an ill-defined zone of maximum winds of around 65 kt. with double and triple peaks.

A comparison of figure 39 with figure 31, both showing data in about the same direction relative to the direction of motion, illustrates the differences in the wind distribution of the two days. Aside from the striking difference in the character of the flow in the eye-wall, it was interesting to notice that outside of the eye-wall the wind speeds on August 28 (the weaker day) were actually higher than on the 27th. The same effect was noticed in the profiles in figures 41 and 32, both on the right front quadrants. This effect, suggesting a spreading of the high-kinetic-energy ring outward, may be a characteristic feature of the dissipation process.

The small-scale fluctuations in wind speed do not seem to be as common in the profiles of August 28 as in those of August 27. This is probably to be expected in view of the decrease in convective activity that presumably occurred with the weakening process. The cloud films indicated a large amount of layered-type clouds with the structure of the wall cloud not as well-defined as on the previous day. Cloud films were available during four of the passes across the eye-wall and two of them were made essentially in the clear. In the penetration from the south (fig. 42) the aircraft was in the clear, between layers, from the 52-mi. radius inward. There were a few small clouds at flight level, but of such short extent as to be unworthy of illustration. The plane went across the eye in a south to north direction passing about 4 mi. west of the center. The penetration was completely in the clear at flight level; bowl-like cloud formations were clearly visible with their apparent center to the right of the track. About 4 mi. north of the center the plane went into cloud and remained in cloud during practically all of the north leg out to the 50-mi. radius. The penetration from the west illustrated in figure 43 was also for the most part in clouds; the break-out into the eye was rather gradual, with partial clearing attained near the 10-mi. radius. From there on the aircraft was essentially in theclear in its path through the center of the eye and across the zone of maximum winds up to the 14-mi. radius on the right. The aircraft then turned around through the south, moved closed to the center, then flew out again, all of this time in the clear at flight level (with cloud layers above and below).

No radar data have been illustrated in the profiles for this day because of poor quality of the radar pictures; as far as could be determined the radar pictures of the eye-wall reflected the changes in the cloud structure as described above. The eye diameter as seen on radar was considerably larger on this day, about 20 mi., and did not have the well-defined ring configuration shown in figure 27.

The horizontal distribution of the wind field (fig. 44) showed a zone of wind of over 100 kt. to the right of the motion at a greater distance from the center than on previous days. This zone did not extend around to the front and rear sections of the eye as far as it had previously. The outward extension of the high kinetic energy core was in sharp contrast to the situation in figure 33; the 60-kt. isotach extended out to about 70 mi. on the right side as compared to only to the 20-mi. radius on August 27.

b. Temperature and moisture fields.

The temperature field on August 28 also showed some significant and very intriguing variations from that of the preceding day. The profiles showed in all cases the existence of a core of very warm air with a well-defined radial extent outside of which the horizontal temperature gradients were small. In this respect the isotherm field resembles that shown for August 27, except that the radial extent of the warm core was only 10 mi. on August 27 as compared to 20-30 mi. on the 28th. Another interesting feature was the fact that the maximum temperatures recorded in the eye, 16°C., or about 13° C. higher than normal, were about 4°C. warmer than those recorded on August 27, yet the pressure had filled by about 16 mb.

The most remarkable observation, which provides the clue to the pressure-temperature riddle, appears clearly in figure 41, where we notice that the center of the warm-air core is displaced well to the left of the wind and pressure center. This relationship was investigated for possible inaccuracies, since it departed so much from what had been observed previously. A second temperature probe aboard the aircraft [6] indicated variations similar to those in figure 41. It should be remembered also that the wind, temperature, and pressure data were punched simultaneously by the digital system; they can be moved relative to the storm center via the compositing technique but the three observations must always be simultaneous. No cloud data were available in this section; the radar pictures were not very clear, but the center could be determined fairly accurately. The radar eye was of the order of 20 mi. in diameter; it had more of a spiraling configureation, rather than the ring-like structure shown in figure 32. The magnitudes of the temperatures in the western sections of the eye and the displacement of the temperature center with respect to the wind and pressure centers were confirmed by the observations made in the south to north pass (fig. 42) and in the penetration from the west shown in figure 43; although in figure 43 the displacement did not appear to be as large. In the horizontal analysis (fig. 45) the center of the temperature vortex was slightly displaced to the rear and left of the wind

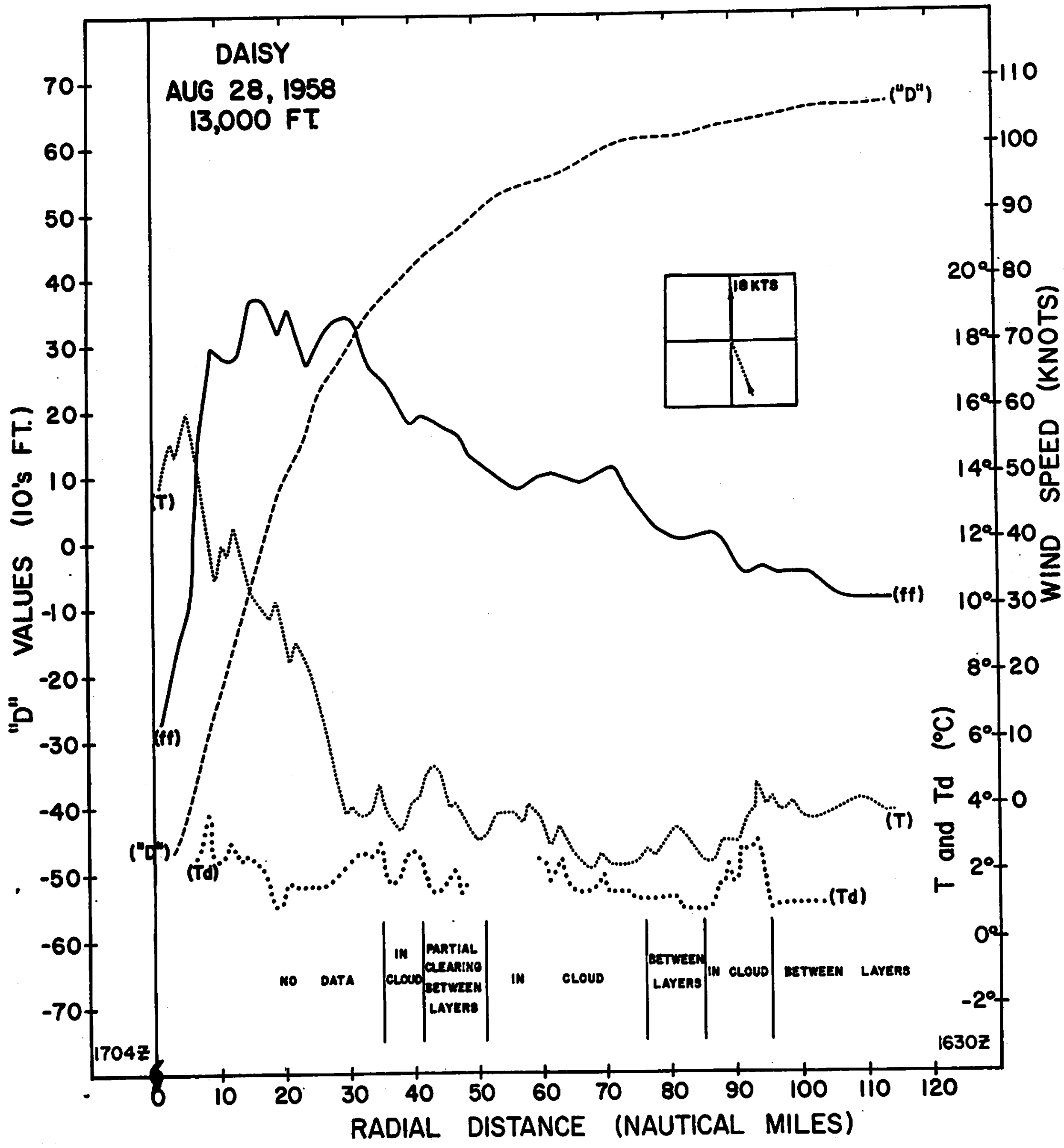

Figure 39. - Data profile at 13,000 ft., 620 mb., August 28, 1958.

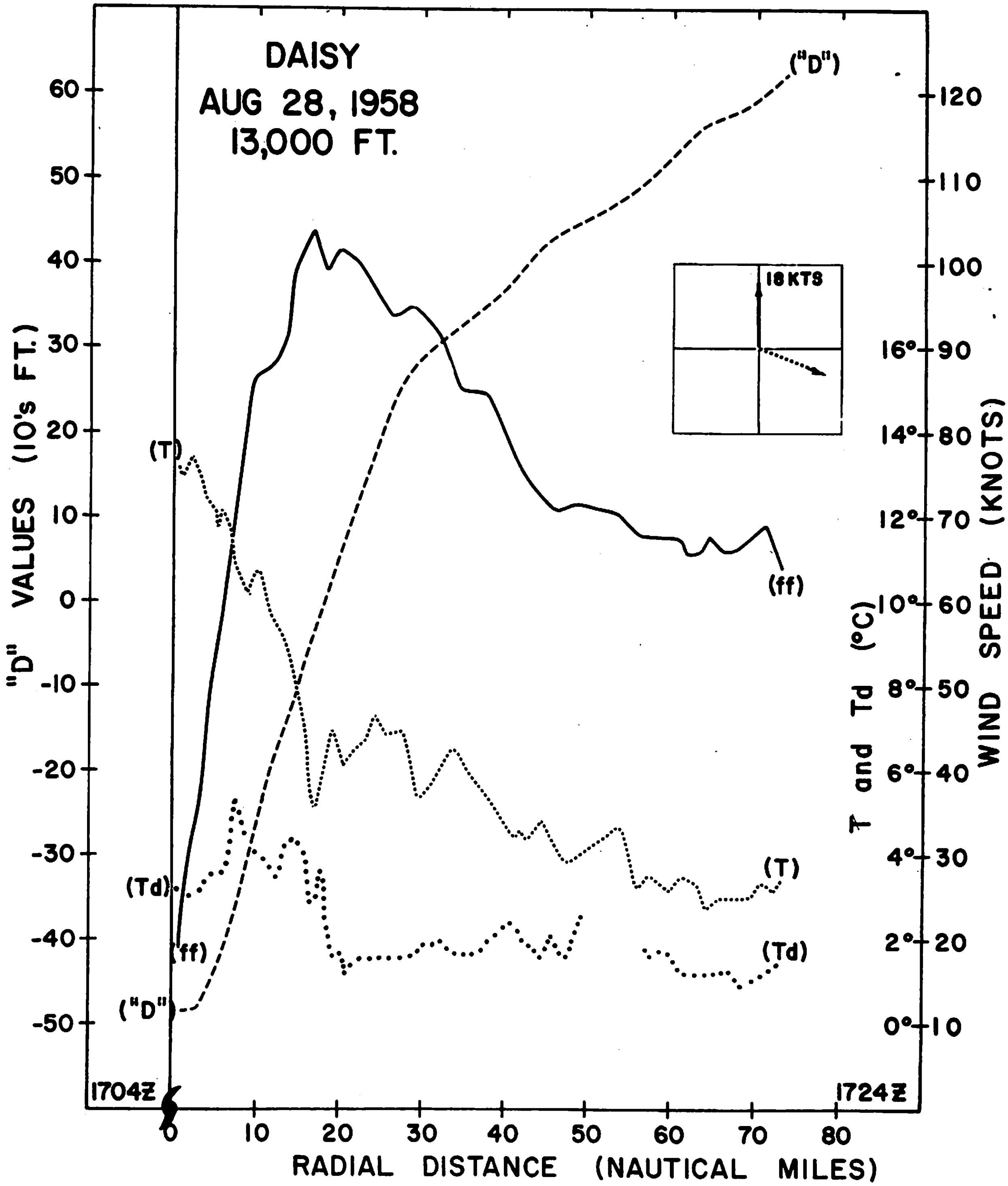

Figure 40. - Data profile at 13,000 ft., 620 mb., August 28, 1958.

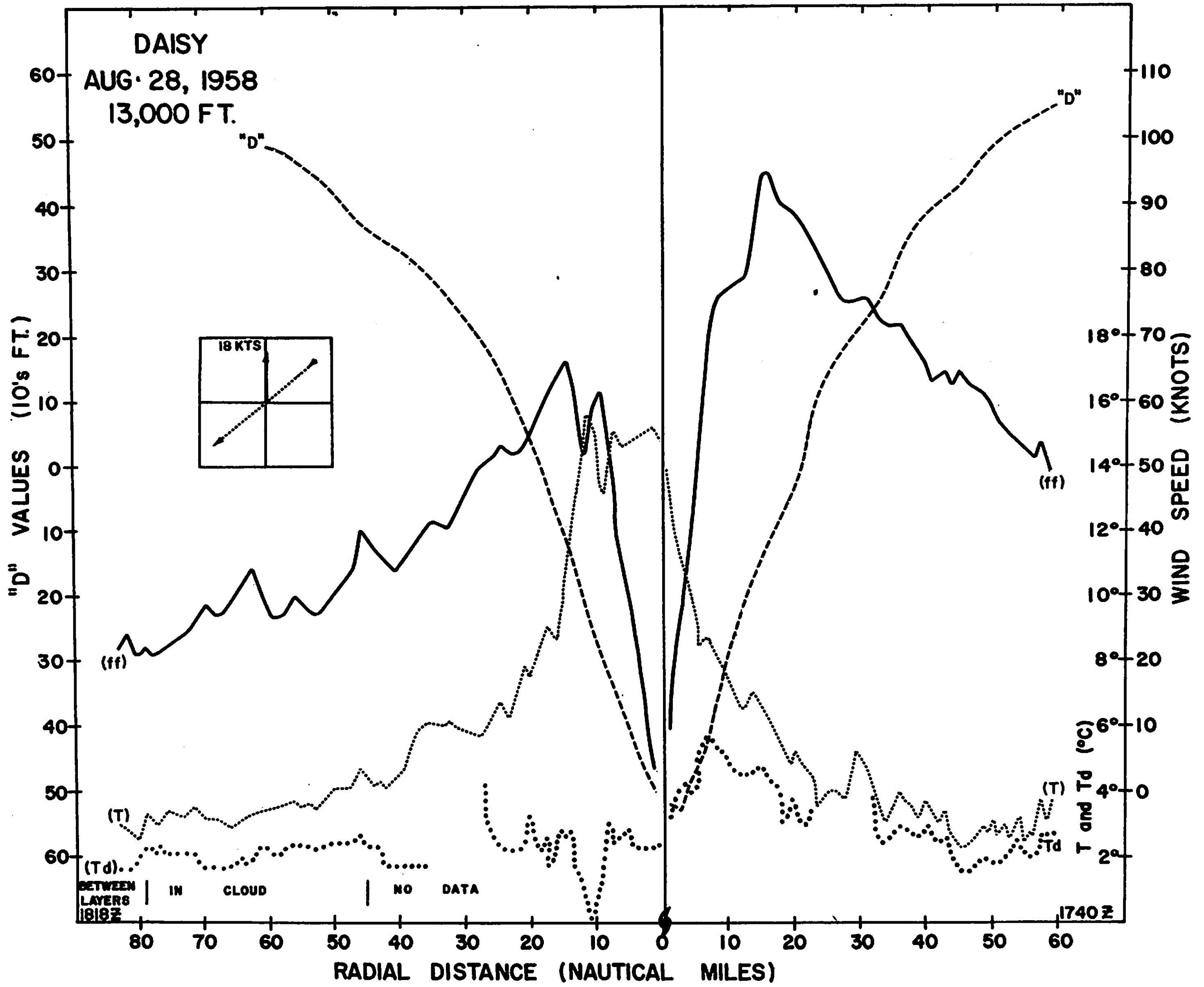

Figure 41. - Data profile at 13,000 ft., 620 mb., August 28, 1958.

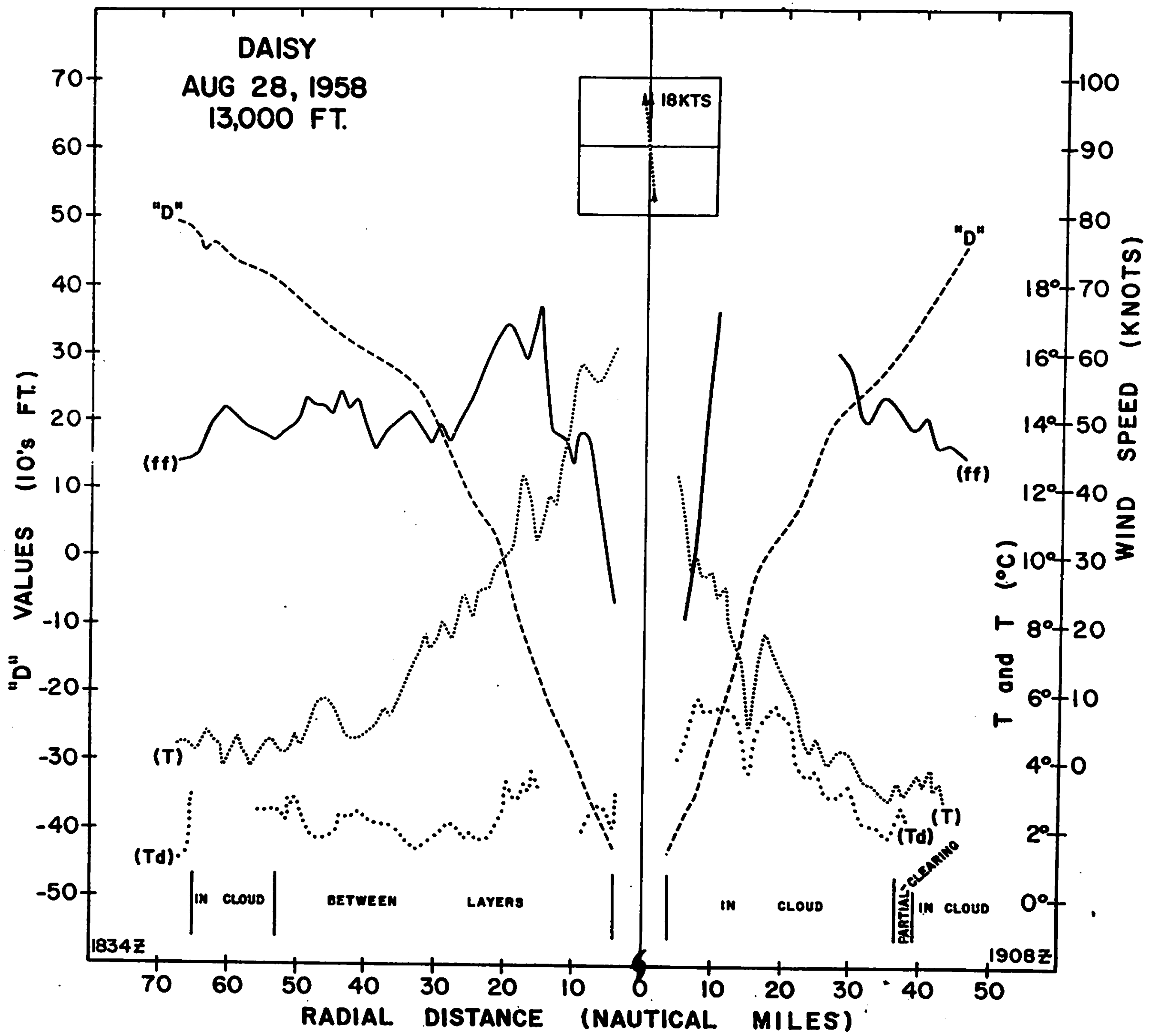

Figure 42. - Data profile at 13,000 ft., 620 mb., August 28, 1958.

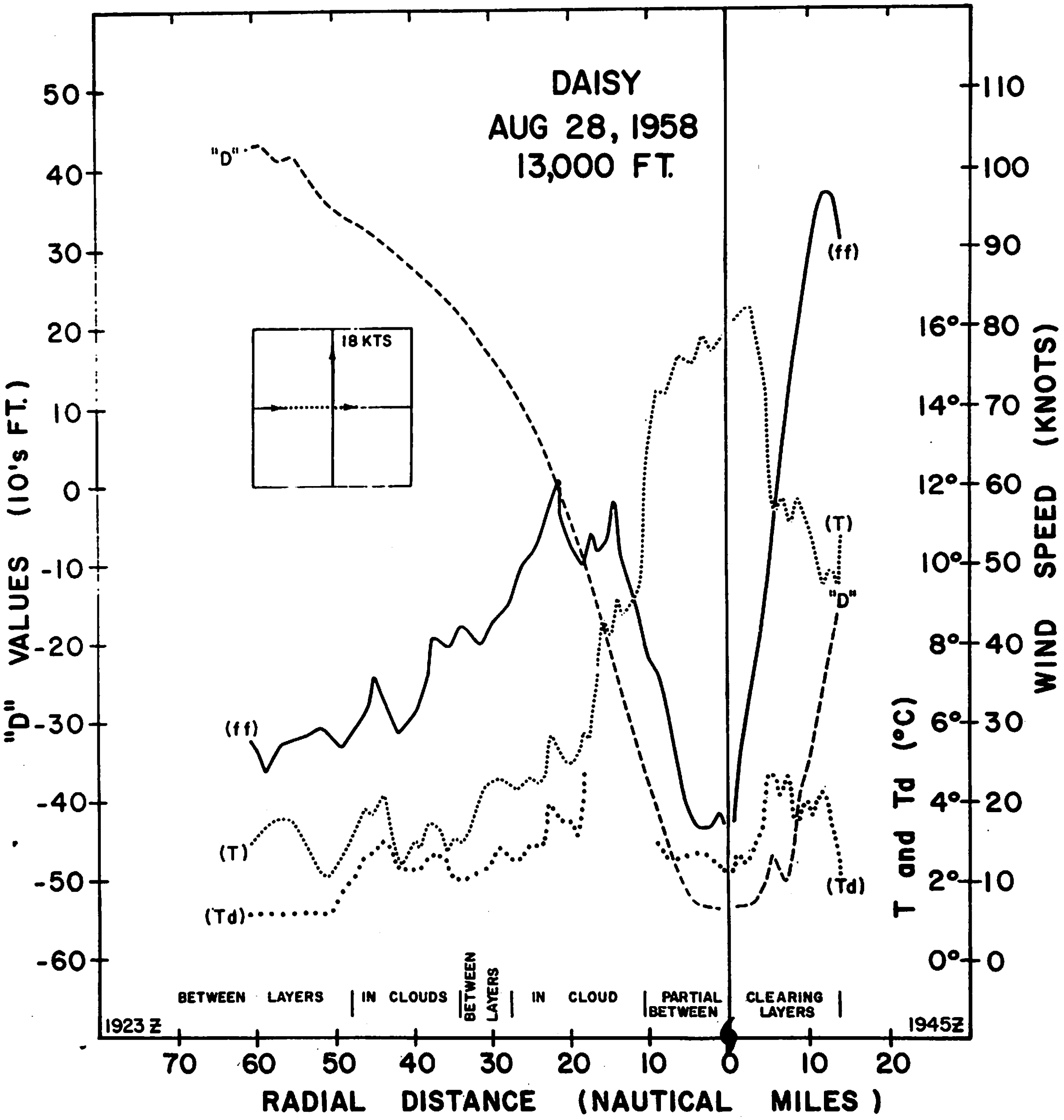

Figure 43. - Data profile at 13,000 ft., 620 mb., August 28, 1958.

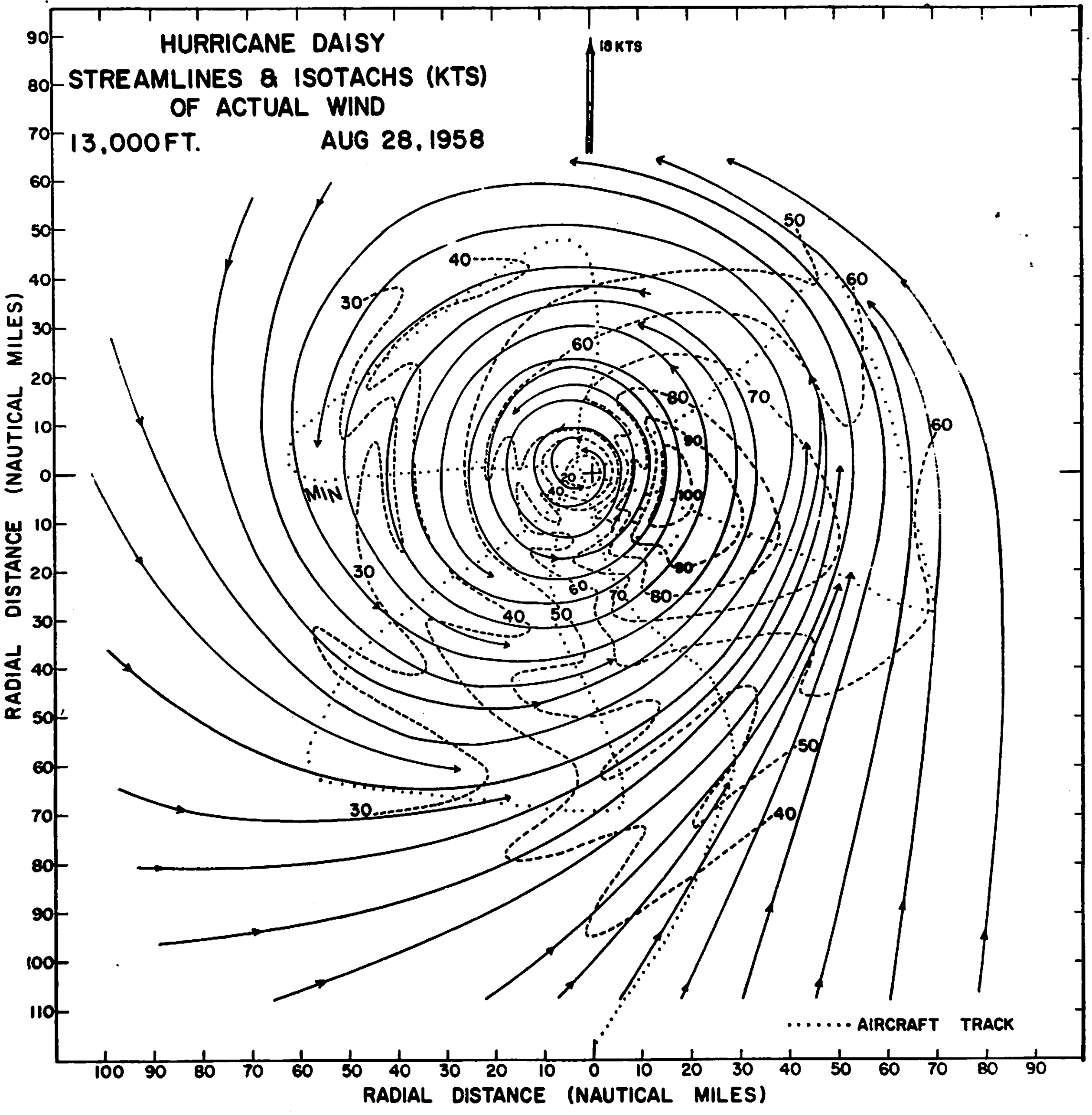

Figure 44. - Horizontal wind field at 13,000 ft., 620 mb., August 28, 1958.

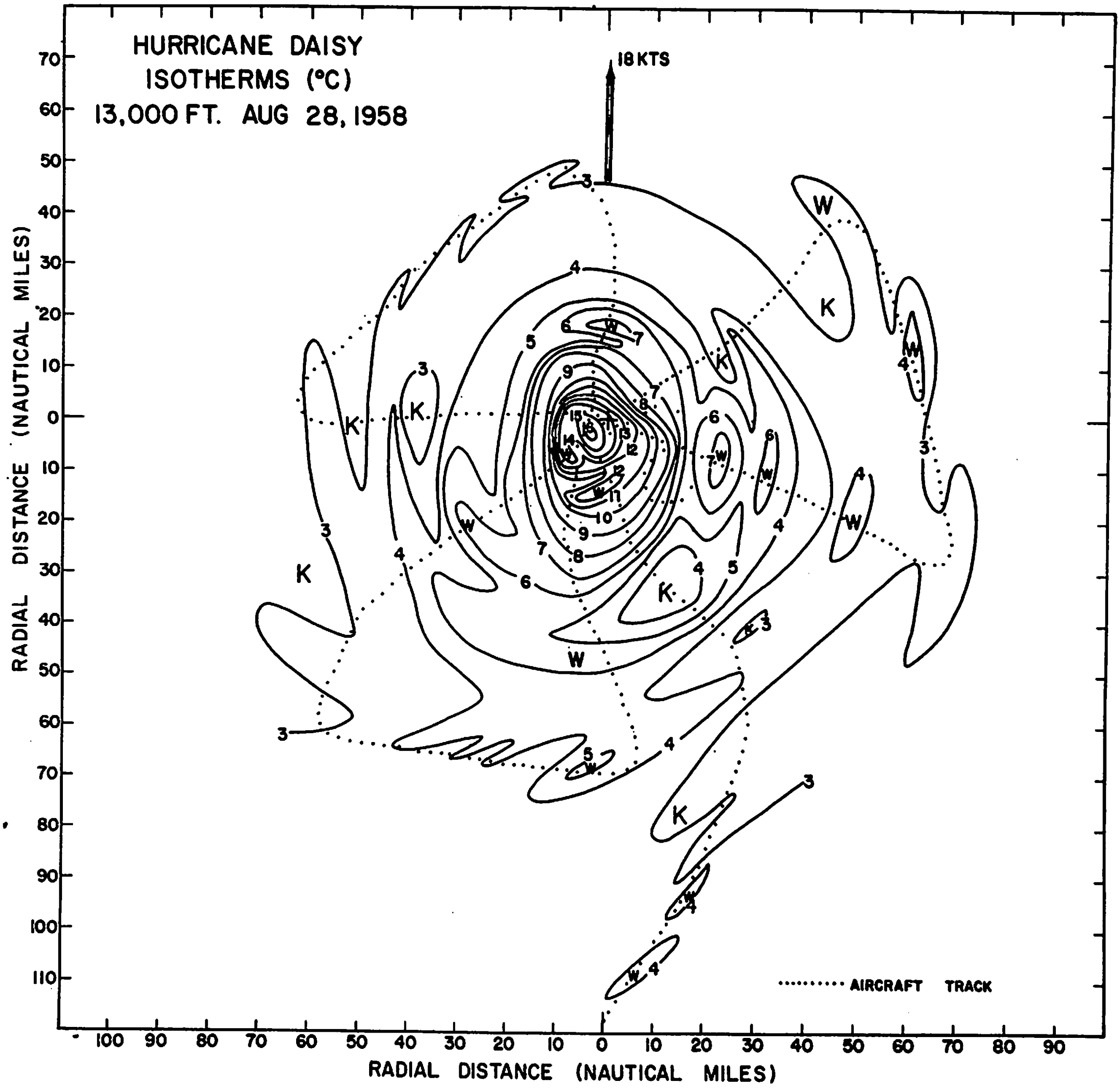

Figure 45. - Horizontal temperature field at 13,000 ft., 620 mb., August 28, 1958.

center. This displacement suggests how it might be possible for the pressure vortex to attain significant filling despite further warming in the eye core. On August 27 the warm core appeared to be very symmetrically located around the center at the two levels from which data were available (figs. 34, 38, and 51); therefore the warm core was apparently located at all levels vertically above the center of the surface pressure vortex. The displacement of the temperature vortex at the middle level on August 28 strongly suggests a vertical slant of the warm core so that the warmest air at each level was not superposed directly above the pressure vortex, and, therefore, an increase in surface pressure took place even though the temperatures were increasing at some levels. Unfortunately, there were no other data on August 28 to verify this picture. Such a disruption of the vertical balance between the thermal and pressure fields may very well have taken place and may be one of the mechanisms for the destruction of the hurricane circulation.

The horizontal field of isotherms (fig. 45) showed a more chaotic distribution than on the previous day. The asymmetry between the two semicircles noticed on previous days was not as pronounced on August 28. Except perhaps in the outer sections of the chart, the temperatures in figure 45 were significantly warmer than the corresponding ones in figure 34.

The dew point temperatures showed the same type of horizontal variations associated with the cloud and precipitation structure discussed previously. As a rule the dew point did not increase very much in the eye on this day.

c. Pressure field.

The minimum "D" value observed at the 13,000-ft. level on August 28 was about -530 ft., indicating a central pressure of around 966 mb. The "D" value profiles depicted a wider pressure vortex than on the previous day, a trend similar to that observed in the temperature field.

8. CHANGES IN THE CIRCULATION OF DAISY DURING THE DEEPENING STAGE

One of the most significant aspects of the Daisy data is that for the first time it has been possible to study a hurricane at two different stages in its life cycle. Unfortunately the data available on August 28 were not as complete as required to yield a comprehensive picture of the three-dimensional properties during the weakening stage. On the other hand, the observations for August 25 and August 27 are quite adequate for a study of the vertical structure of the wind, temperature, and pressure fields and of their time changes during the process of intensification.

To illustrate the vertical fields and the changes with time, space cross sections of wind speed, temperature, and pressure ("D" values) were constructed in a direction more or less perpendicular to the direction of storm motion on August 25 and 27. In the preparation of these cross sections some smoothing of the data was necessary in order to eliminate minor details. The sections for August 25 (figs. 46-48) were based essentially on the observations contained in figures 8-10, 18, and 19 for the left side, and those of figures 8, 9, 12, and 18 for the right side of the circulation. The data at the upper level (240 mb.) were rather incomplete since the flight path did not provide radial passes into the eye; the analyses near the eye at the upper levels included in figures 46-48 were approximated from the horizontal fields.

The analyses for August 27 (figs. 49-51) were based on the observations made along the northwest direction (figs. 30 and 36) for the conditions on the left side and along the south, southeast, and east directions (figs. 31, 32, and 36) for the right side of the circulation. The data in the eye at the upper level were taken from the eye crossing from southwest to northeast. No data were available below 620 mb. on August 27; it would have been reasonably realistic to extend the isopleths to the surface layer on the basis of the data at the middle level, but for the purpose of the present discussion analyses of the upper layers shown in figures 49-51 were entirely satisfactory.

No attempt was made to extend the analysis to the layers above 250 mb. It is evident that the hurricane circulation must eventually dissappear with height and that the anomalies of temperature and pressure, as well as the cyclonic wind circulation, should approach zero at some level above 250 mb. There was no direct information as to where this level was located. In a recent study of the energy balance of hurricane Daisy for August 25 and 27, Riehl and Malkus [22] assumed a top at the 150-mb. level for August 25 and at 100 mb. for August 27. On the other hand, radar data presented by Jordan et al. [10] indicated that the eye-wall cloud system on August 27 extended to altitudes above 60,000 ft, which is normally above the 80-mb. surface. Inspection of figure 55, which illustrates the approximate eye soundings for August 25 and 27, suggests that if these soundings were projected upward to meet the mean temperature curve the zero temperature anomalies in the eye would occur close to the 150-mb. surface on August 25 and just below the altitude of the 100-mb. level on August 27. Therefore, the assumption made by Riehl and Malkus [22] appears to be justified. At the same time this would not rule out individual well-developed convective cells in certain sections of the hurricane (such as observed by Jordan) extending to higher altitudes.

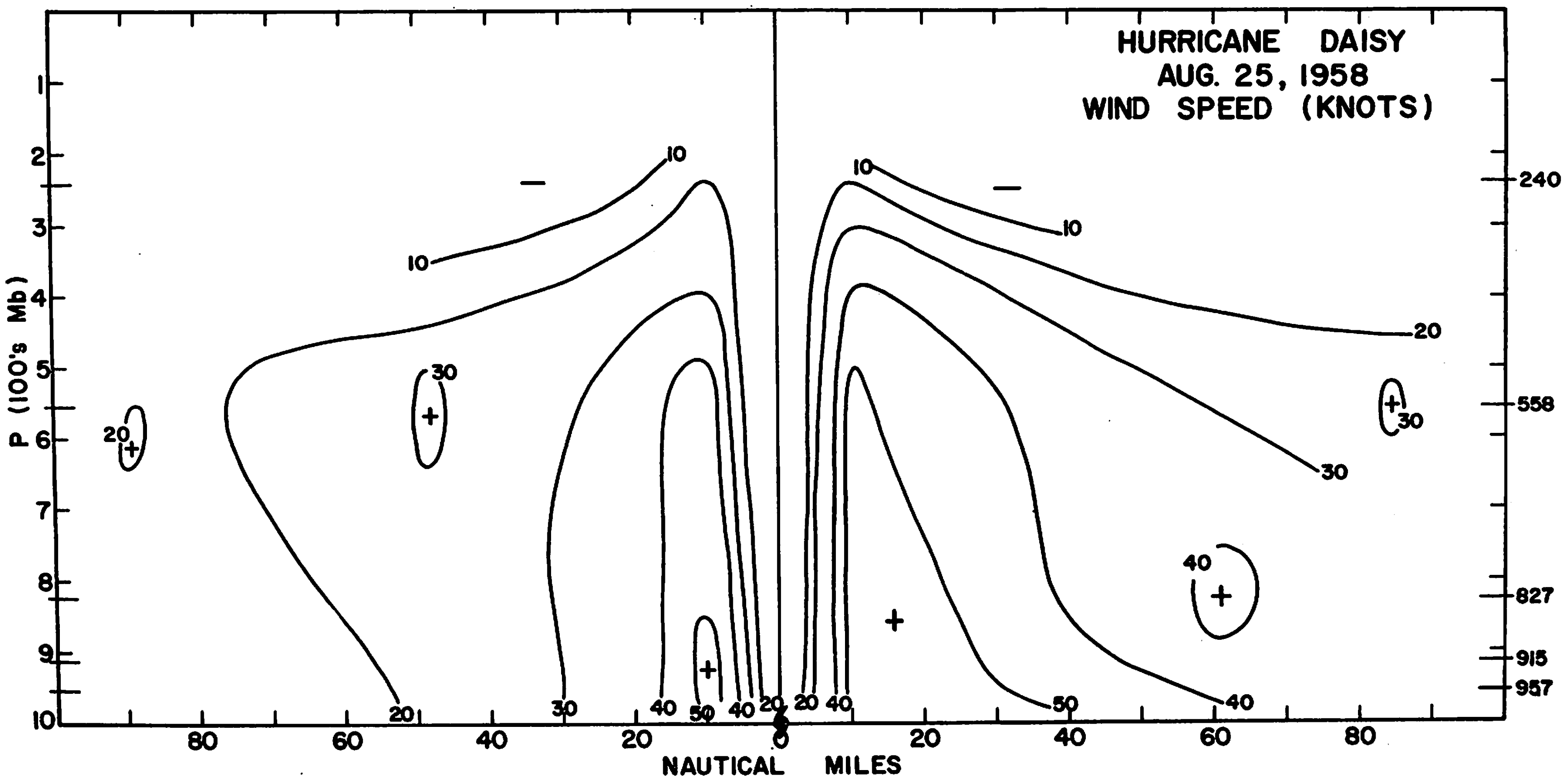

Figure 46. - Vertical cross section of wind speed in a direction perpendicular to the direction of motion, hurricane Daisy, August 25, 1958.

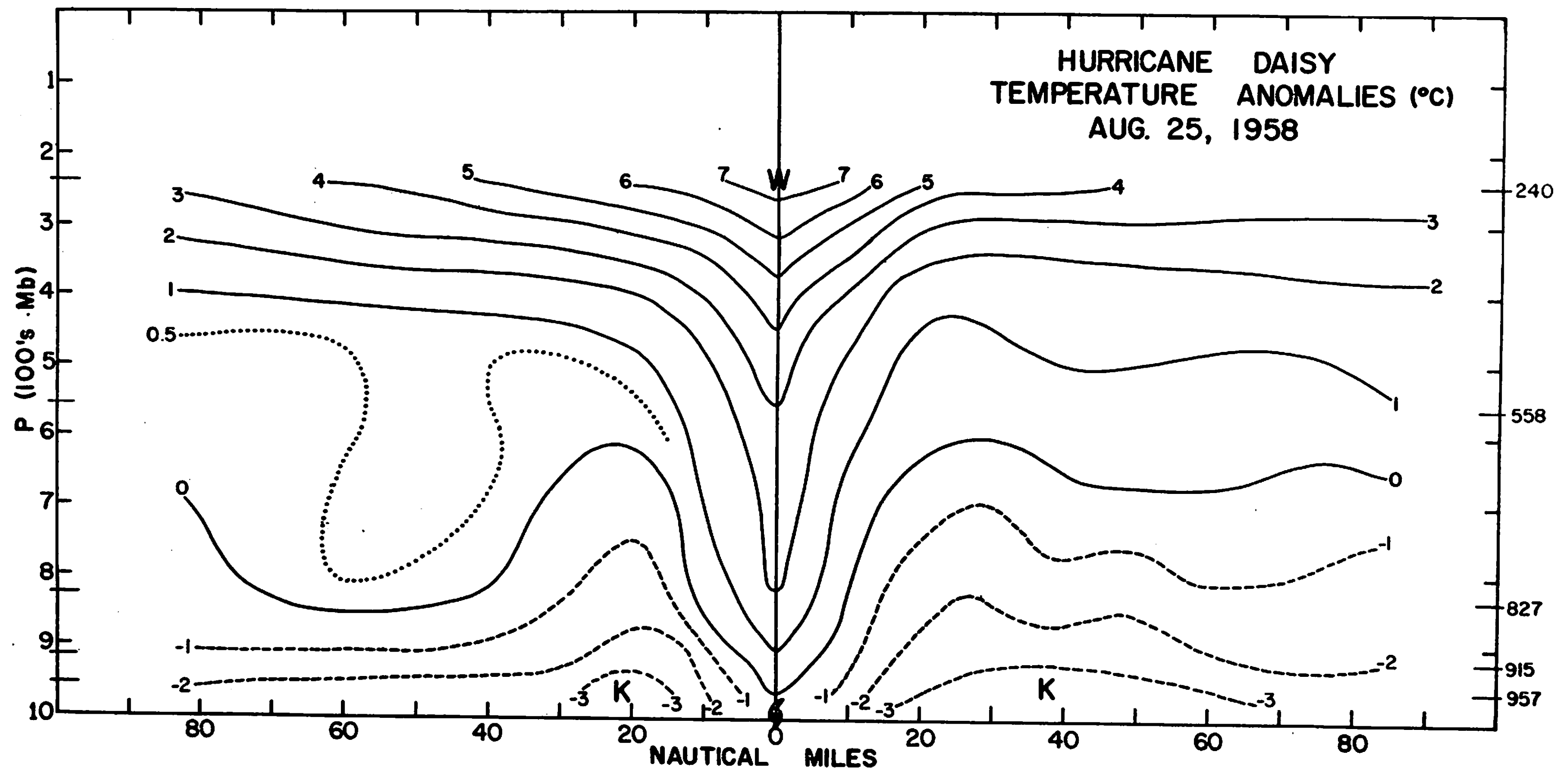

Figure 47. - Vertical cross section of temperature anomalies from the mean August atmosphere in a direction perpendicular to the direction of motion, hurricane Daisy, August 25, 1958. Pressure levels shown at the right edge indicate levels at which data was available.

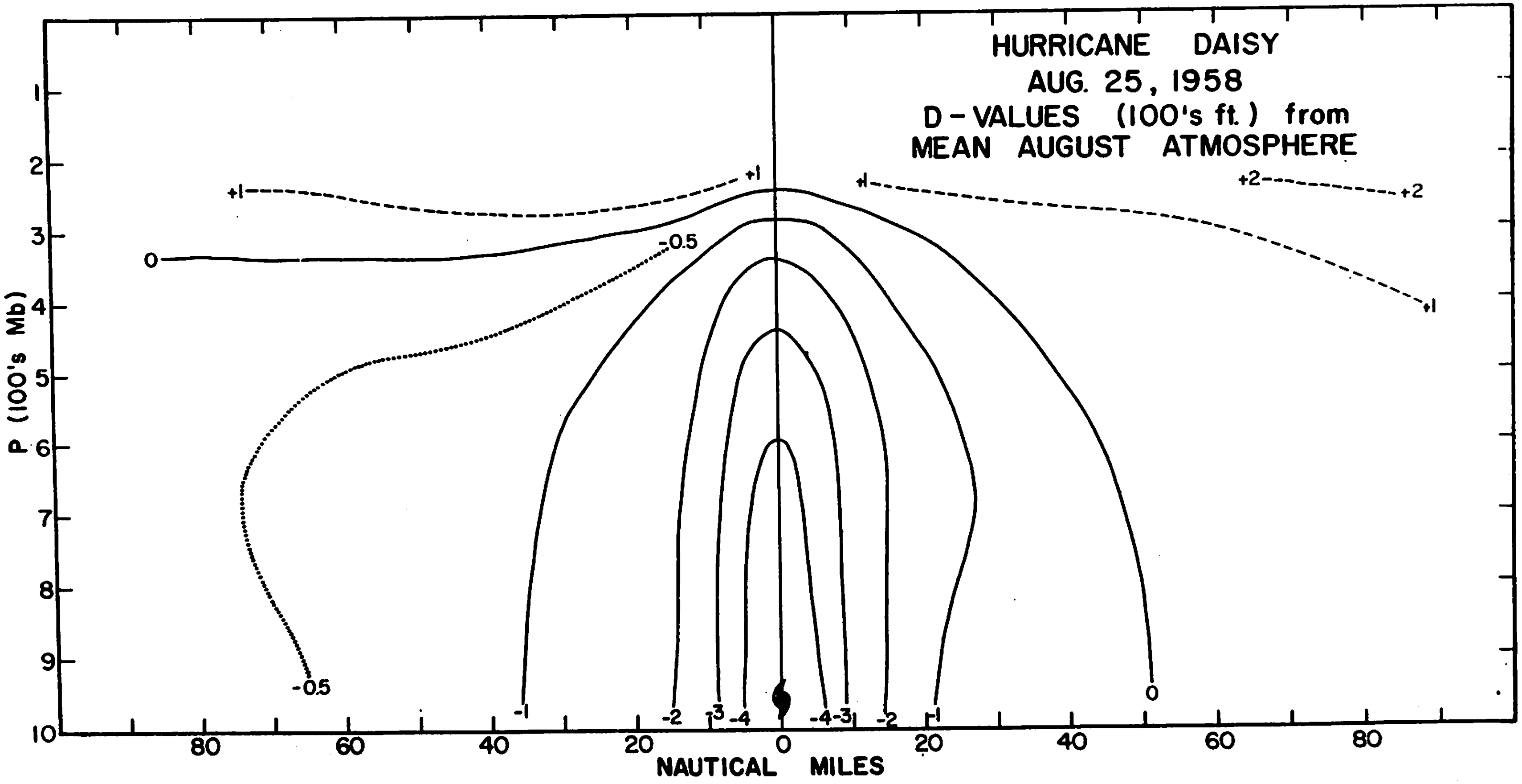

Figure 48. - Vertical cross section of deviations of the altitude of pressure surfaces from the mean August atmosphere in a direction perpendicular to the direction of motion, hurricane Daisy, August 25, 1958.

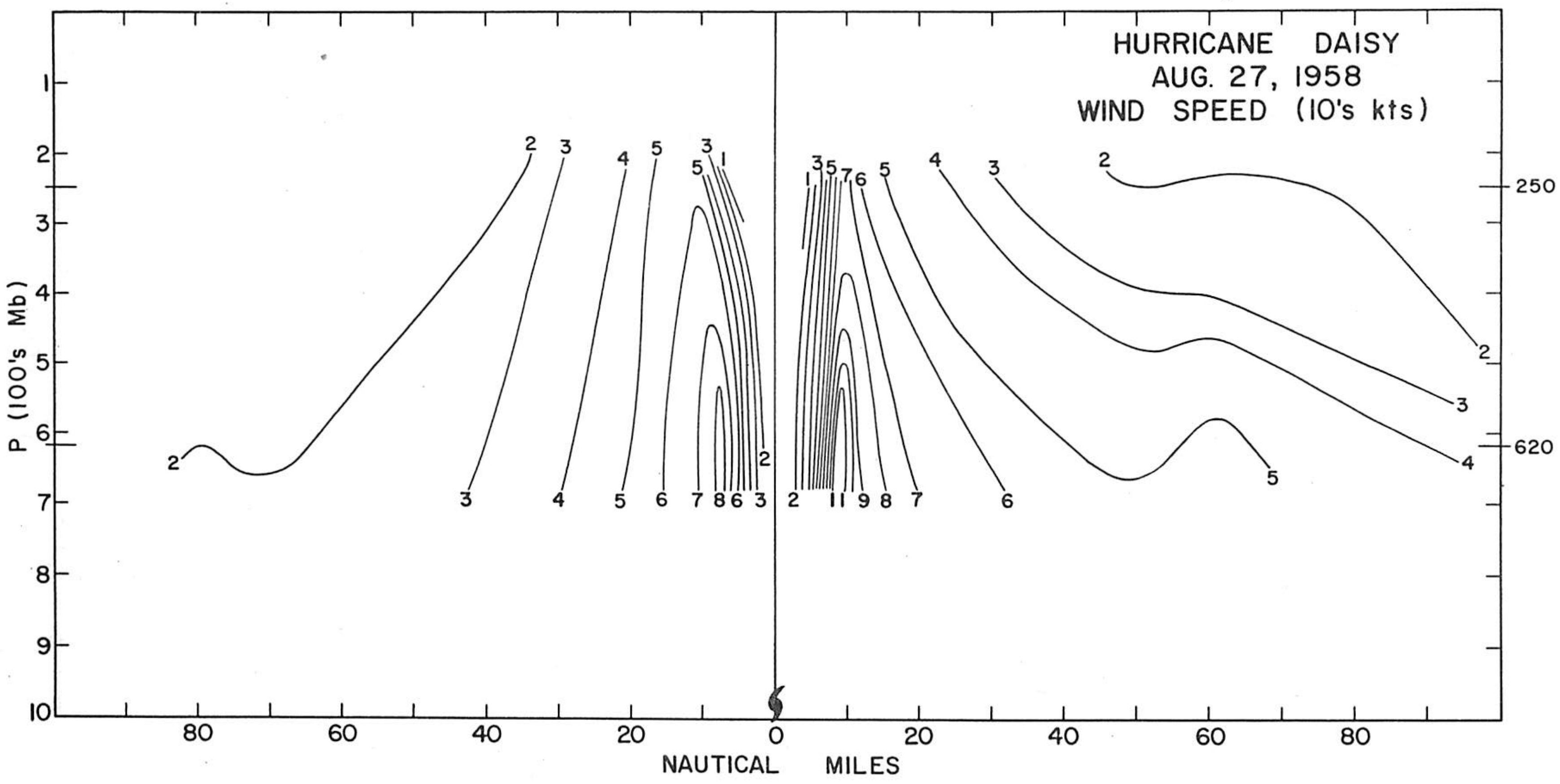

Figure 49. - Vertical cross section of wind speed, August 27, 1958.

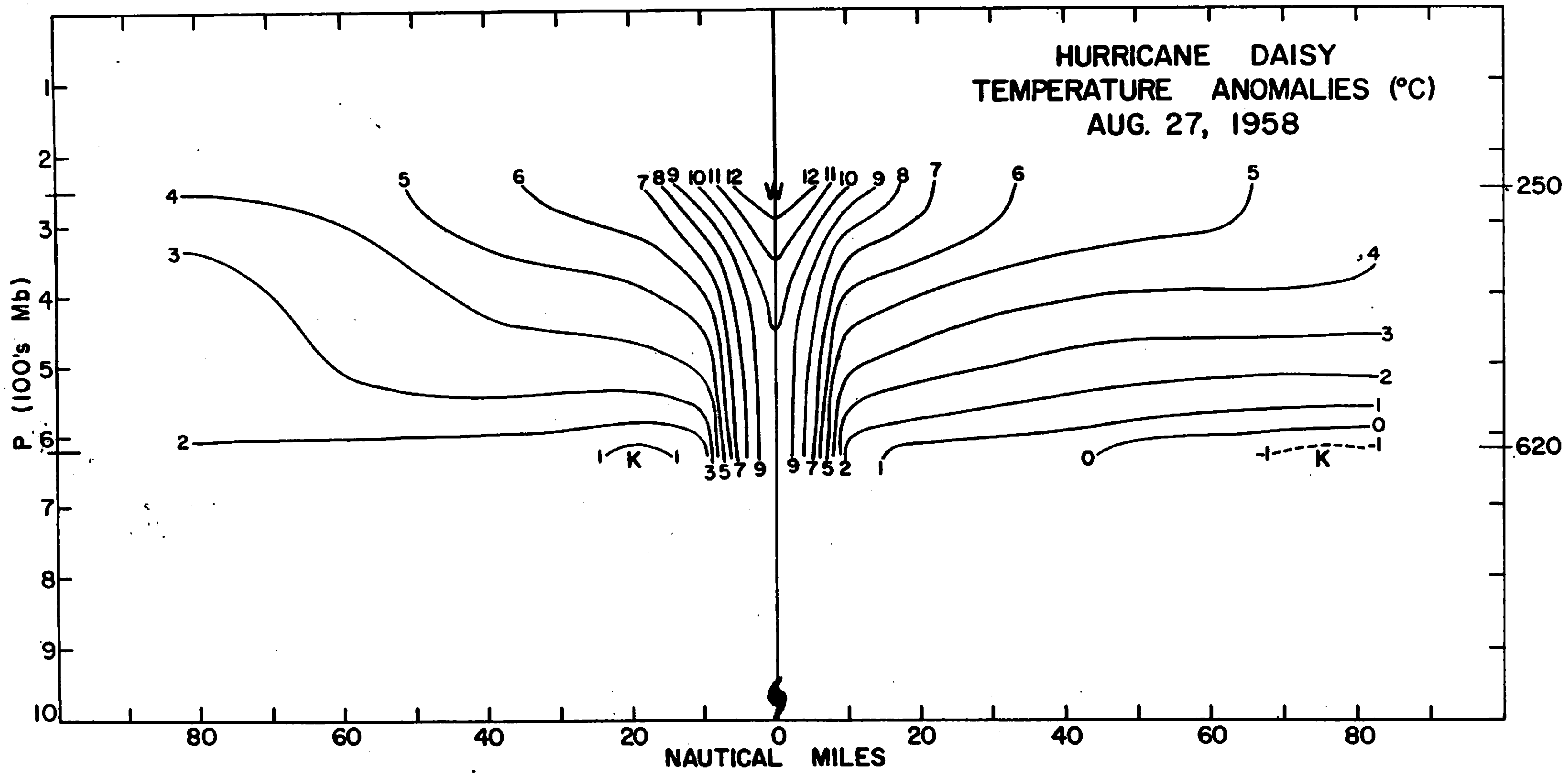

Figure 50. - Vertical cross section of temperature anomalies, August 27, 1958.

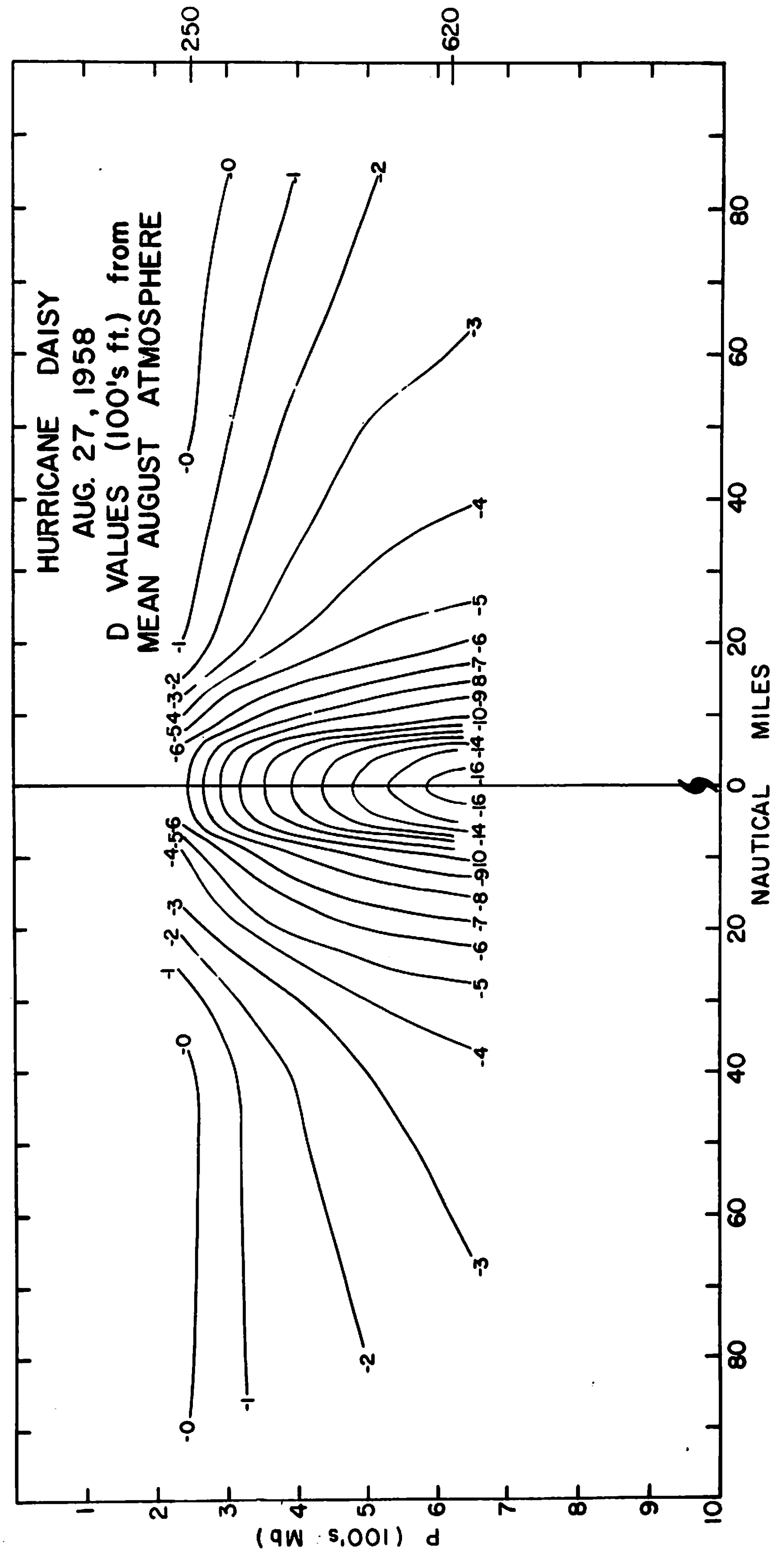

Figure 51. - Vertical cross section of deviations of pressure height, August 27, 1958.

The construction of the vertical sections involves the assumption that the temperature, wind, and moisture stratification remained essentially constant throughout the period covered by the observations. This presents serious difficulties only with regard to the data for August 25, when the observations at the different levels covered a period of about 14 hours during which the central pressure dropped about 10 mb. Therefore, adjustments were made in the "D" values to insure that they were hydrostatically consistent with the temperature and humidity. It was felt that any time changes that may have taken place during the period of study on August 25 were not significant enough to invalidate the conclusions presented in the discussion below.

a. Wind Field.

The most significant feature of the wind field was the degree of concentration of the strong winds near the 10-mi. radius at all levels. This was most striking on August 27 (fig.49). In addition, it seems there was little change in the intensity of the maximum winds between the surface and the middle levels on August 25 (fig.46); and the same was probably true also on August 27. Above 600 mb. there was a more rapid decrease of wind speed with height. It is quite evident that if the tangential speed of the cyclonic vortex in figure 49 approached zero in the vicinity of the 100-mb. level, then there must have been a very marked vertical shear above the 250-mb. level. The vertical sections also illustrate the decrease in the radial extent of the cyclonic circulation with height.

Figure 52 shows the change in wind speed between August 25 and August 27 and brings out clearly that the intensification of Daisy was limited essentially to the zone inside the 20-mi. radius - the eye core. The increments in wind speed were concentrated at the 10-mi. radius - the eye-wall - and were about 20-30 kt. larger in the right side. This is clear evidence of increase in asymmetries in the wind field with deepening. The time-change in wind speed decreased rapidly outward, so that outside the 60-mi. radius there was no appreciable increase in the strength of the winds, although there had been a deepening of close to 50 mb. in the central pressure.

b. Temperature Field.

The temperature field (figs. 47 and 50) showed positive anomalies that increased inward and upward. On August 25 (fig. 47) the horizontal gradients were larger inside the 20-mi. radius. On August 27 (fig. 50) there was a remarkable concentration inside the 10-mile radius. Both figures 47 and 50 show a tendency for the warm air in the eye to spread outward at upper levels. Maximum anomalies of over 7°C. on August 25 and of over 12°C. on August 27 were recorded near the 250-mb. level. Since the anomalies probably approached zero near the 150-mb. level on August 25 and near 100 mb. on August 27 (see fig. 55), they must have decreased rapidly above the 250-mb. level. As suggested by figure 55 it is very likely that the positive anomalies indicated at the 250-mb. level were close to being the largest present.

One very interesting feature in figure 47 was the negative anomaly observed in the surface layers throughout the rain area. Even on August 27 (fig. 50) temperatures colder than normal were actually measured at the 620-mb. level. A similar effect, although not as pronounced and extensive as shown above, was also observed in hurricane Cleo. Temperature soundings taken on August 25 at land stations well outside the hurricane circulation (High Rock, Grand Bahama; and Cocoa, Fla.) were inspected and showed temperatures higher than normal throughout the lower troposphere. Therefore, the cold anomalies observed in figures 47 and 50 appear to be the result of the particular conditions created by the hurricane circulation itself. Figure 47 indicates that the cooling was more pronounced and extensive in the right side of the circulation, where the amount of convective activity and precipitation was also larger. One possible explanation for this coolness could be the evaporation of falling rain (Bergeron [1]).

The changes in temperature with time from August 25 to 27 are illustrated in figure 53, and show first of all, that the warming associated with the process of intensification was largest in the eye. Warming of over 6°C. occurred in the middle troposphere in the center of the eye; the change in temperature decreased rapidly outward. Outside of the eye core at the 620-mb. level, the warming was only of the order of 0°-2°C. and some evidence of cooling can be observed beyond the 50-mi. radius on the right. In interpreting the temperature changes in the upper troposphere, one should bear in mind that actual data were available only near the 600- and 250-mb. levels on both days (For the right side of the section for August 27 there was an additional radial pass near the 450-mb. level.) and that the values indicated in the cross sections are based on approximated soundings. However, it is felt that the field of changes in figure 53 gives a fairly reliable representation of the distribution of warming associated with the deepening of the hurricane.

There are two features of interest in the field of changes outside the eye in figure 53; one is the tendency for less warming just outside the eye wall, the other is the tendency for more pronounced warming outside the 20-mi. radius in the upper levels. The decrease in warming just outside the eye was associated with the pronounced pools of cold air observed in the profiles for August 27. Some of these temperatures near the 20-mi. radius, when plotted on adiabatic charts, gave rise to what appeared to be unrealistic vertical profiles of temperature. As discussed previously there is a suspicion of possible instrumental effects. On the other hand a tendency for colder temperatures to be associated with increased convection and precipitation, completely aside from possible instrumental effects, was detected in the data (see Sections 4 and 7). Therefore, the relative cooling, or less warming, outside the eye-wall may be realistic and due to the increased evaporation resulting from the very intense precipitation.

The warming over the rain area in the upper levels also appears to be realistic, and it is possible to advance an explanation for it. First of all, the configuration of the isolines in figure 53 suggests thermal energy propagation from the eye-wall outward at high levels, which would reasonably follow from the increase in mass circulation (inward at low levels and outward at high levels) in the vertical plane (see Riehl and Malkus [22]). Also from the point of view of the "hot tower" currents - warm isolated ascent in the center of convective cells which have been envisioned (Riehl and Malkus [21]; Malkus et al. [15] Riehl and Malkus [22]), as being responsible for most of the heat transport in the vertical - the increase in convective activity observed from August 25 to August 27 would imply more "hot" currents reaching the upper troposphere, and therefore a relative warming of the upper levels, with intensification.

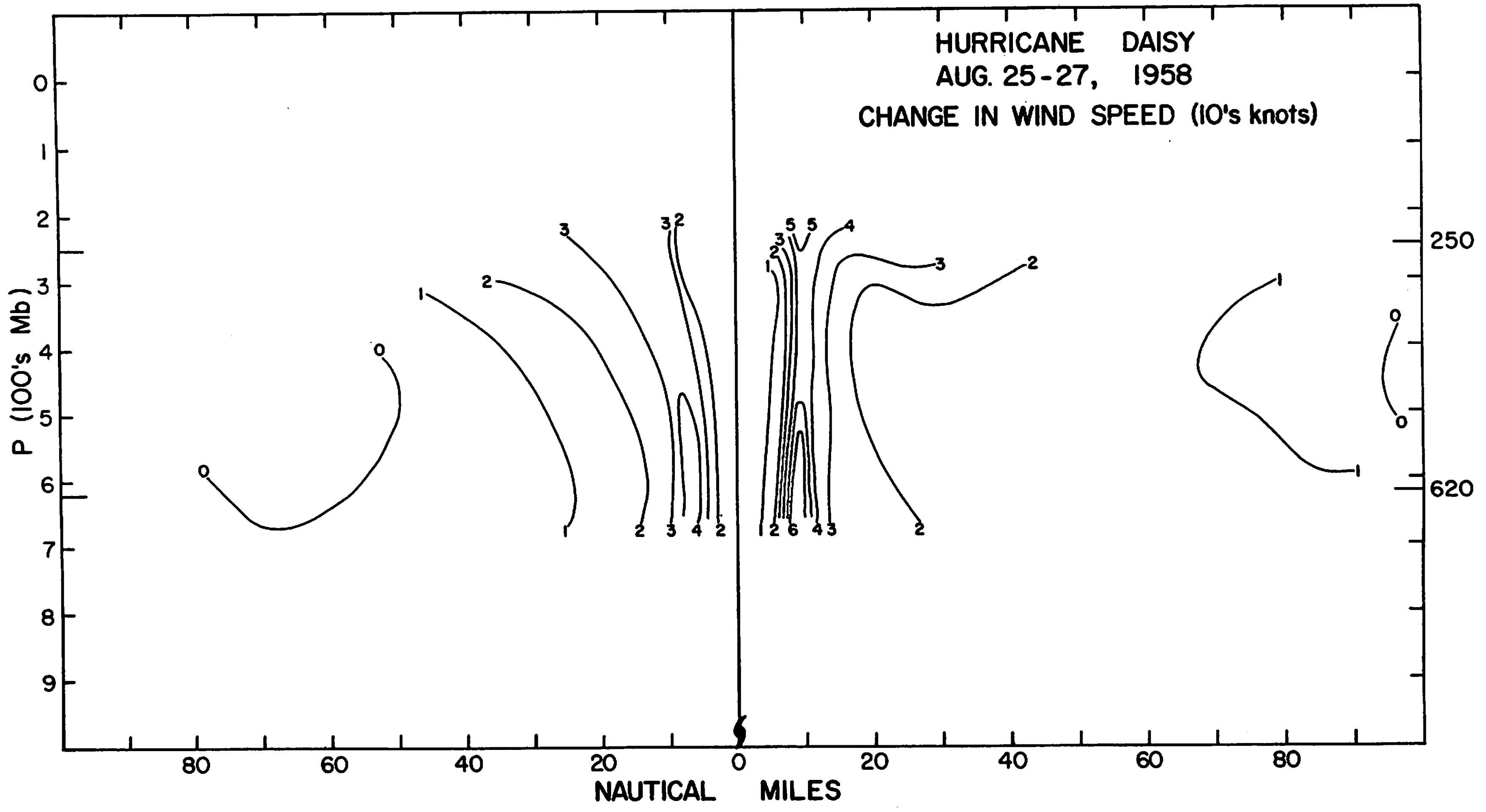

Figure 52. - Changes in wind speed between August 25 and August 27, 1958 in a cross section perpendicular to the direction of motion of hurricane Daisy, obtained by graphical subtraction of figures 49 and 46.

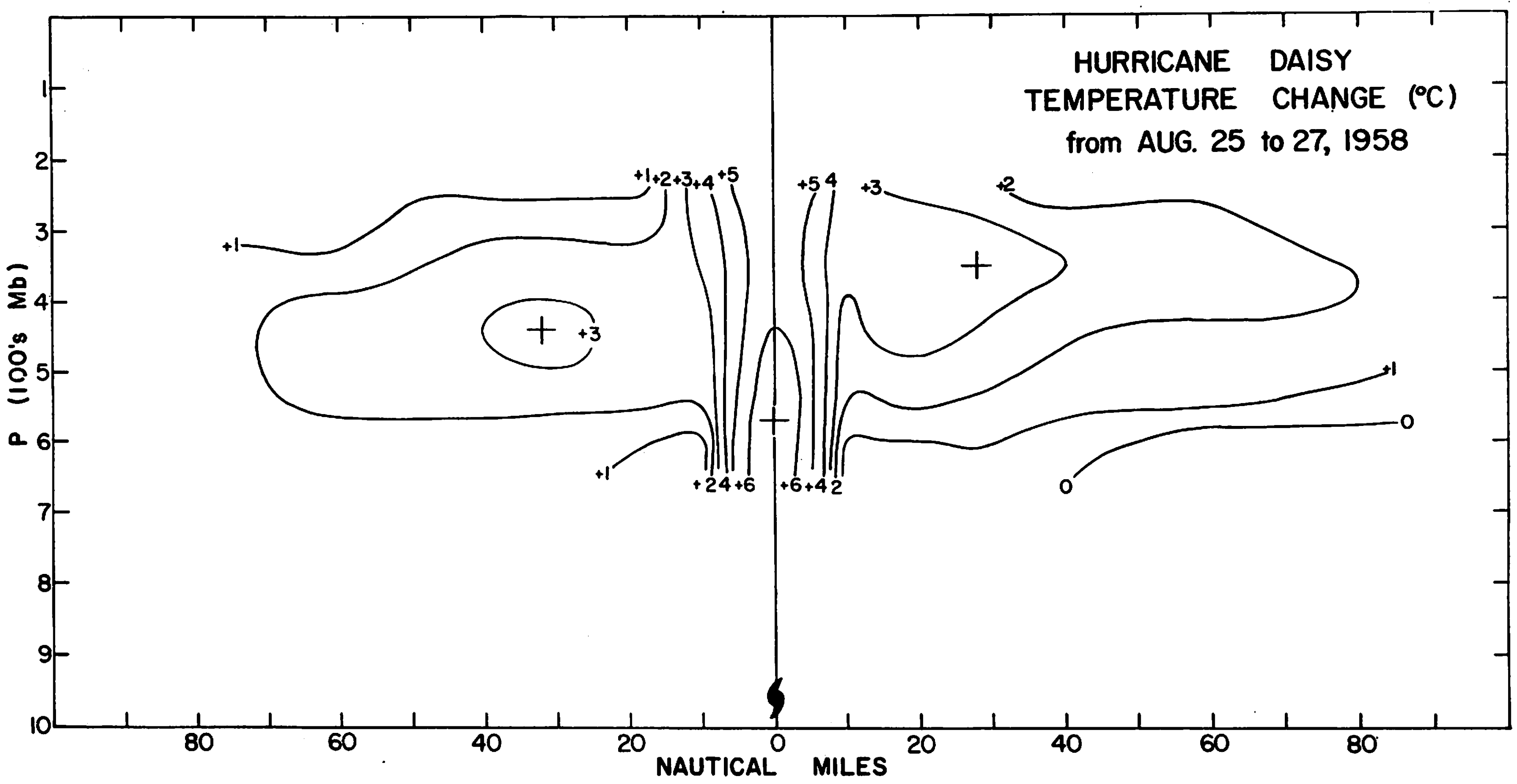

Figure 53. - Changes in temperature between August 25 and August 27, 1958 in a cross section perpendicular to the direction of motion of hurricane Daisy, obtained by graphical subtraction of figures 50 and 47.

Figure 53 suggests that little increase in temperature took place outside the 20-mi. radius in the layers below 600 mb.; in fact, cooling is strongly implied in the right side of the storm. The extension of the above arguments to the conditions at low levels would also justify this observation. The "hot tower" currents presumably rise from the cloud-base level with very little mixing with the environment in the lower troposphere. Therefore, an increase in the amount of convection associated with intensification would not lead to much warming at low levels, since the convective currents would be rising almost moist-adiabatically starting from mean surface conditions - which in the case of Daisy did not change much from August 25 to 27. On the other hand the general increase in falling precipitation would enhance the evaporational cooling. At the same time the increase in the vertical mass circulation would bring more air with near-normal properties from the outside. Therefore, there are reasons to expect that deepening would be accompanied by little or not increase in temperature in the rain area of the lower troposphere.

There is only one disturbing factor in the distribution shown in figure 53, namely, that the center of warming aloft in the rain area appears near the 400-mb. level, which seems to be too low a level for this effect to be noticed, on the basis of the above arguments. There is nothing much that can be added to this, since the analysis procedures involve a great many approximations; it would be entirely possible, with the data at hand, to move the center of warming to a higher elevation if one were determined to do so. Since this result followed naturally from the analyses performed and was completely unanticipated and unsought, it is the writer's impression that the existence of the warming effect in that region of the hurricane is realistic, but it is not possible in this case to attach particular significance to the fact that it appears to be centered at a specific elevation, lower than it should be expected. This is an item of interest to watch for in further analysis of data inside the hurricane area.

Figure 54 illustrates time changes in the temperature soundings inside the eye as obtained from NHRP and dropsonde data. The soundings shown for August 25, as well as the one at upper levels for August 27, were constructed on the bases of the maximum observations at each level measured by the NHRP aircraft. The NHRP observations at middle levels on August 27 showed quite good agreement with the dropsonde soundings obtained by the U. S. Navy on that day. These data indicate clearly warming at all levels above 900 mb. with intensification and cooling with dissipation. Smaller time changes and smaller deviations from normal took place in the vicinity of the surface. This is evidence of the more stable control of air temperatures in the surface layer by the sea surface conditions, as has been discussed in the hurricane literature (Riehl [18]).

c. Pressure field.

The vertical cross sections of "D" values, as well as the time changes from August 25 to 27, are presented in figures 48, 51, and 55. The analyses were based on anomalies from the mean August atmosphere (the "D" value data that appear in the other profiles are deviations from the U. S. Standard Atmosphere). The "D" value data presented in the figures were based on computations made from the temperature soundings starting at the lowest level of observed data, rather than from the observed data at each level. This was done to insure hydrostatic balance between the "D" values and the temperature data. The distribution of height anomalies showed negative magnitudes decreasing upward and outward, which is consistent with the warm-core character of tropical cyclones. The isopleths in the eye on August 27 (fig. 51) have a sort of "hat" structure, which was observed also in hurricane Cleo, and is the result of the concentrated temperature gradient in the periphery of the eye.

The cross section for August 25 (fig. 48) showed anomalies ranging from close to 500 ft. in the center at the surface to zero near the 250-mb. level. The horizontal gradients were concentrated inside the 20-mi. radius; they decreased only slightly up to the 600-mb. level, more rapidly above. If a pressure-height relationship of about 30 ft. per mb. is assumed at the surface, the central pressure on August 25 must have been about 16-17 mb. lower than normal. The normal surface pressure for August is 1015 mb. (Jordan [7]); therefore the minimum central pressure was on August 25 close to 998 mb.

The chart for August 27 showed a more intense low pressure vortex, with horizontal gradients also concentrated inside the 20-mi. radius. The minimum anomaly at the 620-mb. level was below -1,600 ft. As indicated previously the surface minimum pressure on that day was around 950 mb., 65 mb. below normal, which would call for a "D" value at the surface of around -1950 ft.

The time changes in "D" value from August 25 to August 27 (fig. 55) showed a pattern of isopleths similar to the individual cross sections; that is, maximum changes at low levels in the center of the eye with magnitudes decreasing outward and upward. The depression of the isobaric surfaces associated with intensification was more pronounced in the eye core; for example, the height depression near the 600-mb. level was over 1,200 ft.; at the 20-mi. radius this value had been reduced by about 70 percent.

It may be of interest to examine the distribution of the pressure fall with elevation. The time changes can be studied in terms of the height depression of isobaric surfaces or in terms of pressure change at various elevations. One gets a different view of the contribution of different tropospheric layers depending on the units used (table 1). The drop in the surface pressure between the two days was 48 mb., which corresponds to a height change of

Table 1. - Vertical distribution of the pressure fall during the intensification of Daisy, August 25-27, 1958.

Elevation (mb.)	Depression of ht. of pressure level (ft.)	Percentage of surface value	Pressure fall (mb.)	Percentage of surface value
250	700	48	8	17
300	790	54	10	21
400	950	65	15	31
500	1100	76	20	42
600	1250	86	28	58
sfc	1450	100	48	100

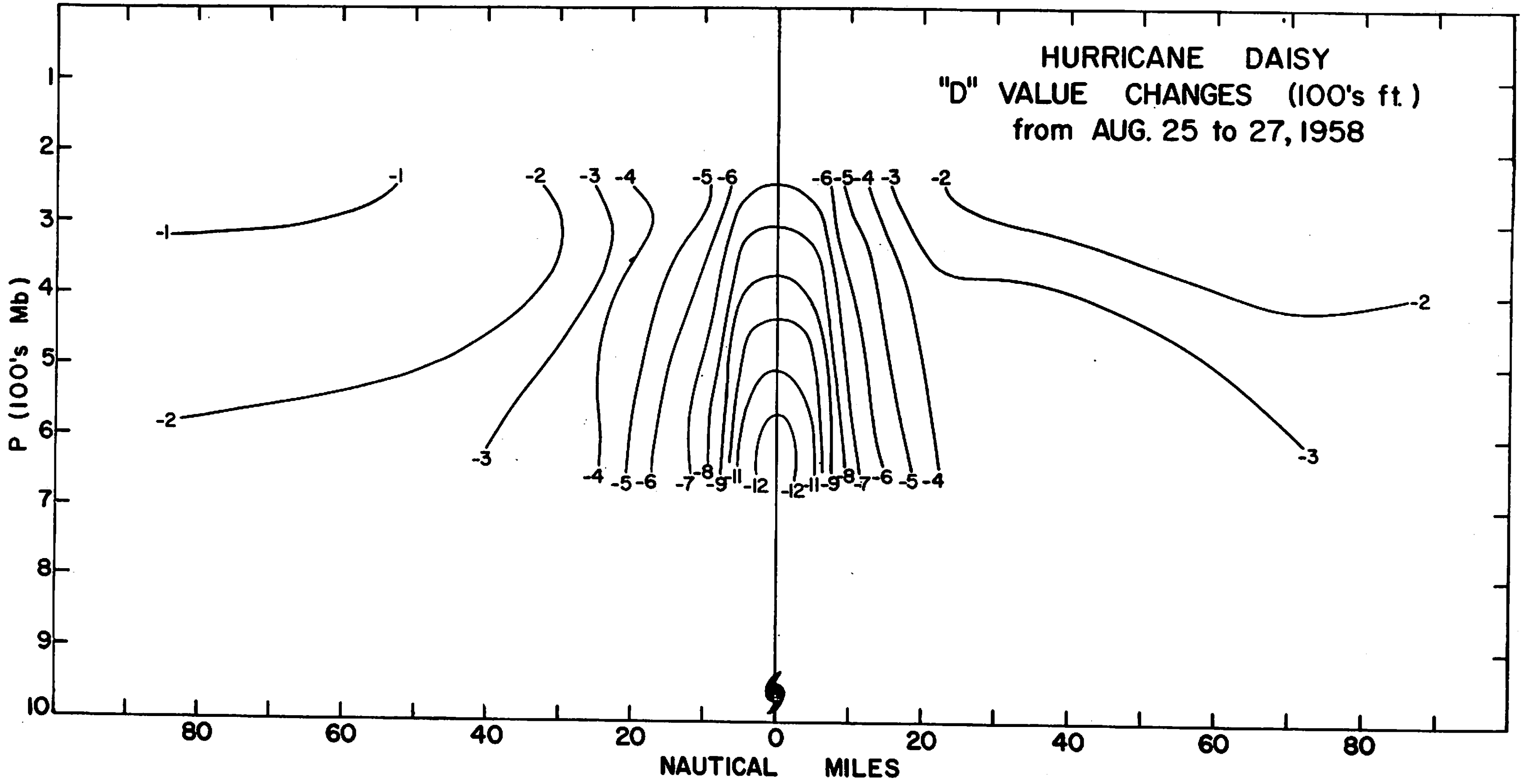

Figure 54. - Temperature soundings in the eye of hurricane Daisy, August 25 to August 29, 1958. The sounding for August 25 (dashed line) was reconstructed from the maximum temperatures observed by the NHRP aircraft; the available observations are shown by dots. The soundings for August 26 and 29 were dropsondes made by Air Force reconnaissance aircraft; the lower section of the sounding for August 27 (solid) is a dropsonde made by a Navy aircraft at 1945 GMT; the upper section (dashed) was reconstructed from the maximum temperatures observed by the NHRP aircraft, actual observations shown by dots. No observation shown for August 28.

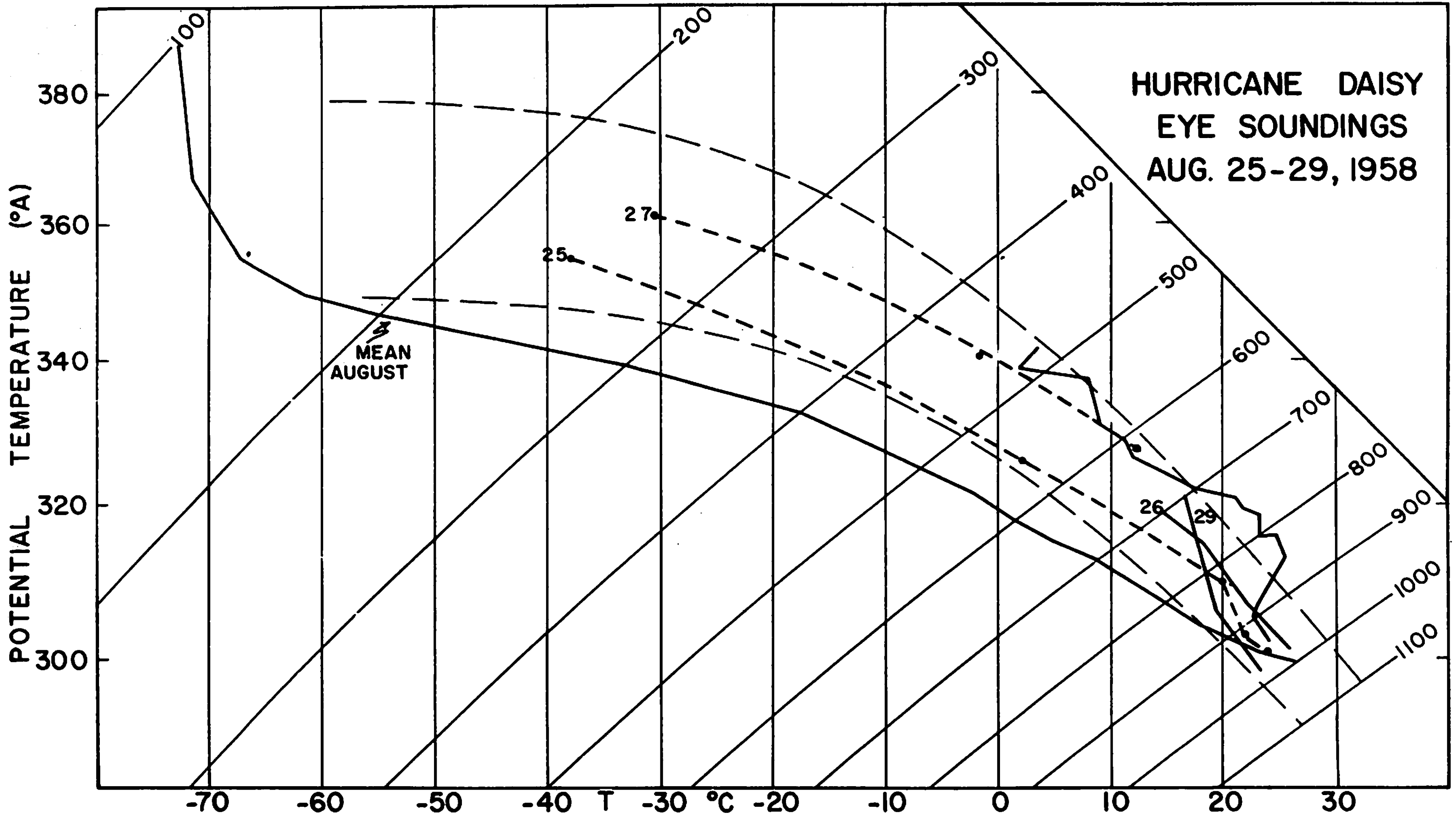

Figure 55. - Changes in the height of isobaric levels between August 25 and August 27, 1958 in a cross section perpendicular to the direction of motion of hurricane Daisy, obtained by subtraction of figures 51 and 48.

about 1,450 ft. This height change was reduced to 86 percent at the 600-mb. level, to 76 percent at the 500-mb. level, and to 54 percent at the 300-mb. surface. Thus, the depression at higher elevations was a rather large proportion of that at the surface (Malkus [14]). However, if these height changes are reduced to pressure units with the appropriate millibar-height relation for each elevation, the pressure reduction near the 600-mb. level becomes 28 mb. or 58 percent of the surface pressure fall. At the 500-mb. level the pressure change is about 42 percent, and at the 300-mb. level 17 percent of the surface value. This indicates a more equitable contribution to the surface pressure drop by the different atmospheric layers. The difference between the two sets of values is naturally due to the density stratification with height. These results were verified using additional eye data obtained with dropsondes by the military reconnaissance aircraft and using fixed heights in kilometers for the vertical coordinate. It was found that about 50 percent of the net pressure drop was contributed in the lowest 4-1/2 km. Since the pressure units are more directly related to mass variation in the vertical column, one must conclude that air motions and mass changes in the lower troposphere make as much contribution to the pressure fall at the surface as those in the upper troposphere. This is not unexpected in view of the significant warming with intesification that was observed in the middle and low levels.

The above analysis gives an indication of the distribution of mass changes with height once hydrostatic balance has been established. It would not be proper on the basis of the above results to make any conclusions about the elevations at which the causal factor in producing the pressure reduction was initially located. It might still be possible that the leading mechanism that triggered the reduction in surface pressure emanated from the upper troposphere.

d. Changes in moisture content.

Vertical cross sections similar to those discussed above could not be prepared for moisture content because of the limitations of the data for August 27. As indicated in the preceding discussions, the humidity data indicated a general increase in values toward the center of the hurricane. The values of mixing ratio on August 25 indicated positive anomalies with respect to the mean August atmosphere (of the order of 0-4 gm. kg.$^{-1}$) over most of rain area, with the anomalies increasing upward and inward. At the 560-mb. level on August 25 the positive anomalies in the eye were about 3-4 gm.kg.$^{-1}$

The time changes of specific humidity (or mixing ratio) recorded in the eye of Daisy during the period August 25 to 29 are illustrated in figure 56. The curve for August 25 has been reconstructed from the maximum values recorded by the NHRP aircraft at each level; the data for the other days correspond to the dropsonde observations shown in figure 55. The maximum values recorded by the NHRP planes on August 27 have also been indicated in figure 56. The data show a definite increase in moisture content during the period of intensification from August 25 to 27, and a decrease afterward with dissipation. The changes were largest in the layer from about 900 to 700 mb., and smaller near the surface and in the upper layers. The large values of moisture content at low levels on August 27 were confirmed by a second dropsonde made about 4 hours previous to the one illustrated, but it also showed higher values in the vicinity of the surface. At the highest levels for which data were available (from 600 to 450 mb.) there seemed to be little difference in the values for August 25 and August 27.

The relative humidity magnitudes shown in figure 56 indicate quite large values in the lower layers on all days. It is difficult to draw conclusions from the relative humidity magnitudes, since they depend both on the temperature and moisture content and tended to show greater variability in space and time. As a rule the highest values of specific humidity did not occur with the warmest temperatures. To the extent that the values indicated in figure 56 are representative, we can say that in the layers below 700 mb. there was a slight tendency for values closer to saturation on the most intense day, but the relative humidity was also quite high on the other days.

An examination of all the readings of relative humidity recorded by the NHRP airplanes inside the 10-mi. radius showed that on August 25 at the 957-mb. level the range was from 81 to 100 percent; at the 915-mb. level the range was from 92 to 95 percent; at the 827-mb. level from 65 to 100 percent; and at the 557-mb. level from 69 to 100 percent. All the readings of 100 percent were close to the periphery of the eye; i.e., in the inner edge of the wall-cloud. On August 27 the range of values inside the 10-mi. radius at the 620-mb. level was 50 to 92 percent; at the same level on August 28 the range was from 37 to 86 percent. This range of values shows a tendency for near saturation with little variability in the surface layers, even on the weak day. The variability increases with altitude, and there was a tendency for drier observations on the more intense days at the upper levels.

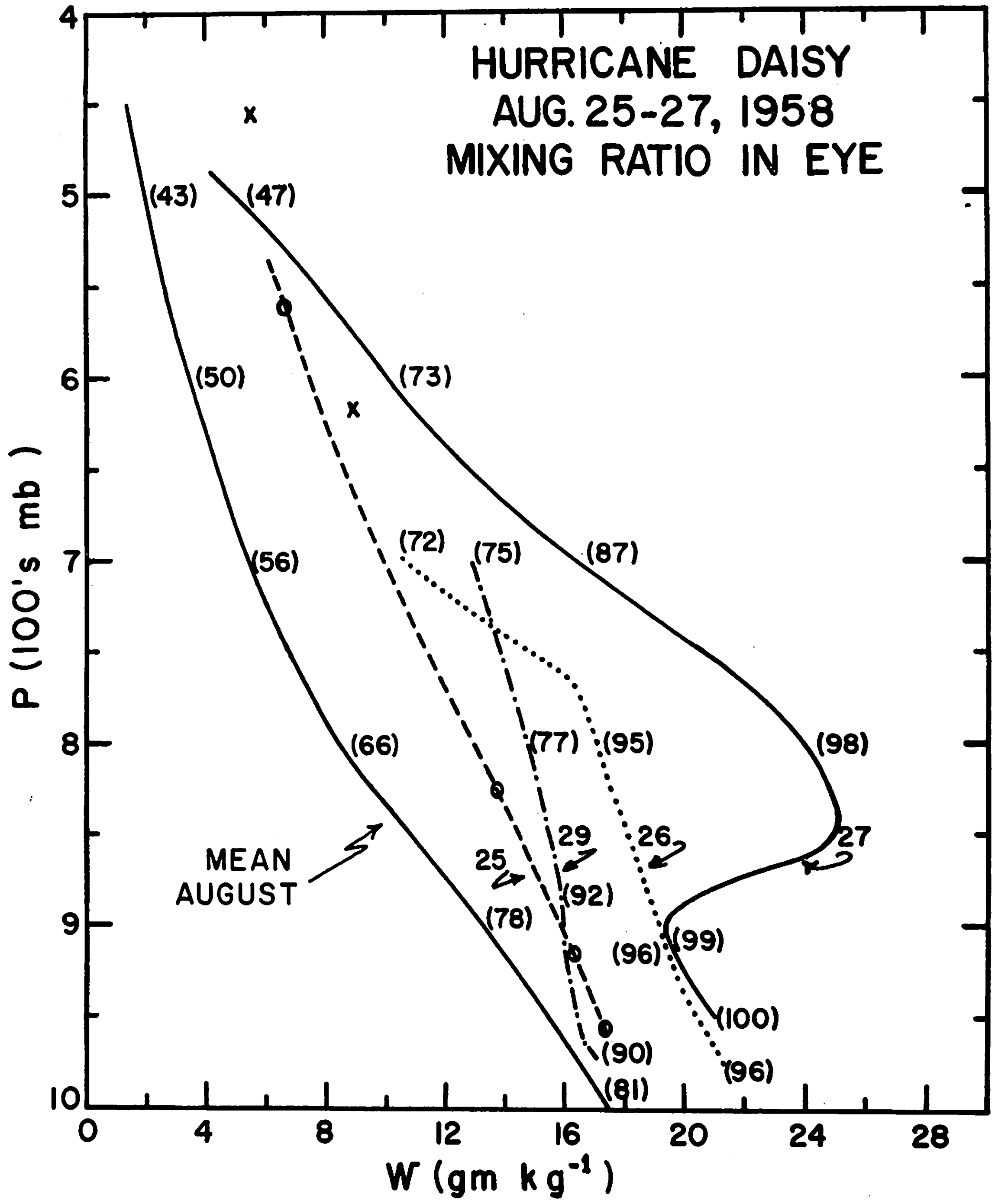

Figure 56. - Variations of mixing ratio in the eye of hurricane Daisy from August 25 to 29; data corresponds to the temperature soundings shown in figure 55. The curve for August 25 (dashed) was constructed from the maximum readings in the eye made by the NHRP aircraft, available observations shown by small circles. The two X's show the maximum readings made by the NHRP aircraft on August 27. The numerical values in parenthesis represent the relative humidity at the corresponding levels; no relative humidities shown for August 25.

9. COMPARISON OF DAISY WITH OTHER HURRICANES

One of the most significant aspects of the development of hurricane Daisy was the rapidity with which the wind, pressure, and thermal fields were transformed into a well-developed, nearly symmetrical, and compact organization. The following important features were already present at the time of the first thorough investigation on August 25, less than 24 hours after the initial formation:

a. development of a nearly circular and almost completely closed eye wall;
b. the appearance of a narrow zone of maximum winds in a position fairly close to the center of the storm;
c. a fairly large degree of symmetry;
d. the appearance of distinct radar bands in a position around the eye that appeared to change little with time.

This is an example of what may be considered as "explosive development," which may be contrasted to cases of slow and gradual intensification in which changes such as were observed between August 24 and August 25 take several days to occur.

The location of the maximum winds in a position so close to the center and in such a concentrated fashion as illustrated in figures 31 and 33 was one characteristic of Daisy that is not commonly observed. One recent similiar case in which reliable measurements revealed winds of over 100 kt. located near the 10-mi. radius was that of hurricane Ione of 1955 (LaSeur [11], Blumen and LaSeur [2]). A more common type of structure and a different type of intensification process was evidenced by hurricane Helene of 1958 (fig. 57), which was also thoroughly investigated by the NHRP aircraft. During the period September 24 to 26, 1958, hurricane Helene was moving in a northwesterly direction at about 6-9 kt. in the area to the northeast of the Bahamas Islands. A perturbation with near tropical storm intensity had existed since September 21. On September 24 the central pressure was close to 1,000 mb.; the wind profile on the right side of the circulation (fig. 57) showed winds of around 35 kt. at the 15-mi. radius increasing to around 50 kt. at the 50-mi. radius; on the northwest side there was a more distinct concentration at the 45-mi. radius. This type of profile can be contrasted with that of Daisy on August 25. On September 25 the central pressure of Helene was close to 987 mb. The zone of maximum winds, with values of about 78 kt., had moved inward to the 25-mi. radius. On September 26 the central pressure had dropped to around 943 mb., deeper tnan Daisy, the maximum winds had increased to around 105 kt., and the zone of maximum winds had moved inward to the 15-mi. radius. There seem to be then two different types of intensification process exemplified by hurricane Helene (fig. 57) and by hurricane Daisy (fig. 58). The structure of the final wind profile, both in regard to location of and to shear outside the zone of maximum winds, is quite different. However, there is presently no reason to believe that a wind vortex as found in Daisy could not result from the deepening process observed in Helene. Two other examples of wind profiles in typical hurricanes are illustrated in figure 59 for hurricanes Carrie of 1957 and Cleo of 1958 [12]. Both showed maximum winds of about equal intensity located at the 20-mi. radius; the central pressure was about the same as that ob-

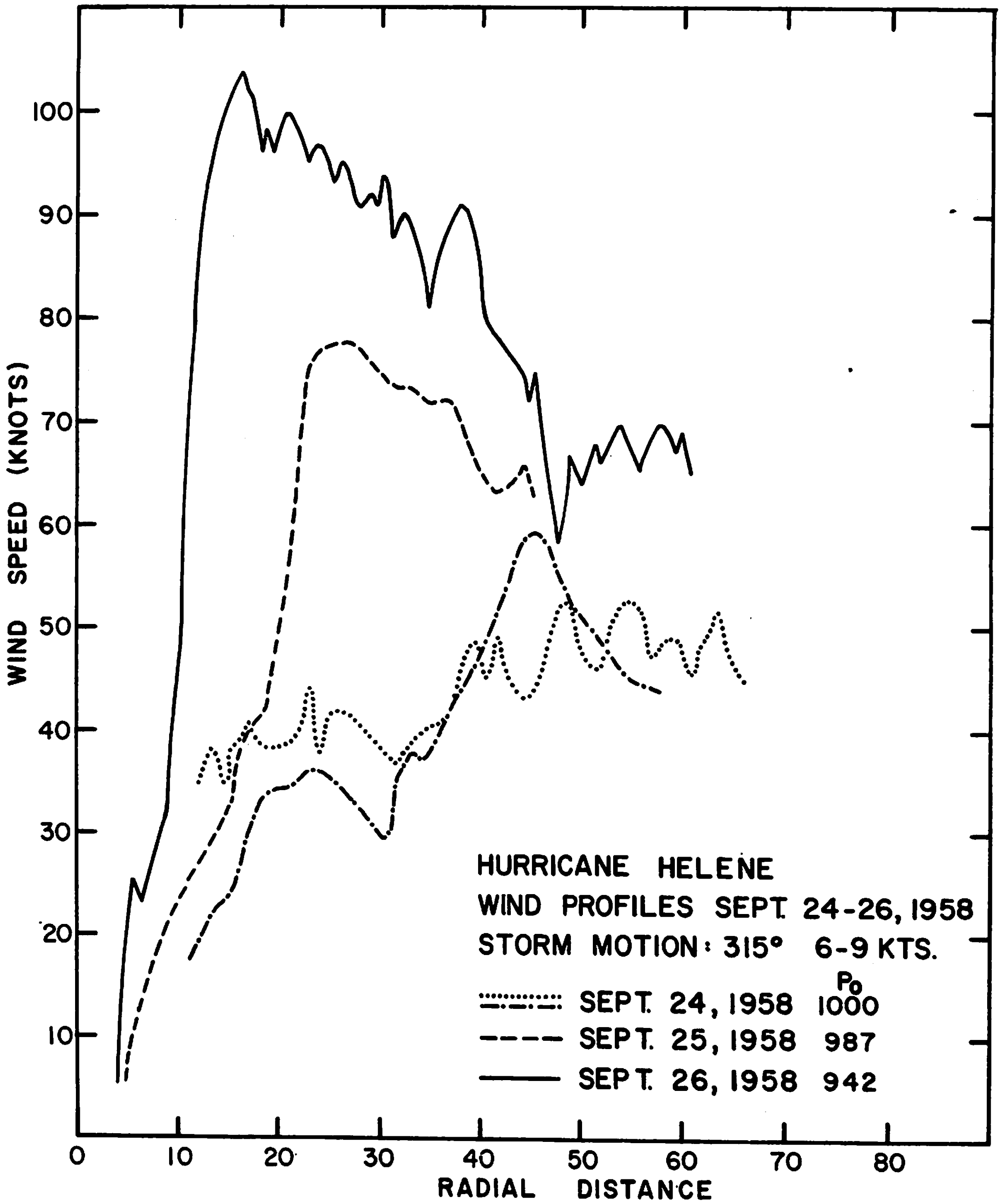

Figure 57. - Wind profiles obtained by NHRP for hurricane Helene. Data for Sept. 24 are at an altitude of 13,000 ft., 620 mb.; dotted curve was obtained in a direction about 110° to the right of the motion; the dot-dashed curve is in a direction just to the left of the motion. The profile for Sept. 25 is at an altitude of 6,400 ft., 800 mb., and in a direction about 65° to the right of the motion; the profile for September 26 is at an altitude of 15,600 ft., 557 mb., and in a direction about 90° to the right of the motion. The minimum central pressure observed on each day is shown in the column labeled P_o.

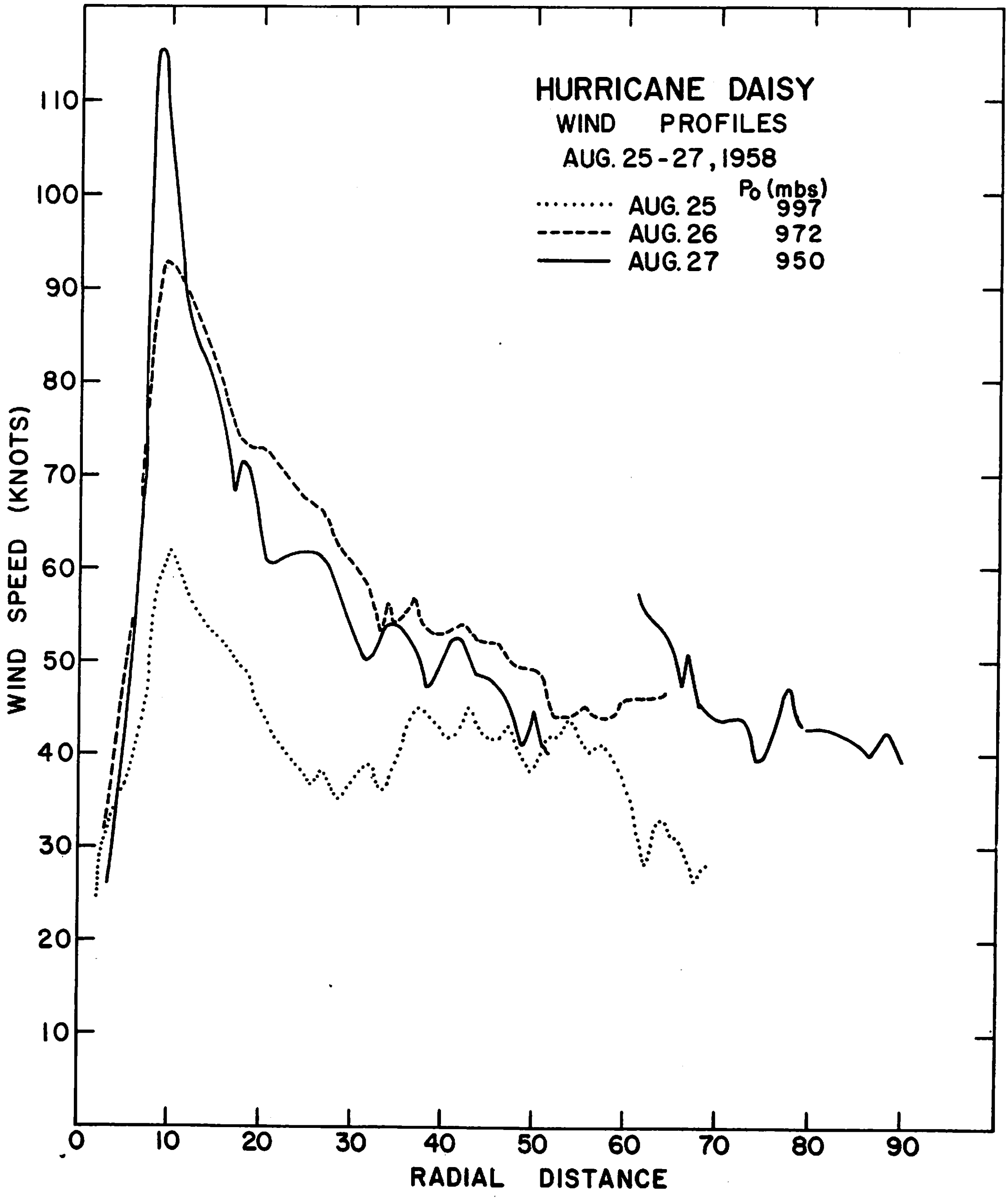

Figure 58. - Selected wind profiles for hurricane Daisy, August 25 to 27, 1958. The data for August 25 are at 5,500 ft., 827 mb.; for August 26 at 6,400 ft., 800 mb.; and for August 27 at 13,000 ft., 620 mb.

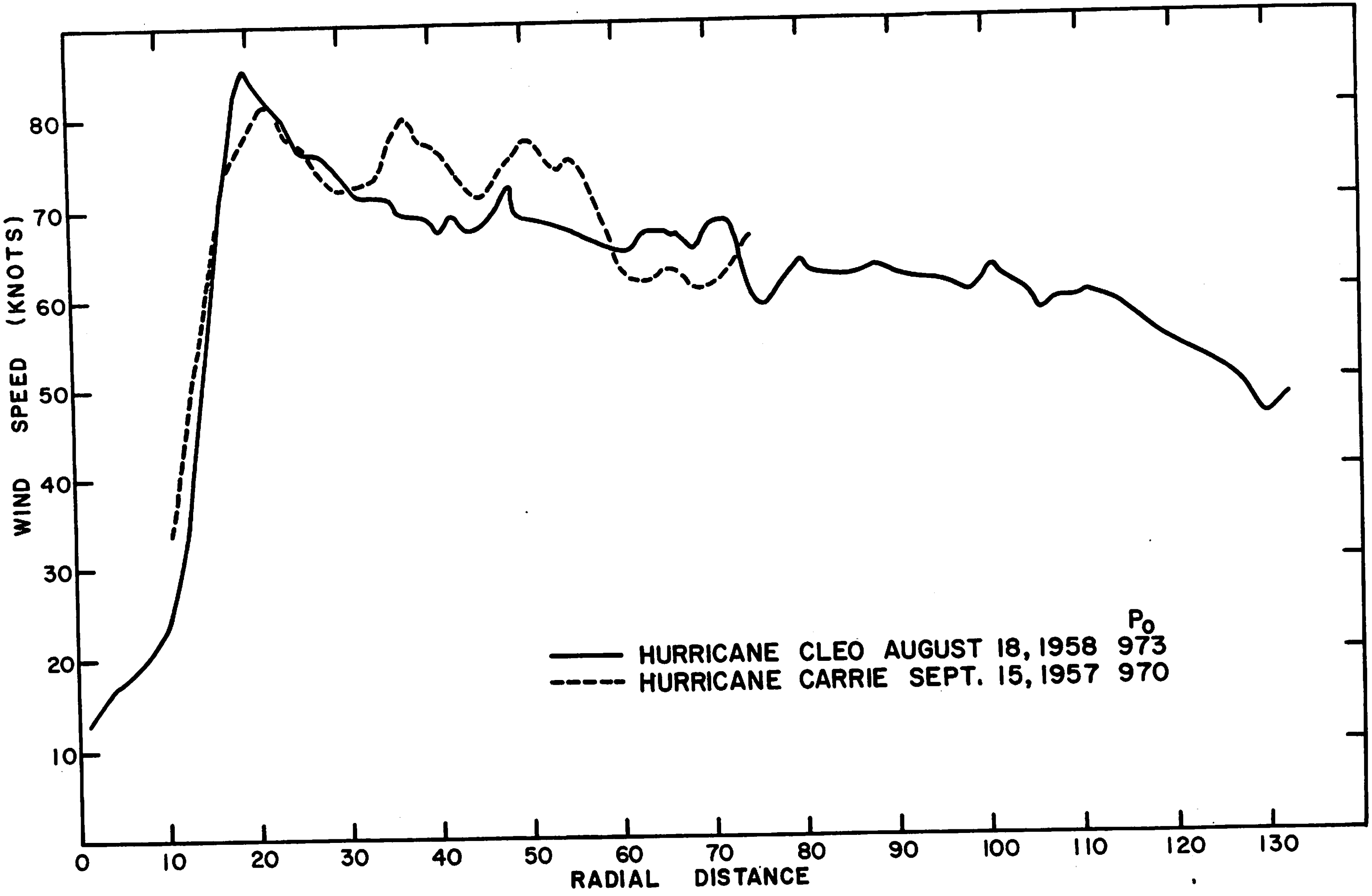

Figure 59. - Selected wind profiles for hurricane Cleo, August 18, 1958, at 800 mb., and for hurricane Carrie, September 15, 1957, at 590-mb., level.

served in Daisy on August 26, but the contrast in the wind profiles is remarkable. Hurricanes Cleo and Carrie were both mature storms past their most intense phase and resembled more the Helene structure on September 25 and 26.

The shape of the wind profiles becomes more meaningful when analyzed in terms of vorticity. The relative vorticity for the Daisy profile of August 27 and for the Helene profile of September 26 (fig. 60) was computed with the assumption that the radius of the trajectories was equal to the geometric radius from the eye center. Kinematic analysis of the field of motion in hurricane Daisy performed at NHRP showed that this assumption was quite reasonable, in the vicinity of the core. The relative vorticity profile for Daisy (fig. 60) showed a sharp drop from a value of 1×10^{-2} sec.$^{-1}$ at the 8-mi. radius (both the curvature and the shear terms were positive at that point) to -0.2×10^{-4} sec.$^{-1}$ at the 11-mi. radius, because of the extreme anticyclonic shear outside the zone of maximum winds. The Coriolis parameter at the latitude of hurricane Daisy on August 27 was around 0.7×10^{-4} sec.$^{-1}$, so that the absolute vorticity was still positive. However, if the Daisy profile were displaced outward only 2 to 3 mi. the absolute vorticity in the region just outside the maximum winds would become negative. Such a distribution would be unstable and readjustments would immediately occur. The vorticity profile in the case of Helene showed values of cyclonic vorticity of about 5×10^{-3} sec.$^{-1}$ near the 12-mi. radius, with a more gradual decrease outward on account of the smaller magnitudes of the anticyclonic shear. It is quite evident that vorticity considerations would restrict the development of concentrated narrow peaks of wind speed unless they were located close to the center of rotation.

This does not explain why or under what conditions one type of wind circulation develops in preference to the other. On the basis of the vorticity argument one is inclined to believe that wind profiles of the Daisy type would be very unlikely to occur in cases in which the wind maximum develops initially away from the center and moves inward with time. These observed differences between hurricanes Daisy and Helene raise some interesting points that warrant further investigation in our search for a better understanding of the problem of hurricane development.

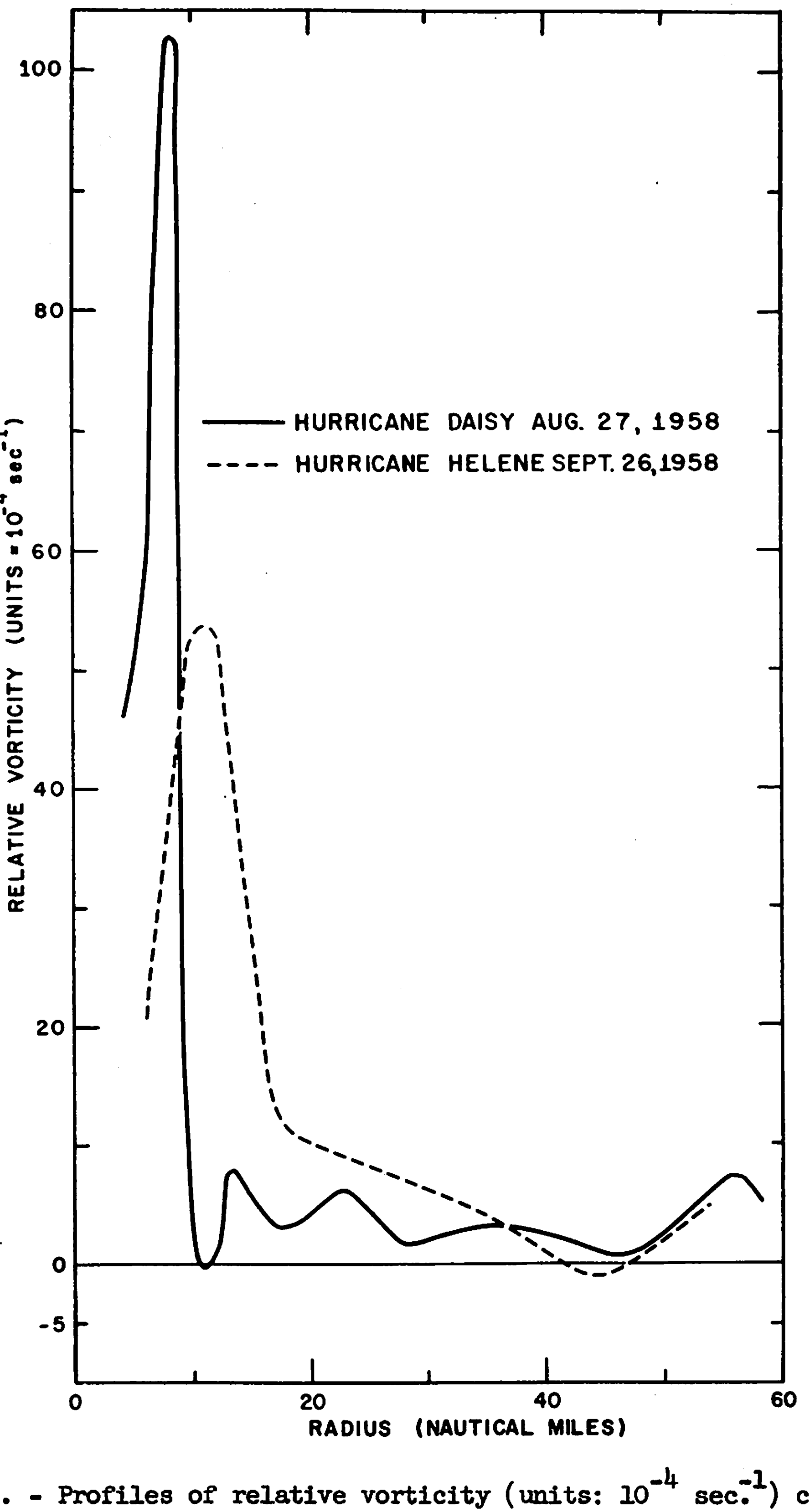

Figure 60. - Profiles of relative vorticity (units: 10^{-4} sec.$^{-1}$) computed from the wind profiles shown in figure 58, August 27, for hurricane Daisy and in figure 57, September 26, for hurricane Helene.

10. SOME REMARKS ON POSSIBLE INACCURACIES IN THE DATA

Nothing much has been said in this report with regard to possible inaccuracies or undetected errors in the data. The analysis procedure used in compositing data around the eye and the synchronization of the various arrays of data are subject to some approximations. Care has been taken to see that none of the conclusions developed here is critically affected by possible inaccuracies of this nature. There are two major areas treated in this report which may be concerned with instrumental inaccuracies that have not been possible to evaluate, and on which some additional comments are added below. These are the observations of cold temperatures in the rain area outside the eye at middle levels, and the reduction in wind speed across precipitation bands. From an analysis of the process by which the air temperature is measured by the vortex thermometer it is quite possible to visualize that the entrance of water droplets into the vortex chamber may lead to temperature readings colder than the reality. There are also lag effects which are extremely difficult to analyze. Numerous instances were noted in the data profiles in which the temperature fluctuated significantly as the cloudiness varied along the path of the aircraft. However, most of the fluctuations can be satisfactorily associated with the air motions of convective scale. Analysis of the readings made by the vortex thermometer in comparison with those made by other temperature sensors aboard the aircraft and by dropsondes leads to the conclusion that the data are essentially correct. On the other hand it is not possible to rule out completely the existence of instrumental errors, so that one should be careful in the treatment of temperature values in regions of strong precipitation.

In regard to the cool-air ring surrounding the eye, it must be recognized that it was observed, in greater or lesser degree, at low and middle levels and under various conditions of precipitation so that it does not seem possible to disregard it entirely on the basis of "too cold" temperatures due to instrumental errors. As mentioned previously, there are plausible reasons to believe that this is a real effect. Here we can mention the cooling effect of precipitation, as suggested by Bergeron [1]. One may also consider the fact that air moving inward at levels above the surface (the so-called "ventilation" effect, (Simpson and Riehl[24])) would be subjected to adiabatic cooling due to the reduction in pressure. In the case of air near the surface it is claimed that the heat flux from the ocean counteracts the adiabatic cooling, but it has not been established how high above the surface this counteracting effect would extend. We can also mention that some of the observed temperatures and lapse rates may be considered "unrealistic," only under the assumption that the lapse rates in the eye-wall should be essentially moist-adiabatic. It has been emphasized lately that moist ascent in convective cells seems to occur only in isolated columns of small and localized extent. Hence, one may speculate as to the probabilities that data obtained by different aircraft at different altitudes and times will yield the representative sampling of temperatures necessary to depict a "moist-adiabatic" ascent.

Much has been written also about the ventilating effect of air from the outside mixing laterally with the ascending columns. There is increasing evidence pointing to significant lateral mixing across the eye-wall between the air in the clear section of the eye and in the rain area (Malkus [13], Miller

[16], Rosenthal [23]), so that, except in the so-called "undiluted" ascending columns, the lapse rate should differ from the moist adiabatic. It is entirely possible that certain temperatures may be unrepresentative of the effect one is trying to depict, and not necessarily in error.

In connection with the wind measurements there is also a factor concerning motions of the underlying surface which it has not been possible to define rigorously. The measurement of winds by the Doppler mechanism is based on a radio signal that goes from the aircraft to the surface and is bounced back to a receiver in the moving aircraft. Analysis of the Doppler effect, displayed by the return signal, permits the determination of the drift angle and of the motion of the aircraft with respect to the surface; i. e., the ground speed. With knowledge of the air speed as given by the aircraft instruments, the solution of the wind triangle yields the wind vector. This procedure assumes zero motion of the reflecting water surface, which normally is a reasonable assumption. In the hurricane area it can be shown that motions of the water due to the wind drift are generally not serious. However, there is the possibility of a signal return caused by the spray or water sheet that is produced by the shearing of the top of the waves by intense winds and which may move at significant speeds. The radio signal may also bounce back from the precipitation shield below the level of the aircraft and lead to spurious effects in the winds. Either of these contingencies results in sudden and drastic reductions in the wind speeds computed similar to those caused by instrument malfunction. There were instances in the flights at middle levels in which the winds seemingly failed completely. In such cases the data were eliminated. However, there may have been instances more difficult to detect, where the winds did not appear to be unreasonable and only momentary lapses occurred. It was an observed fact that the fluctuations in wind speed were larger at the middle levels, but it is also true that if they are caused by vertical air motions of convective scale than they should be larger at middle levels. In conclusion we may state that although the existence of inaccuracies in the wind speed can not be completely ruled out, it is believed that the observations are essentially correct and that some of the minor fluctuations associated with precipitation bands are quite realistic. These features will be treated further in the analysis of other hurricanes. There is every expectation that additional observations will clarify some of these unknowns.

11. SUMMARY AND CONCLUSIONS

In the preceding pages a description of the structure and development of hurricane Daisy, as given by the research data gathered by NHRP, has been presented. All of the radial profiles and selected horizontal charts have been purposely illustrated in order that they be readily available for future reference. An attempt has also been made to discuss, perhaps in more detail than is generally warranted, the characteristics, interrelationships, and general properties of the observations in the hurricane area. In many respects the Daisy data are typical of the hurricane data that have been gathered by NHRP. Of course, the quantity of data gathered, number of flights, and levels flown differ in each hurricane.

The radial profiles and horizontal charts illustrate a large number of small-scale fluctuations, which could be associated with the cloud formations and precipitation bands crossed by the aircraft at flight level. As far as it was possible to determine here, there was no general uniformity in the relationships between wind and temperature variations and convective scale elements. This is not unexpected in view of the large time variations involved in the normal life cycle of individual cells. For instance, both temperature rises and falls were observed inside clouds. Similarly, some occurrences of wind decrease across precipitation bands were recorded, but there were also various cases in which no appreciable change was observed in fairly similar conditions. This may be further indication of the transitory nature of those features of the wind and thermal fields that are closely related to localized convective-scale phenomena. While a study of these variations in the meso- or convective scale is of interest and importance to an understanding of the maintenance of the hurricane system, it is also apparent that for a study of the properties of the cyclonic vortex as a whole there is need to smooth out the minor fluctuations and concentrate on the larger-scale properties. When this is done in the case of Daisy, a picture of a particular vortex structure and growth process is obtained that so far has been found to be characteristic of Daisy and not generally observed in the other hurricanes investigated by NHRP. The remark often has been made by people associated with hurricane research flying in recent years that Daisy was not a typical hurricane at all. These individual properties of hurricane Daisy, both in regard to the structure found each day and the growth process between the weak and the intense day, were discussed in some detail in Sections 8 and 9.

Hurricane Daisy attained great intensity; according to the wind-dependent classification used by Riehl [19] it falls in the category of "moderate" intensity; while on the basis of the minimum pressure criteria used by Jordan [9] Daisy was an "intense" hurricane. Yet it was relatively small in areal extent. The high energy core and low pressure vortex were largely concentrated in a small area around a small and well-defined eye formation. This distinctive eye structure was attained at the beginning of the development cycle, and the growth in intensity from there on, when viewed in a coordinate system moving with the center, was essentially characterized by the intensification in situ of the various fields - increase in wind speed in the eye wall, deepening of the pressure vortex, and warming of the thermal core. In contrast to this, there exists a different type of structure and growth process, illustrated with data from hurricane Helena, in which a rather broad and sluggish circulation with maximum winds far away from the center appears first. Gradually the vortex becomes more concentrated as the system deepens and the wind maximum moves closer to the center of rotation. The end product, at least as illustrated by hurricane Helene, is a wider eye, a less concentrated but just as intense wind speed maximum, and, apparently, a more extensive wind vortex as a whole. There seems to be no essential difference in regard to the magnitude of the maximum winds that can be attained in each case. There is, however, a large contrast in the final shape of the wind distribution with radius, which seems to be determined by absolute vorticity restrictions. It is important that these properties of the wind field be recognized, since the presence of a "Daisy" or "Helene" type of wind field may have useful practical applications in hurricane forecasting. An extensive high-kinetic-energy field of motion with a wide eye, and low anticyclonic wind shears as observed in Helene would lead to greater property damages on striking land. In this respect, it may be remembered that hurricane Helene caused considerable property damage along the Carolina coast, even though the center passed about 30 mi. from the coast.

It was amply demonstrated in this and previous reports (Malkus et al.[15]) that the distribution of clouds and convective cells in Daisy was anything but uniform. The field of precipitation as seen by radar displayed a rather significant asymmetry, with more active and more extensive precipitation bands in the right side of the circulation. There were some prominent radar bands as far as 250 mi. away from the center in the right semicircle which were definitely part of the hurricane system. In the cloud field various instances were illustrated where penetrations inward to distances very close to the eye could be made with no more than a few small cumuli present at flight level and below. On more than one occasion, even on the intense days, penetrations into the eye were made with essentially clear conditions at flight level. As shown in the study by Malkus et al. [15] the cloud films in Daisy showed a very limited number of cumulonimbus cells extending to high elevations. More recently, visual observations by obervers aboard reconnaissance aircraft have confirmed the fact that, even in the eye-wall of very deep hurricanes, there exist only certain sections, generally to the right of the motion, where the convective mass extends to the high troposphere. This is certainly a much different picture of the hurricane than the one that prevailed before the advent of aircraft investigations.

One strong impression left by the study of the Daisy data concerns the importance of the eye-system in the growth of the hurricane. This refers both to the definition of the eye-wall and to the thermal properties inside the eye. As shown throughout this report the major changes in the Daisy circulation during its life history were concentrated in and near the eye core. Inspection of the thermal eye data in the intense period on August 27 indicated the presence of a column of extremely warm air vertically above the low pressure center. This picture in combination with that observed on August 28, (when the central pressure was higher, the maximum eye temperatures at the 620-mb. level were significantly higher than at the same level on the previous day, but the center of the thermal core was displaced with respect to the radar and pressure centers) suggests that a vertical thermal stratification in which the warmest air at each layer is located more or less vertically over the low pressure center is necessary for the creation and maintenance of the low pressures. A disruption of this delicate vertical stratification may be characteristic of hurricanes in the weakening stage.

The hydrostatic computations carried out for the eye of Daisy on August 25 and August 27 indicated that the contribution of the various layers of the troposphere to the deepening process can be viewed differently depending on the way in which the pressure changes are considered. When the deepening is analyzed in terms of changes in the elevation of isobaric surfaces it is found that the depression of isobaric surfaces decreases only slightly with elevation in the lower part of the troposphere, so that the height changes above 500 mb. are a rather large percentage of those at the surface. However, on account of the density stratification, when pressure changes along fixed-height levels are considered, about 50 percent of the pressure fall at the surface is accomplished in the lower 4-1/2 km. This means that in terms of mass changes in the vertical column there was as much loss of mass in the lower as in the upper troposphere. One cannot make any definite conclusions about the contribution of specific layers of the troposphere in triggering the deepening process on the basis of the above analysis. It is quite possible that the leading mechanism producing the pressure reduction was centered in the upper troposphere.

Some comments about possible undetected inaccuracies in the data were offered in Section 10. However, these pertain to fluctuations in the scale of the convective motions inside the hurricane area. It is not believed that they affect the conclusions concerning the major properties of the hurricane vortex, which have been amply documented and have displayed many interesting features worthy of further investigation. It is hoped that publication of these Daisy data, and observation of other hurricanes which will follow in the near future, will stimulate new ideas for research in the problems of hurricane formation, structure, and maintenance.

ACKNOWLEDGMENT

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