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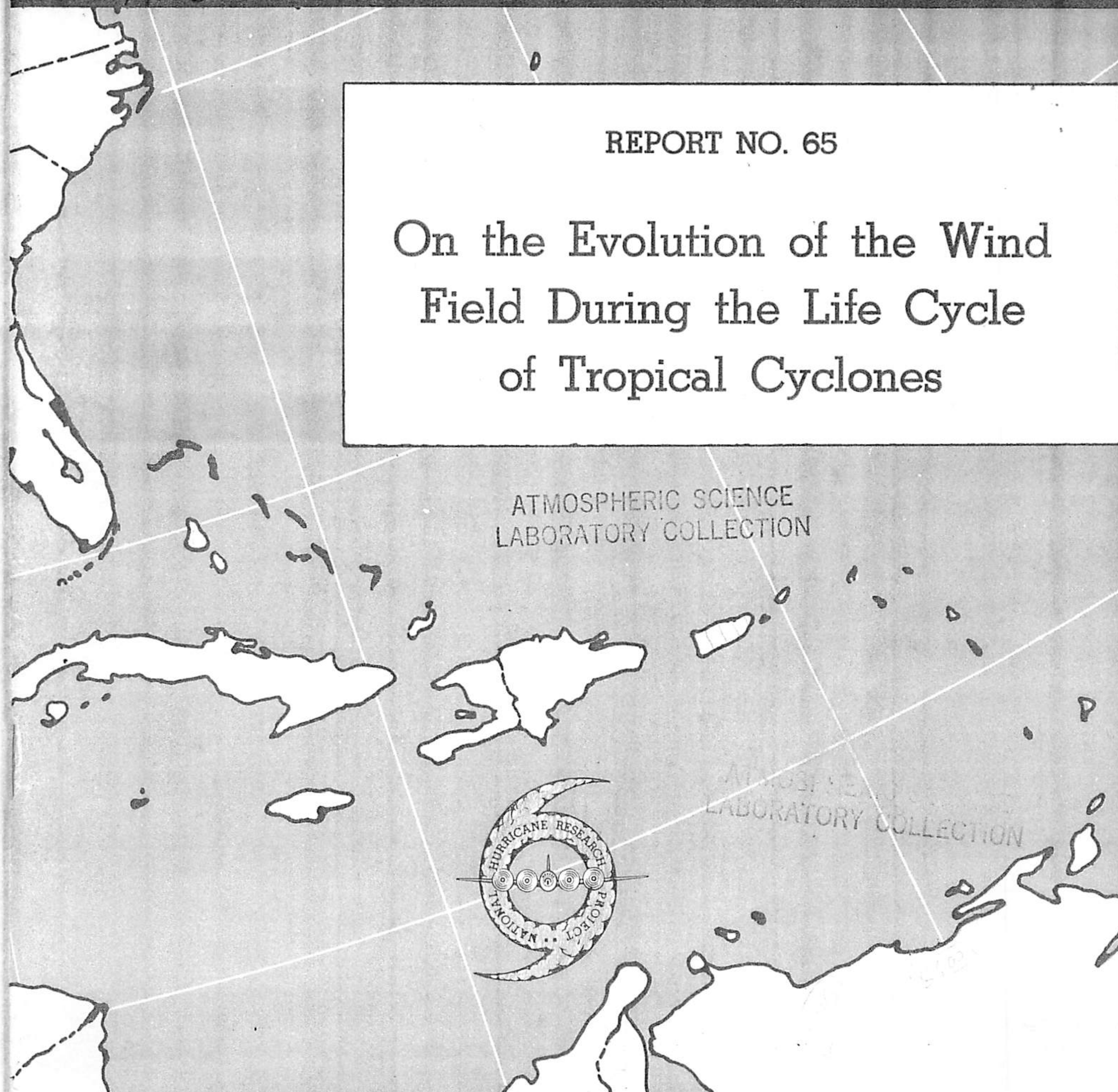

REPORT NO. 65

On the Evolution of the Wind Field During the Life Cycle of Tropical Cyclones

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

NATIONAL HURRICANE RESEARCH PROJECT

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by
José A. Colón
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Washington, D. C.
November 1963

NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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ON THE EVOLUTION OF THE WIND FIELD DURING THE LIFE CYCLE OF TROPICAL CYCLONES

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ABSTRACT

The structure of the wind field of tropical cyclones and its changes with time during the intensification and dissipation stages are studied by means of radial wind profiles recorded by the Weather Bureau research aircraft. It is found that hurricanes seem to conform to two types of evolution. In one type, exemplified by hurricane Daisy of 1958, a characteristic wind-maximum located at a small radius - or small eye - developed quite early in the genesis stage; growth than proceeded with little or no decrease in eye-diameter and resulted in a wind configuration with a very concentrated zone of maximum winds and large values of anticyclonic shear. In another type of evolution, exemplified by hurricanes Helene of 1958 and Carla of 1961, there was initially a rather disorganized wind field with large radius of maximum wind - or large eye; as intensification proceeded the eye diameter was reduced significantly and the wind profiles were characterized by less anticyclonic shear, less concentration at the radius of maximum wind and, in general, a more extensive circulation. The indications are that the Daisy type of evolution leads to a smaller wind circulation (areally) than the Helene type. Data from a sample of about 15 different storms show that eye diameter tends to decrease as the central pressure decreases, but in the Daisy type the reduction is insignificant. In the dissipation stage, filling of the central pressure is invariably accompanied by an increase in eye diameter, decrease in the maximum winds, but increase in storm size.

The mathematical representation of the wind profile was studied by computing values of alpha to satisfy the relation $v\ r^{\alpha} =$ const.; values ranging from 0.2 to 0.6 were obtained. The Daisy type of wind vortex had higher values of alpha than the Helene type. Some discussion is offered pointing to the influence of an early eye formation and its initial size on hurricane development and evolution. Some practical applications of the relationships evolved in this study in hurricane forecasting are mentioned.

1. INTRODUCTION

In a study of hurricane Daisy (1958) (Colón, [2]), it was revealed that that hurricane had a rather unique structure and growth process. Furthermore, these features of Daisy were quite different from those observed in other hurricanes; for example, Helene (1958). Some of these properties of hurricane Daisy and hurricane Helene are summarized later in this report. It appeared evident to the writer that the differences and similarities between those two vortices posed a problem of fundamental importance for an understanding of hurricane evolution, and that a more searching study was warranted.

An investigation of hurricane data directed toward verifying some of the aspects of hurricane evolution revealed by the Daisy and Helene data is reported below. Attention will be focused on the configuration of the wind field of several hurricanes, as shown by radial profiles of the total wind, and its changes with time as the hurricanes went through their normal life cycle of intensification and decay. The discussion, for the most part, is concerned with the intensification phase, but some comments are made in a final section about the observed changes in the dissipation stage.

The research program on hurricanes, carried out by the National Hurricane Research Project during the last six years, has succeeded in accumulating detailed information on the structure of several hurricanes at various stages in their development. This collection, although limited in some respects, was found adequate for the purpose of the present study.

For years there has been great interest in the evolution of the radial distribution of winds in the hurricane. Attempts have been made to develop simple models of the wind distribution, which would permit determination of the maximum winds near the center, given some observations on the periphery. Recently there have been some attempts at a thorough and systematic application of the complete equations of motion for various vortex models and their integration by numerical methods, starting from specified boundary conditions on the periphery (Riehl and Malkus [16], Rosenthal [17]). So far, mostly steady-state models have been employed and they have been partially successful in describing some of the major features of hurricanes. One would expect that, eventually, nonsteady theoretical models that describe adequately the structure and evolution of the hurricane vortex will be developed and tested. Since the success of these models must be determined by comparison with observations, it is necessary that we have a clear picture of what normally takes place during the life cycle of hurricanes. The collection of wind data introduced below provides a good picture of this aspect of hurricane behavior.

Some discussion of synoptic aspects of hurricane genesis is also offered below in an attempt to account for the observed characteristics of hurricane generation.

2. DATA SAMPLE AND ANALYSIS METHOD

The data were analyzed in the form of radial profiles of the total wind. Profiles recorded in a direction to the right of and perpendicular to the direction of motion of the storm center -- or as close to this direction as possible -- were selected for all cases in which the research aircraft flew into hurricanes, and for which the data were available for analysis. Figure 1 shows the tracks of the storms discussed.

The data for hurricanes Ione and Edith of 1955 were obtained from published reports (LaSeur [11], Blumen and LaSeur [1]); all the rest were obtained from the National Hurricane Research Project files. Ordinarily, research missions were flown by one or more planes at intervals of close to 24 hours. Therefore, time changes were studied mostly over periods of one day. In some cases, data were obtained on only one day. In these cases, inferences can be drawn only about the properties at a given time, but not

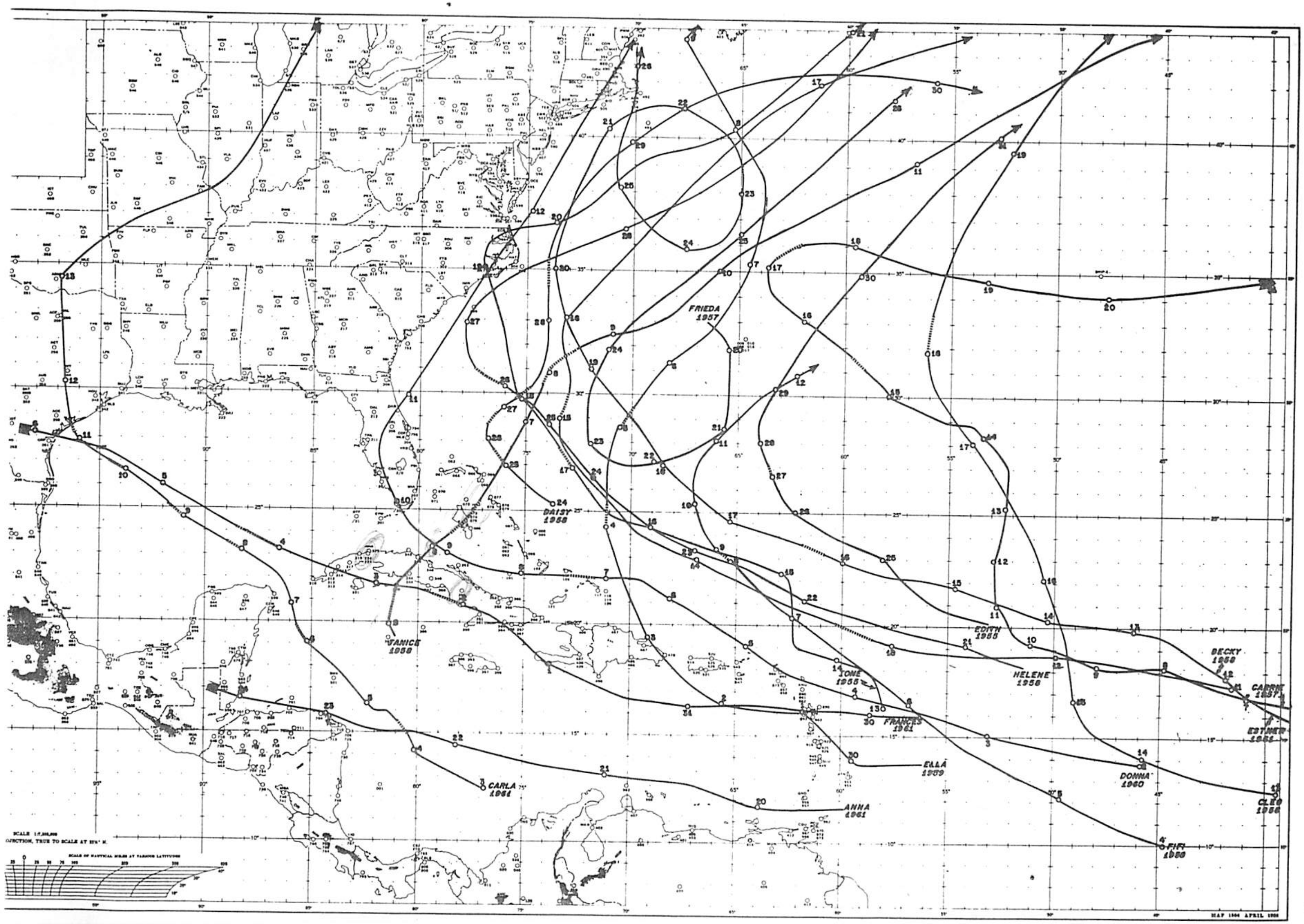

Figure 1. - Tracks of the tropical storms and hurricanes discussed in this report.

about changes with time. There were, however, a total of 12 hurricanes with data on more than one day. This permitted some sensible conclusions concerning the characteristics and variations in the wind structure. In some of these hurricanes, notably, Daisy and Helene of 1958 and Carla of 1961, there were rather complete and clear pictures of the evolution of the hurricane vortex during the intensification stage.

The variations in intensity were measured by means of the central pressure. It seems that this parameter is a more reliable and conservative measure of intensity than the maximum winds and is not as likely to be biased by sampling procedures. Our main interest in this discussion is directed to the configuration of the wind field and its time changes, and not to the observed magnitudes of the flow. Therefore, the profile of the total wind serves the same purpose as the profile of the relative wind. The actual and relative winds differ by a constant vector - the motion of the storm - and there is little or no difference between the configuration of their radial profiles. For some aspects of the study the relative winds were utilized.

The wind data were obtained at altitudes ranging from about 2,000 to 14,000 feet. However, data recorded at different altitudes on different days were all combined and used more or less indiscriminantly. As shown by Hawkins [5] the strength and configuration of the mature hurricane wind field changes very little with altitude in the lower half of the troposphere, so that combination of data for different levels does not impair the conclusions derived in the present study.

3. PROPERTIES OF HURRICANES DAISY AND HELENE (1958)

Most of the material will be discussed in reference to what was observed in hurricanes Daisy and Helene of 1958. The pertinent details concerning these two hurricanes are presented in figures 2-10. A thorough discussion of the Daisy data was presented elsewhere (Colón [2]), and a comprehensive description of the Helene data is in preparation.

Attention is called to the following factors concerning hurricane Daisy:

a. Daisy developed rather suddenly near the Bahama Islands on the afternoon of August 24, 1958. It was first investigated by research aircraft on the morning of August 25, and found to possess winds of hurricane intensity.

b. The time variations in central pressure (fig. 2) show values of close to 1000 mb. on August 25, which, then, decreased steadily to a minimum of 948 mb., observed late on August 27. Afterward the central pressure increased at a slightly more gradual rate as the hurricane moved northward into middle latitudes. The life cycle of Daisy thus consisted of an intensification stage which lasted for about 72 hours, followed by a dissipation stage.

c. The wind field on the initial day (fig. 3) showed a well-defined vortex with a characteristic zone of maximum winds centered at the 10-mi. radius; maximum winds were 60-65 kt. On the second day, August 26 (central pressure 972 mb.), there was a more intense and concentrated zone of maximum winds, still located at the 10-mi. radius; the speed decreased rapidly

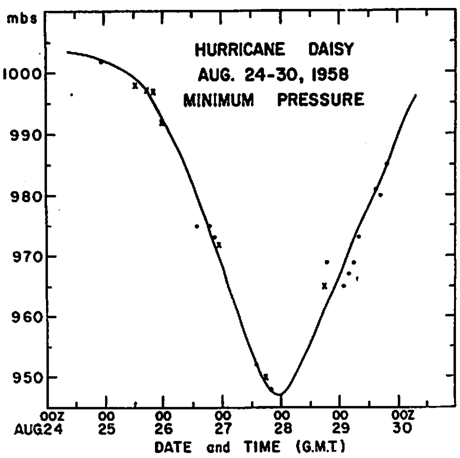

Figure 2. - Time changes in the central pressure of hurricane Daisy. The x's indicate values estimated from NHRP data; the dots show values recorded by dropsondes by the military reconnaissance aircraft.

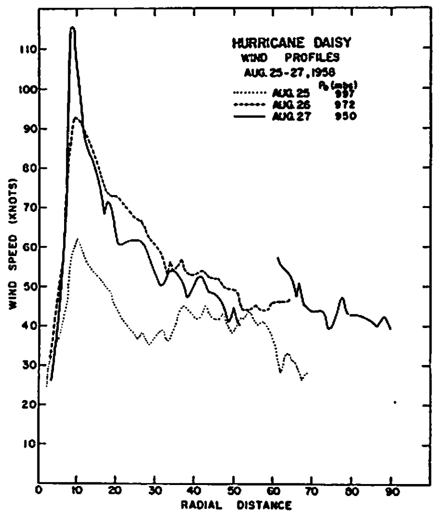

Figure 3. - Selected wind profiles recorded in hurricane Daisy, August 25 to 27, 1958. The data for Aug. 25 are at 5500 ft. (827 mb.); for Aug. 26 at 6400 ft. (800 mb.); and for Aug. 27 at 13,000 ft. (620 mb.). p_o stands for central pressure. All profiles were obtained in directions close to perpendicular to the motion in the right semicircle. The same is true for all other profiles illustrated in this report, unless specifically indicated otherwise. Except as noted, all data on this and other figures were obtained by the research aircraft of the U. S. Weather Bureau.

outward. On the third day, data were obtained close to the point of maximum intensity. There was an even more concentrated wind maximum, maximum speeds about 116 kt., but no appreciable change in the radius of maximum winds. The anticyclonic shear outside the 10-mi. radius was quite pronounced; at the 30-mi. radius the speed had decreased by about 50 percent. There was little change in strength outside the 50-mi. radius over the 3 days. The end result was a small, but intense, wind vortex.

d. The radar on the first day (fig. 4) showed a well-defined and almost circular inner band, which changed little in shape or size during the intensification stage (fig. 5).

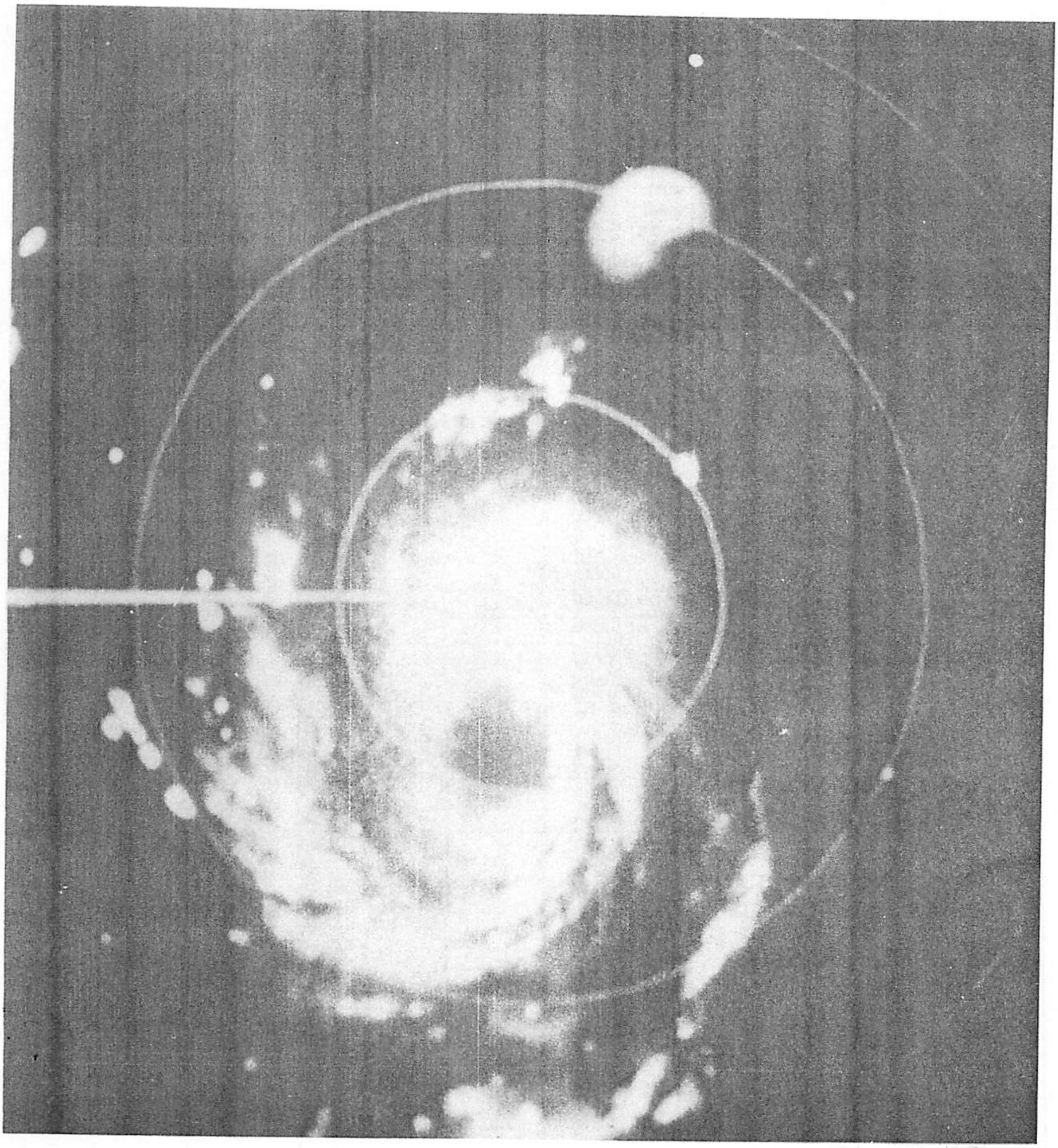

Figure 4. - Photograph of the radar scope showing the eye of hurricane Daisy at 2146 GMT, Aug. 25, 1958. The aircraft was flying at 35,000 ft. (238 mb.). Range markers are 20 n. mi. apart; the top of the photograph is North.

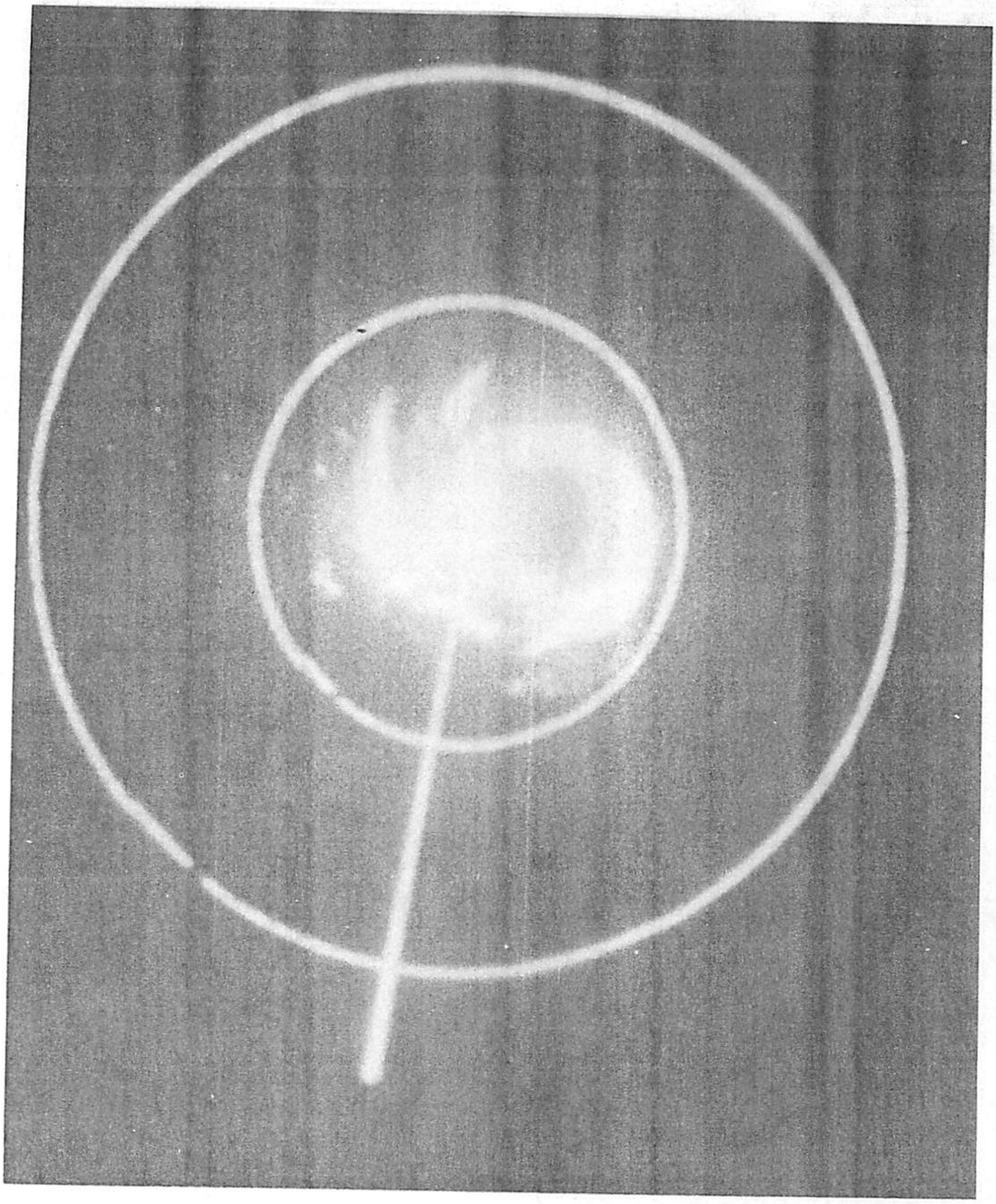

Figure 5. - Photograph of the eye-wall radar band of hurricane Daisy as seen by the aircraft flying at 13000 ft. (620 mb.) at 1753 GMT, Aug. 27, 1958. Range markers 20 n. mi. apart. Top of the photograph is North.

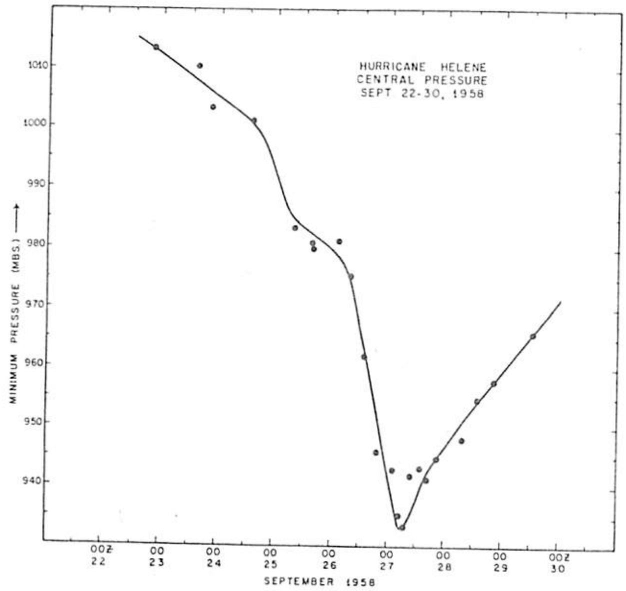

Figure 6. - Time changes in central pressures in hurricane Helene, Sept. 22-30, 1958.

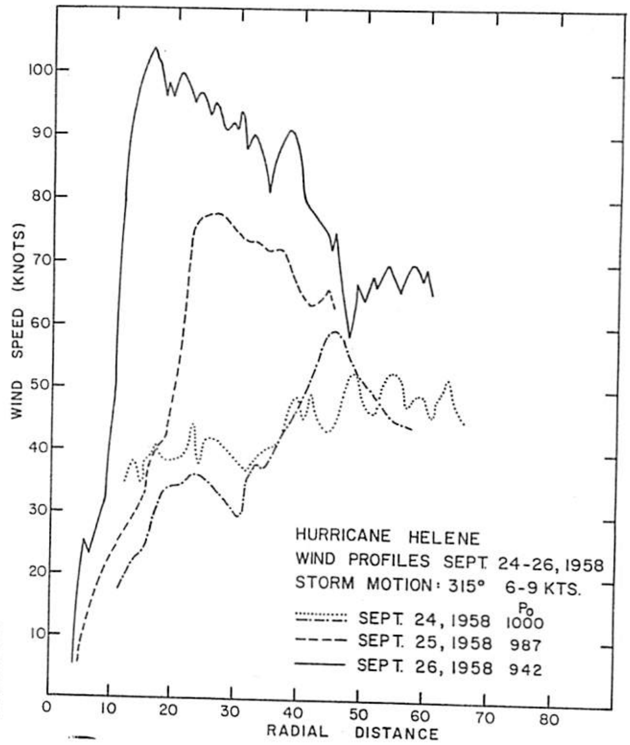

Figure 7. - Wind profiles recorded in hurricane Helene, Sept. 24-26, 1958. Data for Sept. 24 are at 13,000 ft. (620 mb.); for Sept. 25 at 6400 ft. (800 mb.) and for Sept. 26 at 15,600 ft. (557 mb.). The dot-dashed profile for Sept. 24 was obtained in a direction just to the left of the motion; all other profiles were at right angles to the motion, on the right semicircle.

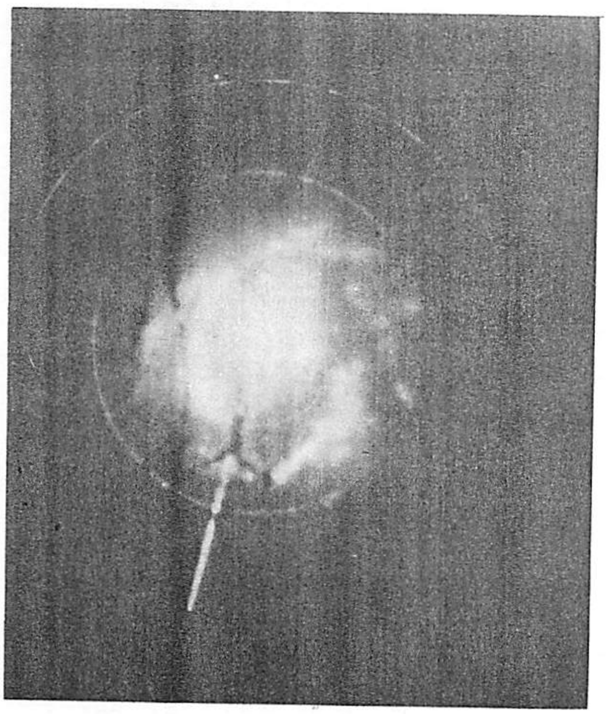

Figure 8. - Photograph of the eye-wall radar bands in hurricane Helene at 1836 GMT, Sept. 24, 1958. The aircraft was in the center of the eye at an altitude of 13,000 ft. (620 mb.) Range markers 20 n. mi. apart. Top of the photograph is North.

The following points are made concerning the intensification of hurricane Helene (figures 6-10):

a. Hurricane Helene had a more prolonged development stage. It was initially detected as a weak circulation on September 21 (fig. 1), maximum winds of about 35 kt. were recorded in squalls. The system moved northwestward as it intensified. Maximum intensity was attained near the coast of North Carolina on September 27, at the point of recurvature.

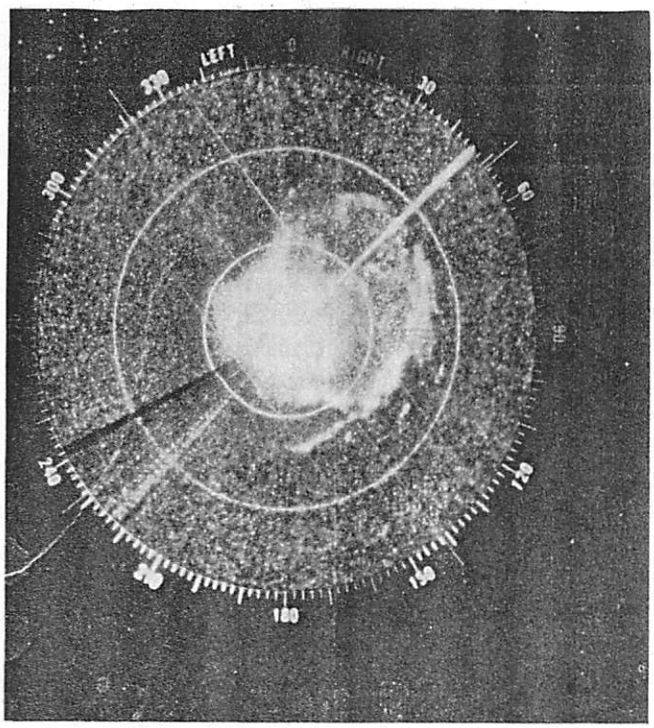

Figure 9. - Photograph of the eye-wall radar band in hurricane Helene at 1809 GMT, Sept. 25, 1958. Aircraft near the west wall of the eye at an altitude of 6400 ft. (800 mb.). Range markers 20 n. mi. apart. Top of the photograph is North.

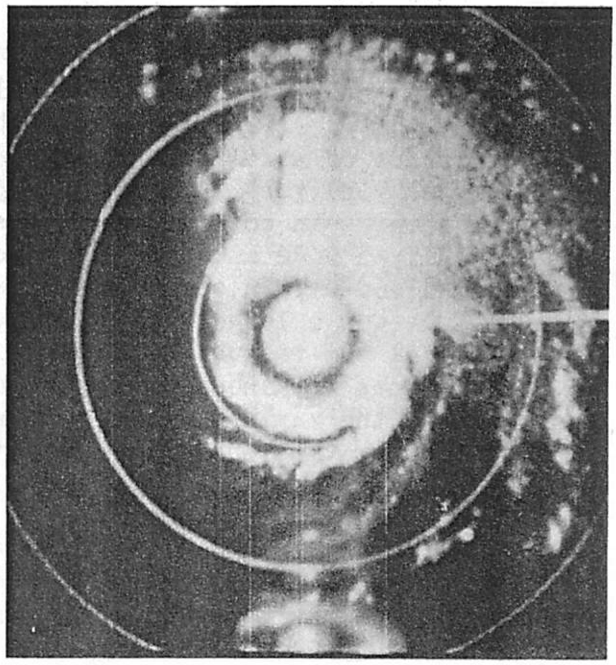

Figure 10. - Photograph of the eye-wall radar band in hurricane Helene at 1729 GMT, Sept. 26, 1958. Aircraft in the center of the eye at an altitude of 34,200 ft. (248 mb.). Range markers 20 n. mi. apart. Top of the photograph is North.

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b. The central pressure (fig. 6) decreased gradually from about 1013 mb. on September 22 to 1000 mb. on September 24. After September 24 there was a more rapid intensification to a minimum central pressure of 933 mb. recorded early on September 27. Afterward the pressure increased as the dissipation stage ensued.

c. Data on the wind field were available on, and after, September 24. At that time (fig. 7) there were maximum winds of about 50-55 kt. located at about 45 mi. from the center. There was some organization in the wind field to the extent that there was distinguishable zone of maximum winds, more pronounced in the left side of the storm. As the central pressure decreased on the following two days, the wind speed increased and the radius of maximum winds decreased. The resulting profiles showed little concentration at the radius of maximum winds, and very gradual decrease in speeds outward. On the final day the maximum speed was about 105 kt. located at the 16-mi. radius. The wind vortex turned out to be rather extensive.

d. The radar configuration showed on September 24 (fig. 8) a somewhat disorganized and very wide eye-wall structure. The appearance is more of two separate spirals meeting together in the presumed center. On the second day there is a better organized central ring, open on the west side. This opening on the west side is not too evident in figure 9 because of the "noise" in the center of the scope, but it appeared clearly in other photographs. The inner diameter was about 35-40 mi.; the radar eye seems to be elongated in the NNE to SSW direction. On the third day (fig. 10) the eye wall was completely closed into a fully developed and nearly circular ring. The central opening is about 18 mi. in diameter, the outside diameter is about 36 mi.; that is, the width of the ring is about 9 mi.

In summary, hurricane Daisy went through an intensification process in which growth occurred from an initially well-defined and small vortex, in such a way that there was no appreciable change in the diameter* of the wind eye, or radius of maximum winds (R_m). The final result was a small and concentrated wind vortex, with a wind profile characterized by large anti-cyclonic shear. In contrast, Helene showed a growth process in which there was initially a wide and somewhat disorganized wind system, which organized and intensified with a steady decrease in the radius of maximum winds. The final result was a large, but intense, system with not much concentration of wind speed at the radius of maximum winds and gradual decrease in speed outward. Both hurricanes attained about the same central pressure and comparable magnitude of the maximum winds. Actually, the maximum winds in Daisy were somewhat higher than in Helene, even though the central pressure was not as low.

After observing these features, several questions came to mind. Were those differences and similarities representative of a general and systematic pattern of behavior observed also in other hurricanes, or were they due to fortuitous occurrences with little or no significance? How can the differences in structure and growth process be explained? How does it come about that a hurricane follows one or the other pattern of behavior?

4. PROPERTIES OF THE WIND FIELD IN OTHER HURRICANES

To answer the first question, we investigated the sample of hurricanes to see whether the growth process and/or configuration of the wind field could be fitted into a "Daisy" or "Helene" type. A storm was classified as of the Daisy type if it showed significant changes in central pressure with no appreciable change in eye diameter; and/or, if the wind field was characterized by a small eye with a narrow zone of maximum winds, with rather large anticyclonic shear outside, located in a position very close to the center of the eye. A storm was classified as of the Helene type if the growth process showed deepening of the central pressure accompanied by significant reduction in the radius of maximum winds (R_m) and/or the configuration of the wind field was characterized by a lack of concentration of the maximum winds in the eye wall with low values of anticyclonic shear. The decision as to whether the observed changes in R_m were significant or not was determined subjectively; however, most of the wind data are illustrated in this report.

The above implies that each set of conditions necessarily go together. This has been found to be generally the case; some discussion of this point is offered later in this report.

The sample of storms investigated included five hurricanes that reached central pressures below 950 mb.: Ione (1955), Daisy and Helene (1958), Donna (1960), and Carla (1961); four hurricanes that attained central pressures

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*The term eye diameter as used occasionally in this report refers to the diameter of the wind eye or approximately equal to twice the radius of maximum winds. This is done mostly to avoid repetition of terms.

from 950 to 980 mb.: Carrie (1957), Cleo (1958), Frances (1961), and Hattie (1961); and three whose minimum pressure was between 980 and 1000 mb.: Edith (1955), Janice (1958), and Anna (1961). All of them showed evidence of having reached a stage of development in which there was a distinguishable zone of maximum winds and eye structure. The sample included also four systems: Frieda (1957), Becky (1958), Ella (1958), and Fifi (1958), whose minimum central pressure was above 1000 mb. and never reached more than tropical storm intensity. These storms showed lack of organization of the wind field, with no characteristic zone of maximum winds and eye structure.

It was found that the Helene type of growth and wind structure seemed to occur with slightly greater frequency than the Daisy type. Two well documented cases of the Helene type, with data available on several days, are hurricanes Carla (figs. 11, 12), and Janice (fig. 13). The case of hurricane Carla is quite impressive; the central pressures (fig. 11) showed a steady decrease from values of about 1003 mb. on September 4, when Carla was developing in the western Caribbean, to a minimum of about 936 mb., recorded when Carla went inland on the Texas coast on September 11. The wind field (fig. 12) showed initially, on September 4 to 6, a very disorganized structure. On the 4th there was weak flow on the right side of the storm, maximum winds of 25 kt. appeared at the 55 mi. radius. Actually the maximum winds on this day, of the order of 40 to 50 kt., were located on the left semicircle. On the 6th there was a peak wind of 45 kt. at the 40-mi. radius on the right side. Again on this day maximum winds of about 60 kt. were observed on the left side. An interesting feature of the profile for the 6th is the peak in wind speed at about the 5-mi. radius on each side of the circulation. The next profile was obtained on September 8 when Carla was entering the Gulf of Mexico. At that time there was a better organized wind vortex with a clearly defined round eye (with diameter of 60 mi.).

From September 8 to 11 the eye diameter decreased from 60 to less than 40 mi. The maximum strength increased only slightly. The decrease in maximum winds from the 10th to 11th was probably due to the fact that the profile for the 11th was obtained along the Texas coastline; the forward semicircle was already over land, and disorganization of the wind field might have been already under way. One very remarkable feature about Carla was the horizontal extent of the strong winds; the profile on September 8 showed winds of over 50 kt. extending to the 230-mi. radius.

Other examples of the Helene type of wind structure are hurricanes Edith (1955), Carrie (1957), and Cleo (1958). However, in these cases, data were available on only one day. The Edith profile (fig. 14) (Blumen and LaSeur [1]), was recorded during the intensification stage, which suggests a Helene type of growth process. The profiles for Cleo (fig. 14) and Carrie (fig. 15) were obtained while they were in the dissipation stage. The profiles show the characteristic shape of the Helene vortex, but one cannot say definitely what type of growth process had originally taken place in these hurricanes.

Examples of the Daisy type of wind vortex were more difficult to find. Data over several days giving as complete a picture as in Daisy were not existent for any other storm. The closest example to the type of wind profile observed in hurricane Daisy on August 27 was that recorded in hurricane

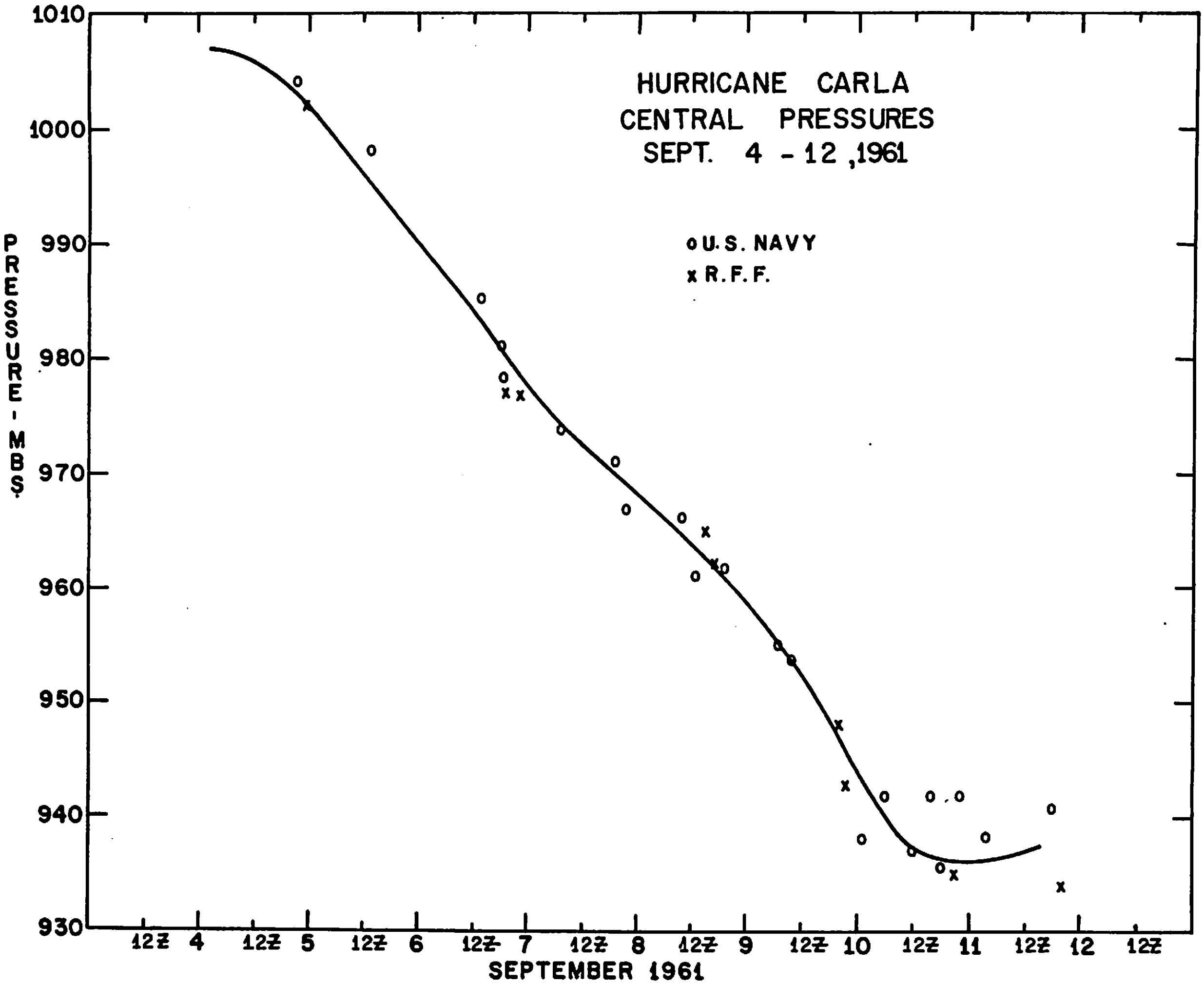

Figure 11. - Changes in the central pressure of hurricane Carla, Sept. 4-12, 1961. Data obtained from dropsondes by the U. S. Navy reconnaissance aircraft and by the research aircraft of the U. S. Weather Bureau, Research Flight Facility.

Ione (1955) on September 17, 1955 (LaSeur [11]). This profile (fig. 14) shows a pronounced concentration with maximum winds of 100 kt. at the 10-mi. radius and extreme anticyclonic shear outside it. Unfortunately, data were available on only one day. The Ione profile was obtained during the intensification phase, close to the point of maximum intensity. From the evidence noted in other cases, it appears very likely that the growth process may have been similar to that observed in Daisy.

One fairly good example of the Daisy type of growth process was evidenced by hurricane Frances (1961) in the period after October 4, 1961 (fig. 16). Frances was first investigated on October 1, shortly after development had started. The central pressures on October 1 and 2 were 1003-1000 mb. The wind field showed a small center with maximum winds located fairly close to

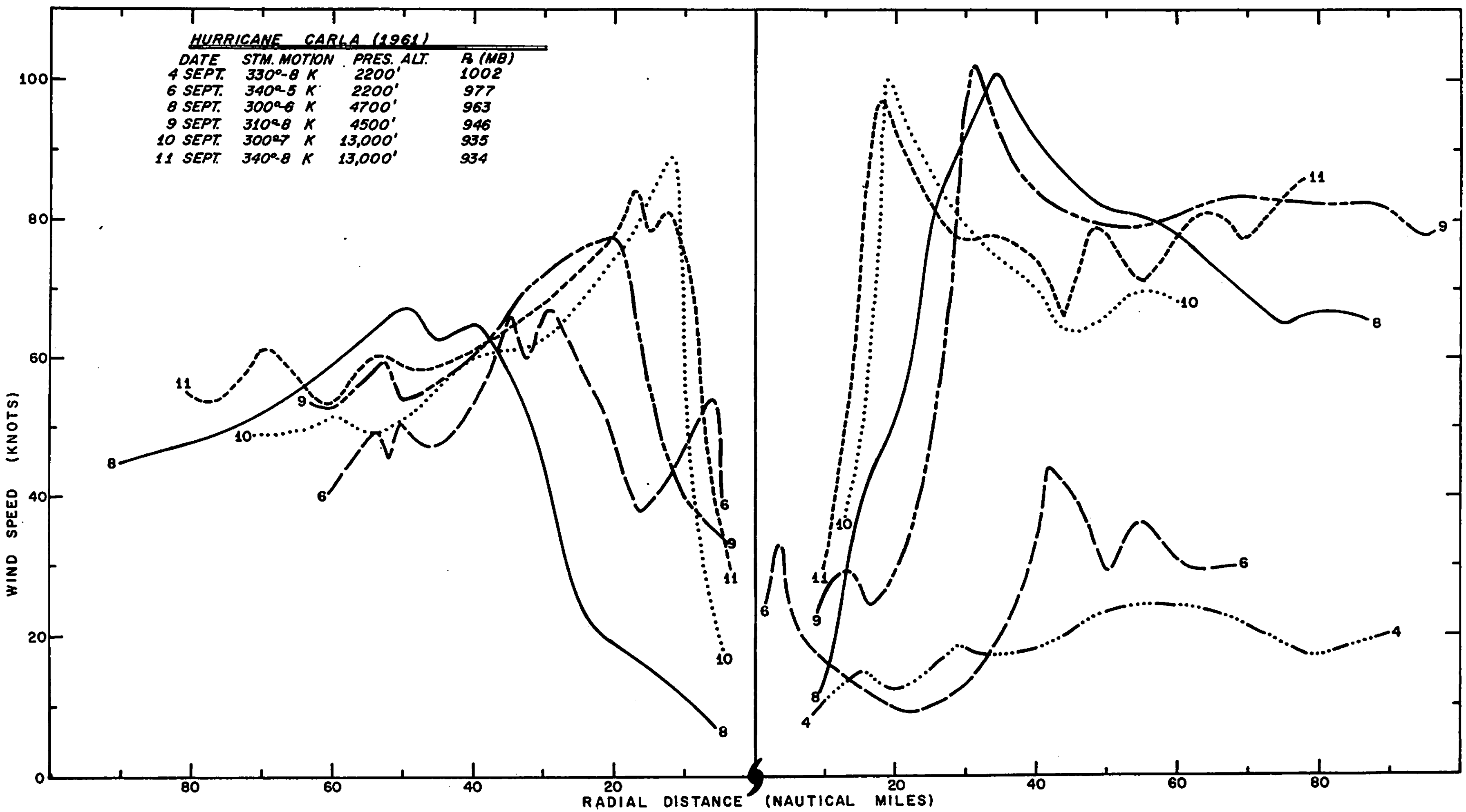

Figure 12. - Wind profiles recorded in hurricane Carla, Sept. 4-11, 1961.

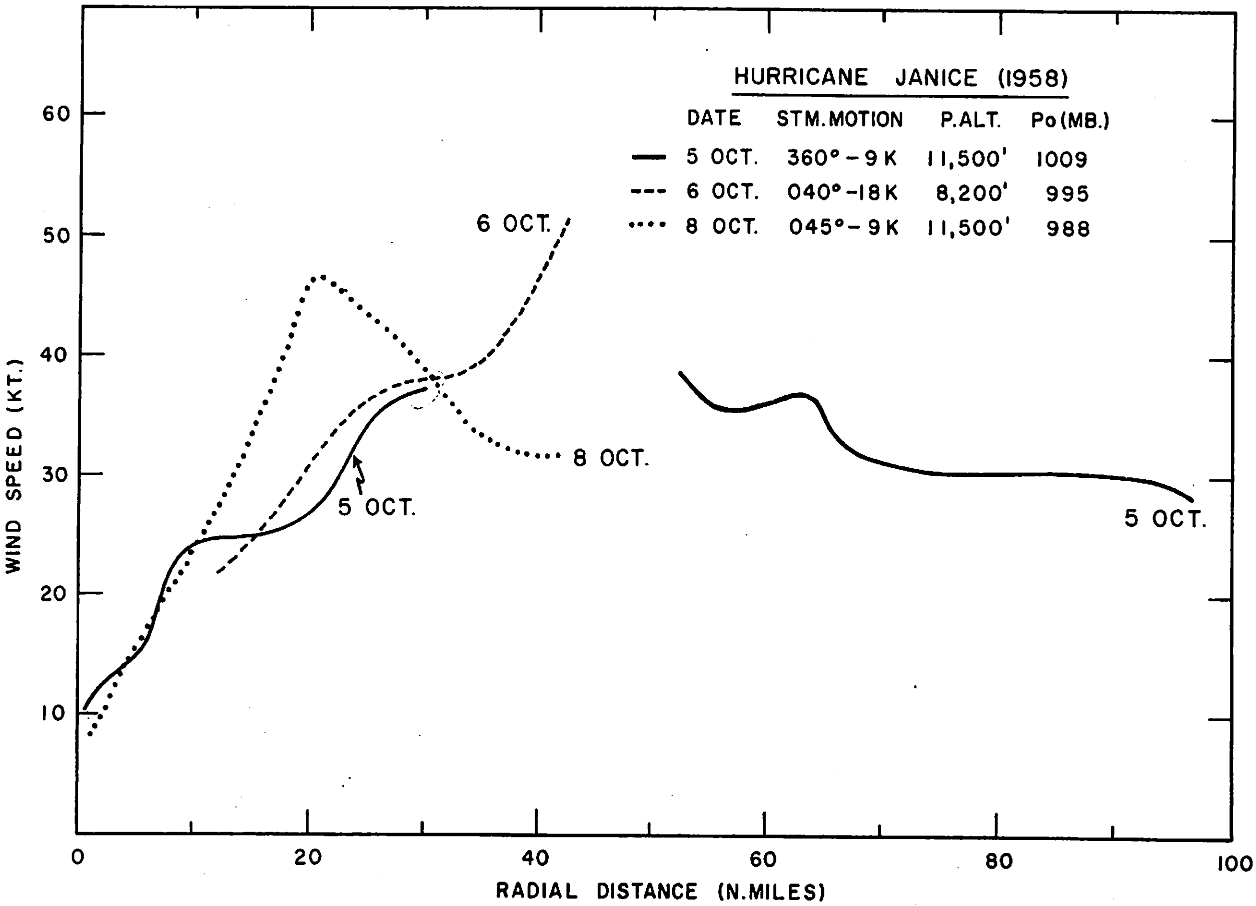

Figure 13. - Wind profiles recorded in hurricane Janice, Oct. 5-9, 1958.

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the center of circulation, but with a somewhat disorganized structure. Frances weakened as it approached and crossed the island of Hispaniola on October 3. After it moved into the Atlantic Ocean there was quite a rapid redevelopment and when Frances was next investigated by the research aircraft on October 4, it showed a fairly well defined vortex with maximum winds of 60 kt. located near the 10-mi. radius; the central pressure was then 989 mb. The next day, October 5, the central pressure had decreased to 953 mb., the maximum winds had increased to 90 kt., but the radius of maximum winds remained unchanged. The wind profile showed the characteristic concentration and fairly large anticyclonic shear of the Daisy type of wind vortex.

Other hurricanes which resemble hurricane Daisy more than Helene but for which the data are rather inconclusive, are Donna (1960), and Anna and Esther (1961). Donna was a well-developed hurricane, of great intensity at the time it was first discovered, so that there is no information about the growth process. The data showed a small eye and a wind configuration of the Daisy type (fig. 17). The same was true for Hurricane Esther (1961) (fig. 17). Anna (1961) developed quite rapidly; the research aircraft penetrated the circulation about 24 hours after formation and found a characteristic concentration of maximum winds very close to the center. The profiles (fig. 17) are more indicative of the Daisy type of vortex.

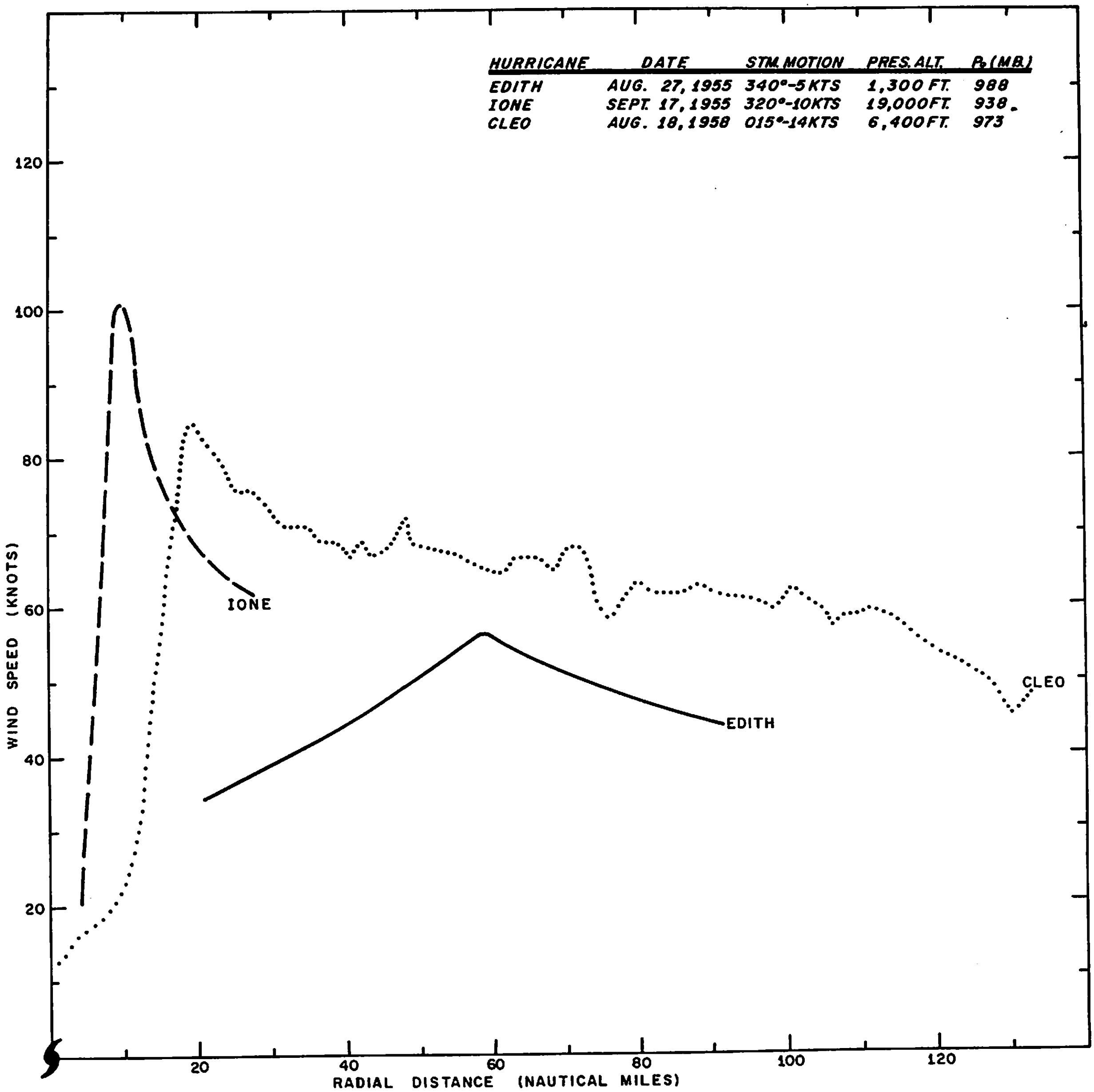

Figure 14. - Wind profiles recorded in hurricanes Ione (1955), Edith (1955) and Cleo (1958). Data for Ione obtained from LaSeur [11] and for Edith from Blumen and LaSeur [1].

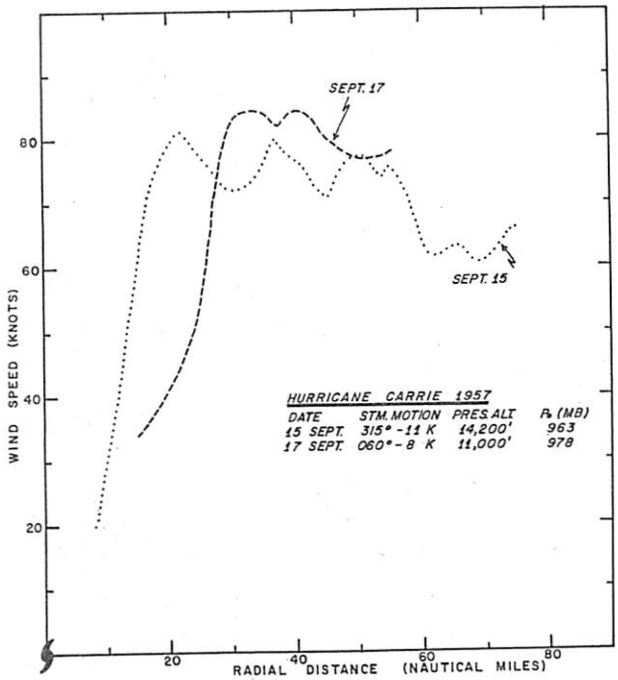

Figure 15. - Wind profiles recorded in hurricane Carrie, Sept. 15-17, 1957

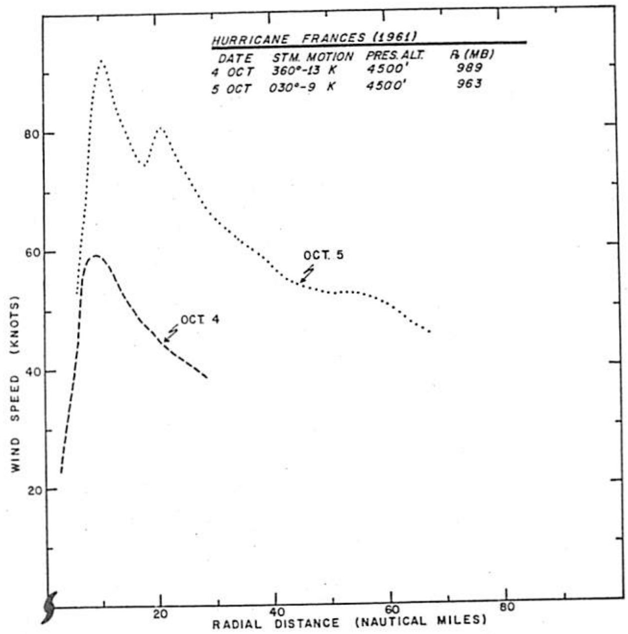

Figure 16. - Wind profiles recorded in hurricane Frances, Oct. 4-5, 1961.

In the four storms in which the central pressure did not go below 1000 mb. there was no characteristic organization of the wind field and no distinguishable zone of maximum winds (figs. 18-21). In some cases there was a lack of a characteristic eye. The observed maximum winds were located far away from the center of circulation. If they were to be classified according to the criteria set above, one would have to put them with the Helene type of development. All of these systems existed for days with little change in intensity or structure, so that development was slow and gradual as in the Helene type.

In summary, if all cases are included, there were 10 cases of the Helene type and 5 of the Daisy type. If only hurricane cases are included, then there were 6 cases of the Helene type and 5 cases of the Daisy type. There were cases in which the cataloging was somewhat difficult. This is not surprising, in view of the complexity and unsteadiness of the processes involved in the generation of hurricanes. The evidence, although limited, strongly indicates that the differences between the Daisy and Helene vortices reflect a pattern of behavior to which hurricanes seem to conform in greater or lesser degree. Although there is always a risk in trying to simplify things too much, there is also merit in that simplification helps to emphasize specific phenomena of interest and importance that should be investigated and studied further. The conclusions in regard to the Daisy and Helene types appear to be well founded and point to specific and definite differences in hurricane evolution that require explanation.

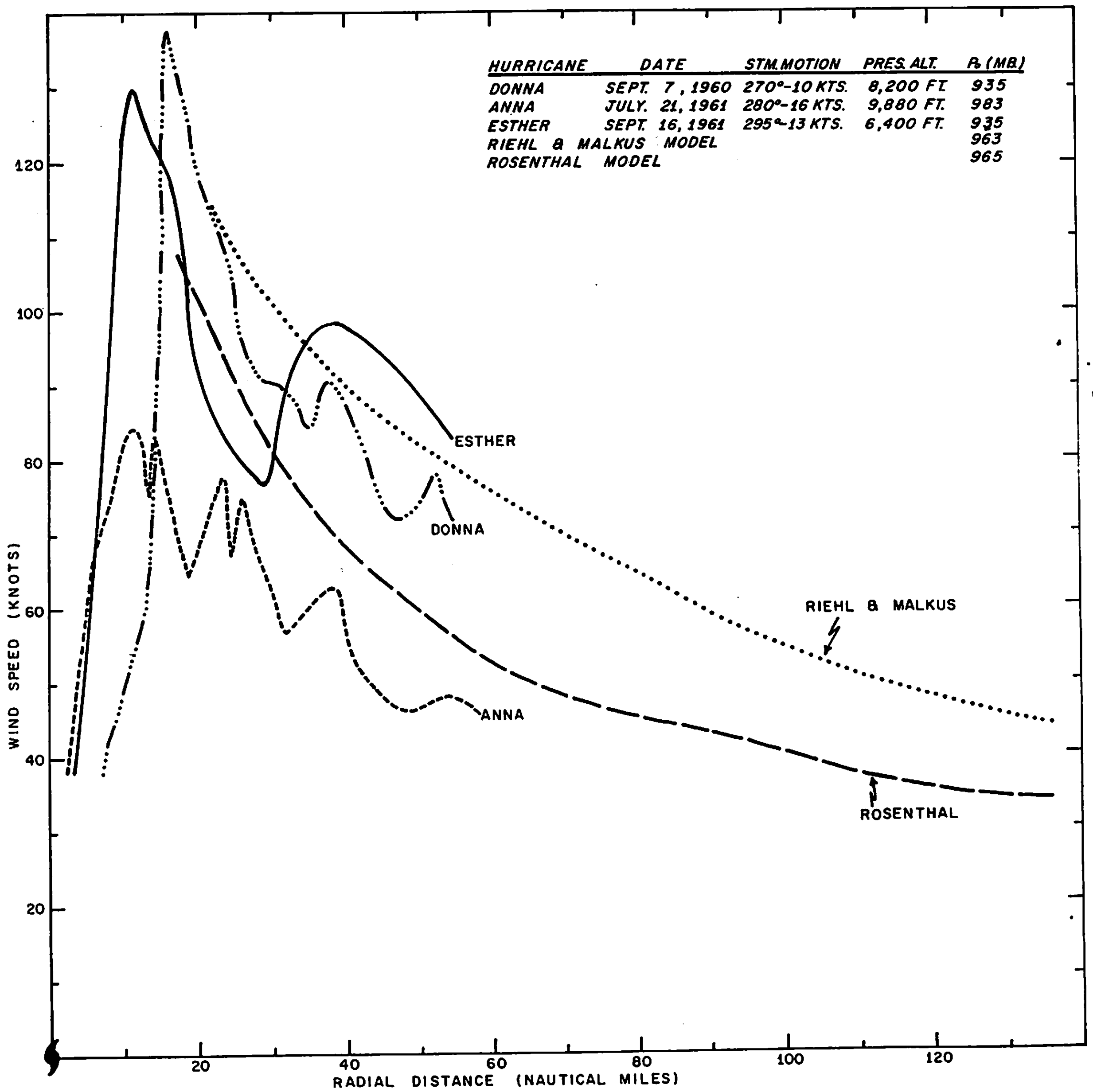

Figure 17. - Wind profiles recorded in hurricanes Donna (1960), Anna (1961), and Esther (1961). Included also are the wind profiles obtained in the theoretical models by Riehl and Malkus [16] and Rosenthal [17].

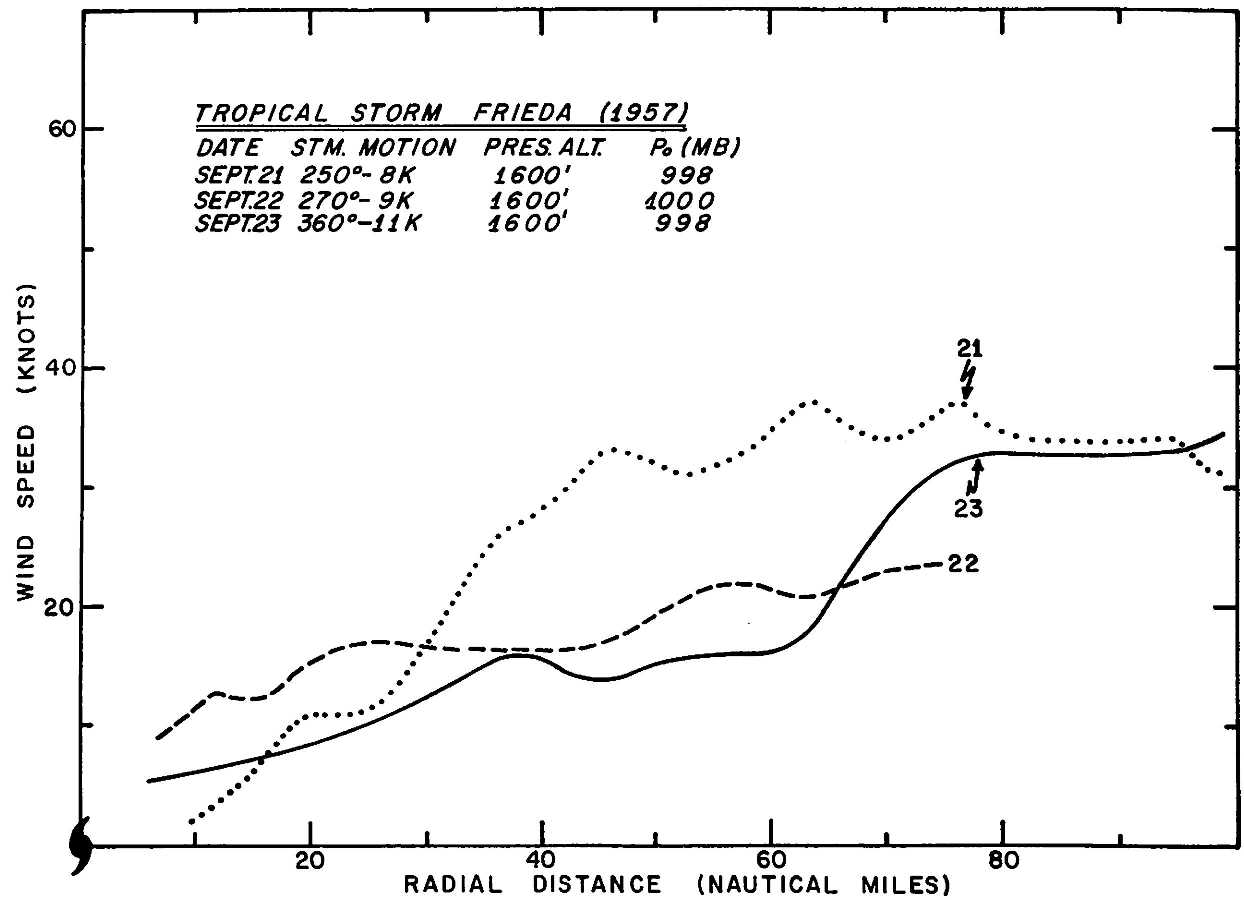

Figure 18. - Wind profiles recorded in tropical storm Frieda, Sept. 21-23, 1957.

The important question is how and why do these differences come about. One would be inclined to think that all hurricanes respond to the same physical processes that determine their formation and growth and that differences in behavior and structure are due to variations in the state of the ambient atmosphere and ocean that result in gradations in the intensity or effectiveness of the generating impulses. Discussion of some synoptic and convective aspects of hurricane genesis that might bear on the question above are presented in Section 7. First, it might be of interest to investigate the interrelationship between certain features of the hurricanes, such as eye diameter, central pressure, size, etc., as revealed by the sample of observations, and to study the variations in the pressure field accompanying the intensification process.

5. RELATIONSHIP BETWEEN CENTRAL PRESSURE, EYE DIAMETER, MAXIMUM WINDS, AND STORM SIZE

Figure 22 shows a plot of central pressure versus radius of maximum winds as shown by the data sample discussed previously. The x's in figure 22 indicate observations on hurricanes classified as the Helene type, the dots indicate observations in hurricanes of the Daisy type. As a whole, there is a large scatter, with no clear-cut relationship. However, if the observations

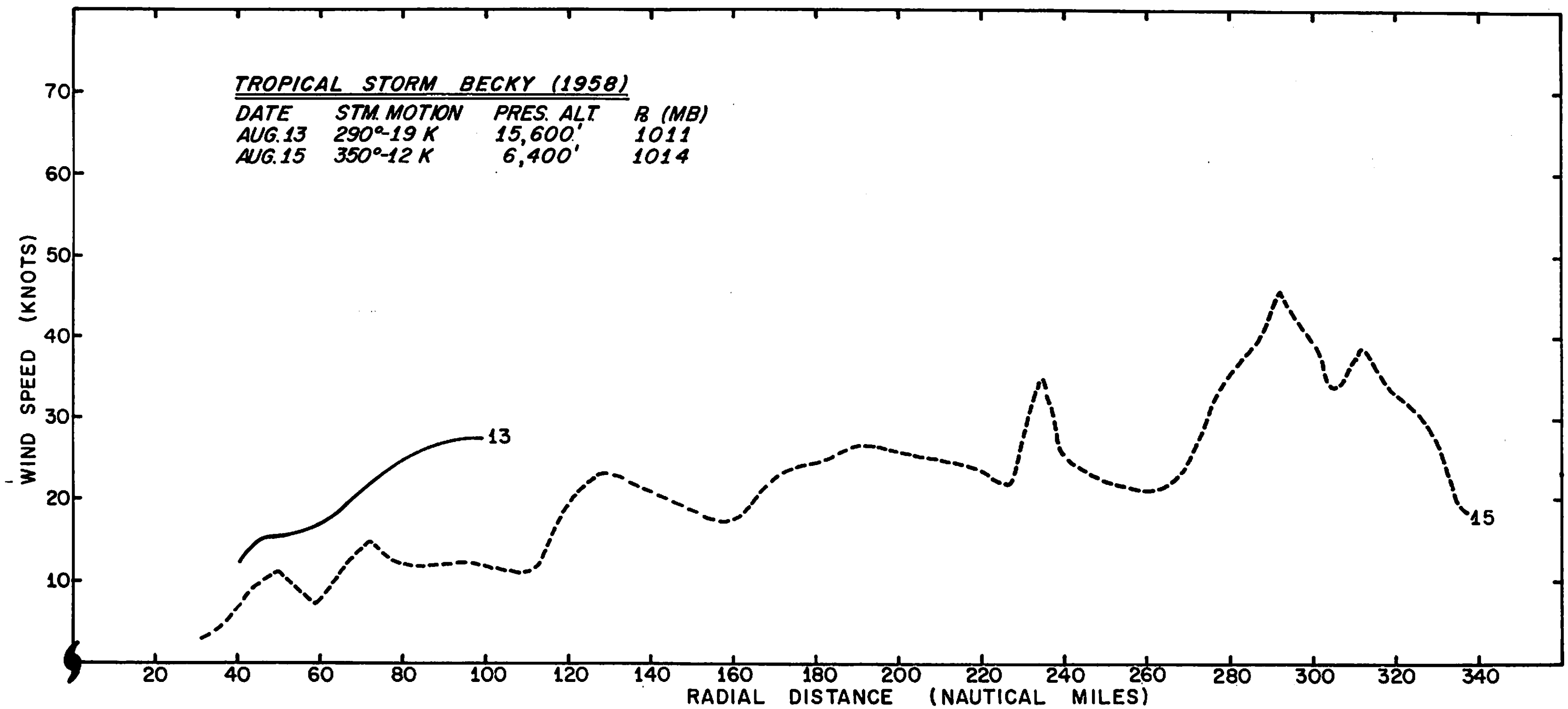

Figure 19. - Wind profiles recorded in tropical storm Becky, Aug. 13-15, 1958.

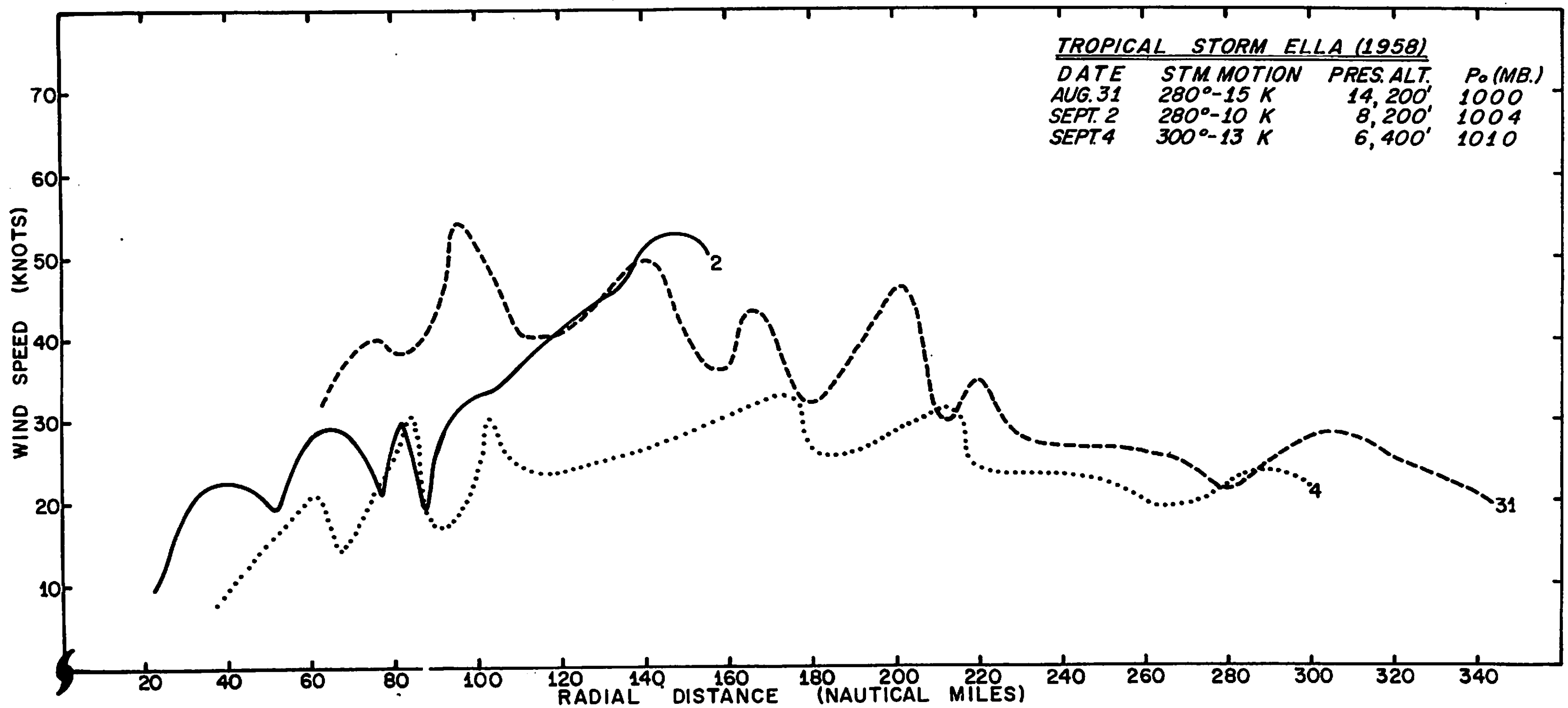

Figure 20. - Wind profiles recorded in tropical storm Ella, Aug. 31-Sept. 4, 1958.

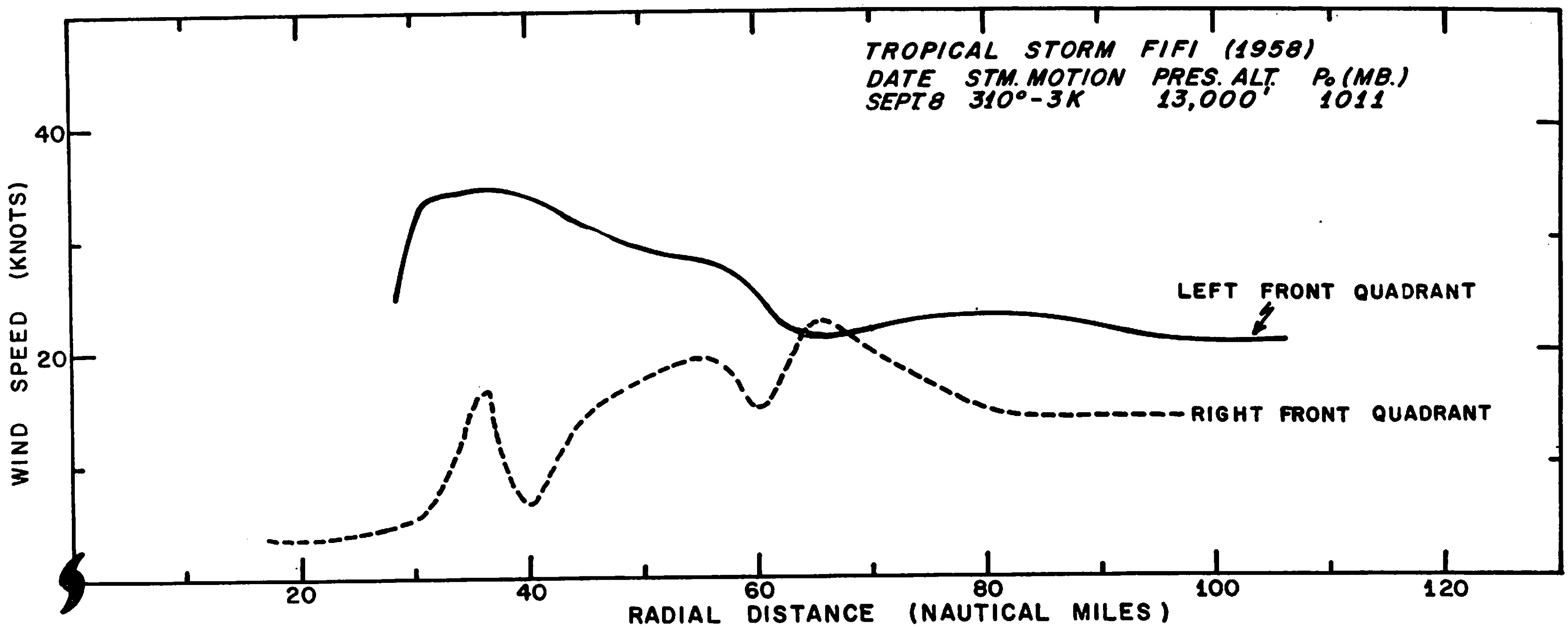

Figure 21. - Wind profiles recorded in tropical storm Fifi, Sept. 8, 1958.

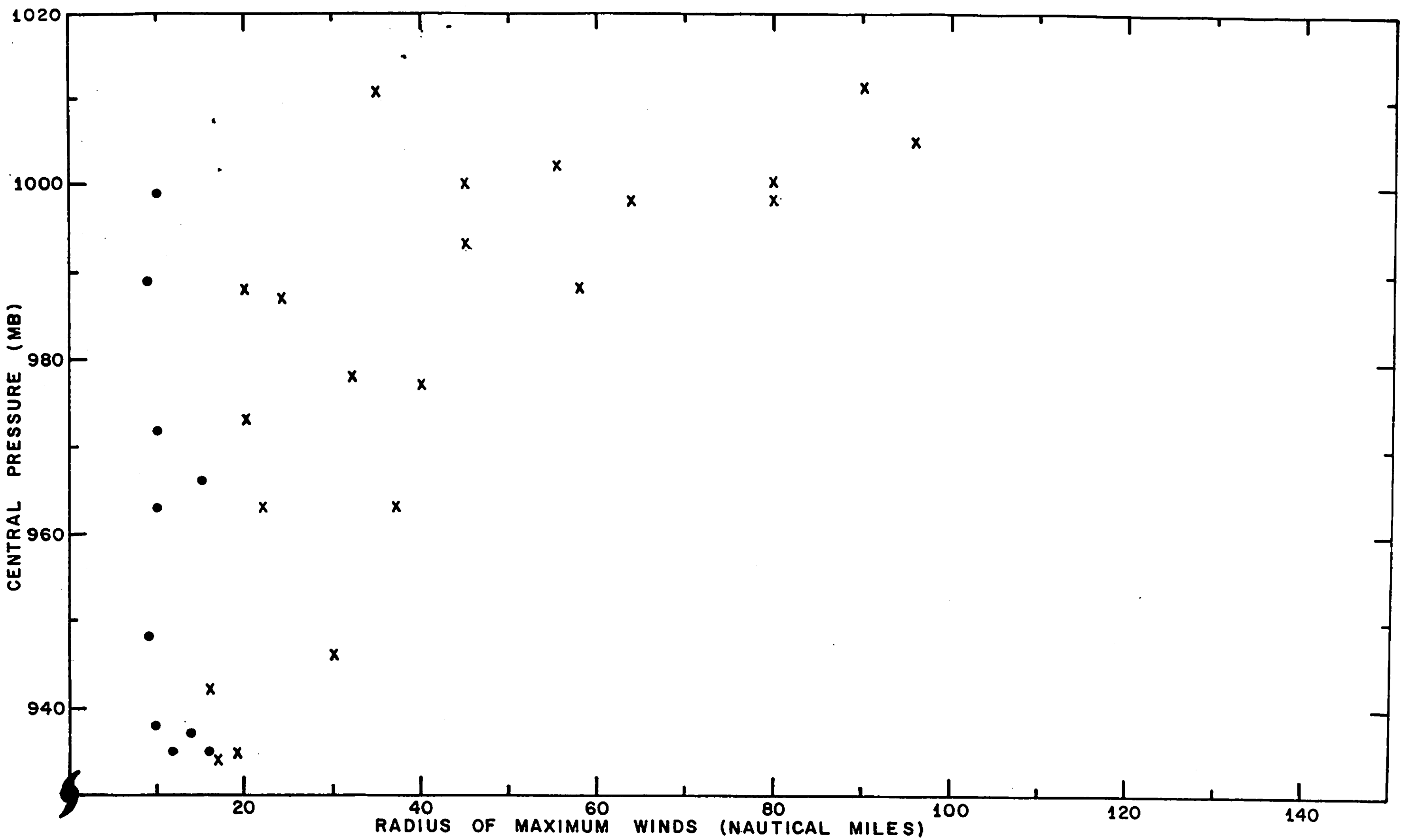

Figure 22. - Relation between central pressures and radius of maximum winds as recorded in the sample of storms under study. The dots indicate the observations in hurricanes classified as of the Daisy type, the x's indicate observations in the Helene type of systems.

of the Helene type are studied separately from those of the Daisy type, in the intensification stage a more meaningful correlation is apparent.

For the Helene type there is an unmistakable, direct relationship between the eye diameter - or radius of maximum winds - and the central pressure. In the Daisy type of vortex the tendency is for constancy of the eye diameter with deepening of the central pressure. In the formative or weak storms that are trying to get organized, significant variations in R_m may take place with no appreciable change in central pressure.

There were initially in the literature some conflicting reports about the relationship between eye diameter and intensity; but with more recent data this matter is now being clarified. Jordan [6] presented a study of central pressure versus eye diameter for a sample of 46 observations taken in eight separate typhoons. His diagram shows evidence of a slight tendency for larger eye diameters to be associated with lower central pressures. A sample of observations on time duration of the calm area of the eye versus central pressure, prepared by Depperman and quoted by Dunn [4], indicated longer calm area for weaker storms. Duration of calm area is also a function of storm motion, but unless there was a wide disparity and selectivity concerning storm motion, the Depperman data suggest smaller eyes for deeper storms.

Recently Jordan [8] showed data for very deep typhoons, which also indicate smaller eyes for deeper typhoons. One might mention also that theoretical work by Kuo [10] indicated lower R_m for lower central pressure, while Kleinschmidt's work [9] suggested larger R_m for lower central pressure.

The data shown in figure 22 suggest a clearer and more systematic relationship. During the intensification stage, once an eye formation has been attained, there is a class of hurricanes in which the eye, quite small from the beginning, remains nearly constant with intensification; while in another class, the eye, large initially, decreases in size with intensification. During the dissipation stage, the evidence (to be discussed later) indicates that in all hurricanes the eye diameter increases as the central pressure increases. For this reason the relationship should be interpreted with respect to each individual hurricane and notice should be taken of the stage in the life cycle.

The diagram of maximum winds as a function of central pressure (fig. 23) shows the well-known direct relationship; inclusion of data for all hurricanes does not materially affect the scatter. A plot of maximum winds as a function of radius of maximum winds (not illustrated) is very much affected by the type of hurricanes involved. In the Daisy type the maximum winds may increase with no appreciable change in R_m, while in the Helene group the tendency is for higher maximum winds to be associated with smaller eyes. In hurricane Carla, however, the maximum winds did not change much in the period from September 8 to 10 while the eye decreased markedly.

The other important and interesting feature of the hurricane, which may be associated with intensity, is the size of the storm. It was noticed quite early that tropical storms showed marked variations in size and it was also noted that the central pressure did not seem to be a determining factor (Dunn [4], Riehl [14]). The data shown here confirm that the size of the wind circulation is not a function of central pressure or maximum winds. There is a strong indication (see figs. 4, 14) that small hurricanes are generally associated with small radius of maximum winds. It appears also that size is essentially a function of the process of evolution and that the development process as depicted by hurricane Daisy generally leads to a small hurricane, while the Helene and Carla type of evolution leads to a more extensive vortex.

6. TIME VARIATIONS IN THE PRESSURE FIELD DURING THE INTENSIFICATION STAGE

To assist in the interpretation of the time variations in the wind field it is worthwhile to inspect the variations in the pressure distribution that accompanied the variations in the wind field of hurricanes Daisy and Helene. These are shown in figures 24 and 25 in the form of radial profiles of the height of the 700-mb. level.

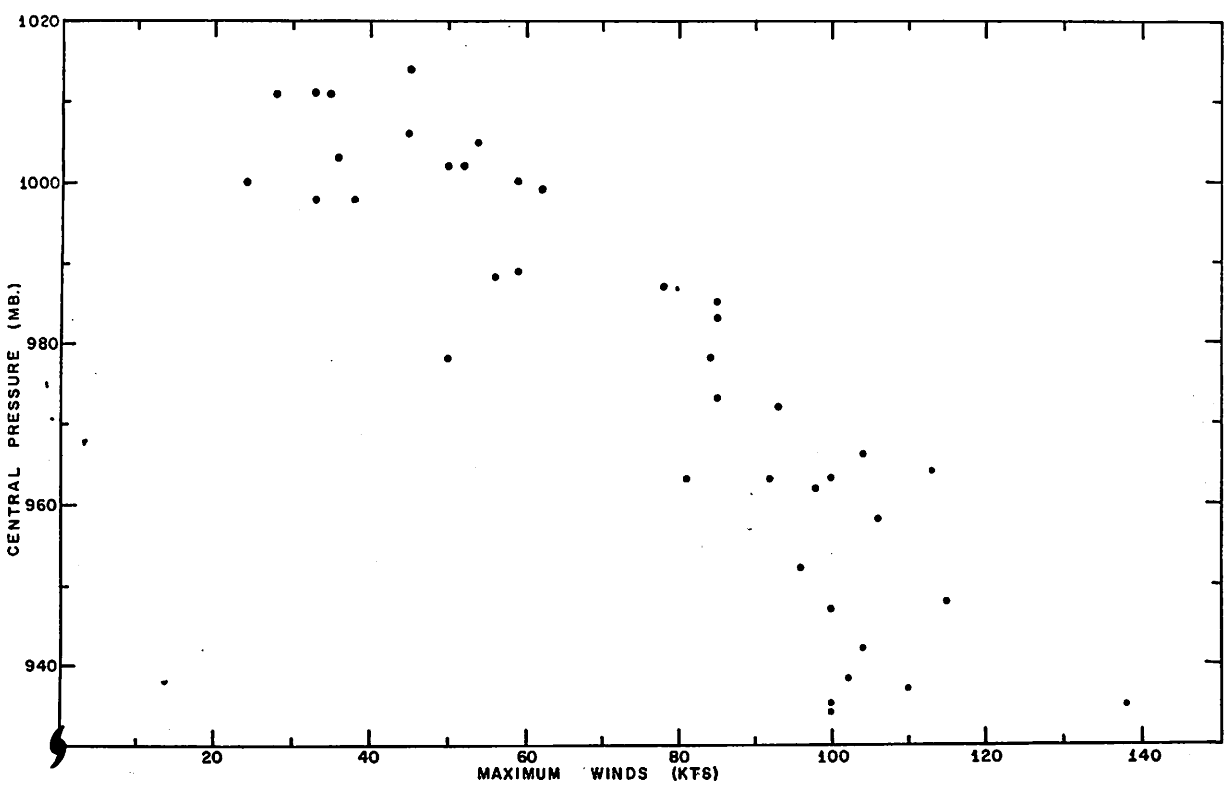

Figure 23. - Relation between central pressures and maximum winds.

The profiles of D-values were actually made at different levels on the three days, but for comparison they have been adjusted to the 700-mb. level. This adjustment was done with the minimum surface pressure and D-value at the center as reference points and use of Jordan's eye extrapolation nomogram (Jordan [7]). This procedure assumes that the horizontal distribution of D-values changes little with altitude in the range between 5,000 and 14,000 feet. None of these assumptions is believed to seriously impair the picture depicted in figures 24 and 25 or the conclusions derived from them.

On the initial day Helene showed a pressure profile in which there was very gradual increase from the center outward to the limit of the data; there was no particular concentration of gradient. The deepening of this pressure field in the next two days was characterized by a more pronounced reduction in the inner core, inside the 50-mi. radius. One consequence of this distribution in the pressure reduction is that the point of maximum pressure gradient was displaced inward as the deepening progressed. Adjustment of the wind and pressure fields would also prescribe a reduction in the radius of maximum winds. In the case of Daisy, the pressure on the initial day showed more reduction in the eye relative to the outside and more concentration of gradient near the center, as would be expected from the distribution of winds. The deepening of pressure with time shows also, as in the case of Helene, a much larger reduction in the eye, which has the effect of increasing the pressure gradient tremendously in the eye wall. In this case, however, because of the form of the profile from the initial day, there was little or no change in the radial position of the zone of maximum pressure gradient and, consequently, little variation in the point of maximum winds.

If the D-value drop at various radii between the initial and last days is expressed in terms of the total drop at the center, it is found that in hurricane Daisy the reduction at the 10 mi. radius (the radius of maximum winds) was 80 percent, at the 20-mi. radius (twice the radius of maximum winds) it was 47 percent. In the case of Helene the depression at the 10-mi. radius was about 97 percent of that at the center, at the 16-mi. radius (the radius of maximum winds on the final day) the depression was about 83 percent and at the 32-mi. radius (twice R_m) the depression was about 49 percent of that at the center. Thus, both in Daisy and Helene more than one-half of the reduction in pressure - and, similarly, of air mass in the vertical column - took place inside a radius equal to twice the radius of maximum winds.

It is implied in the remarks above that in cases where R_m is initially large, a reduction in central pressure (p_o) leads to a reduction in R_m; in cases where R_m is initially quite small, a reduction in p_o has little or no effect on R_m. These were facts of observation in hurricanes Helene and Daisy. It is possible to advance a likely explanation behind this relationship and to visualize further that it should hold, as a rule, in other hurricanes. If we take the position that the pressure field leads the wind field, then, starting with a relatively weak vortical pressure field, as observed in hurricane Helene, a much larger reduction in pressure at the center than outside, would cause an increase in pressure gradient inward from the initial point of maximum wind and gradient. The wind would turn toward lower pressure and accelerate; an increase in wind speed downstream would follow and, eventually, a new state of quasi-balance between maximum

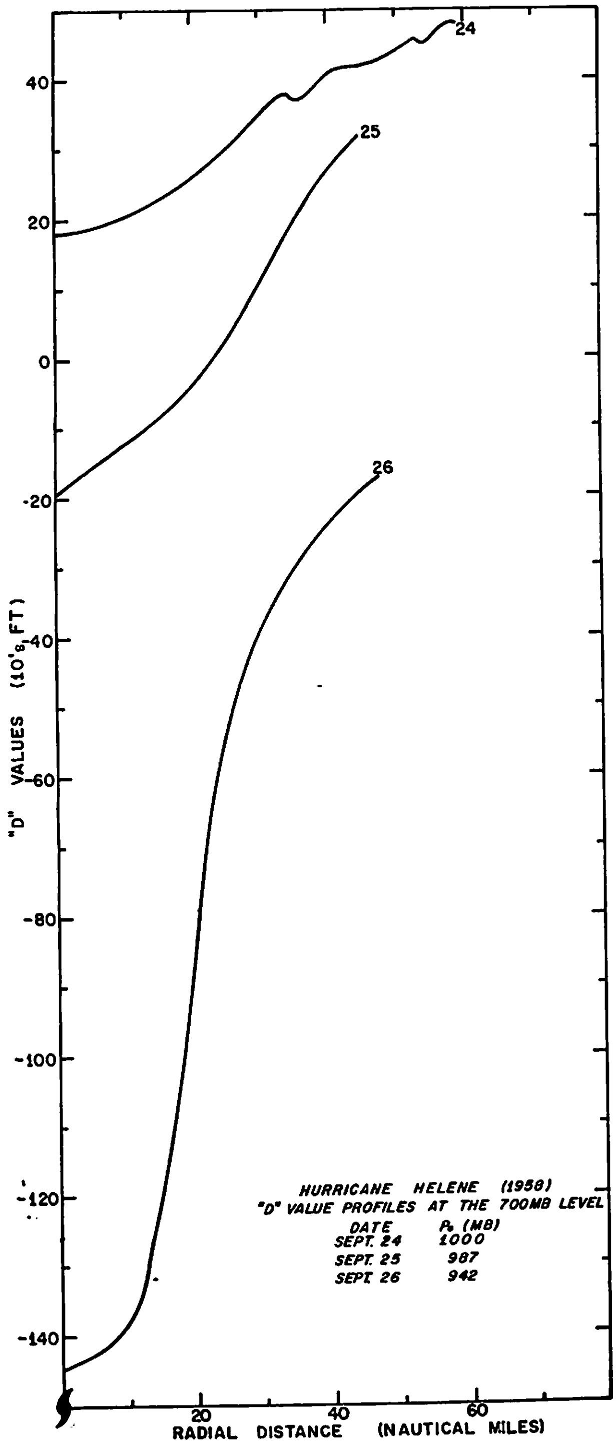

Figure 24. - Profiles of the D-values at the 700-mb. level in hurricane Helene, from Sept. 24 to 26, 1958

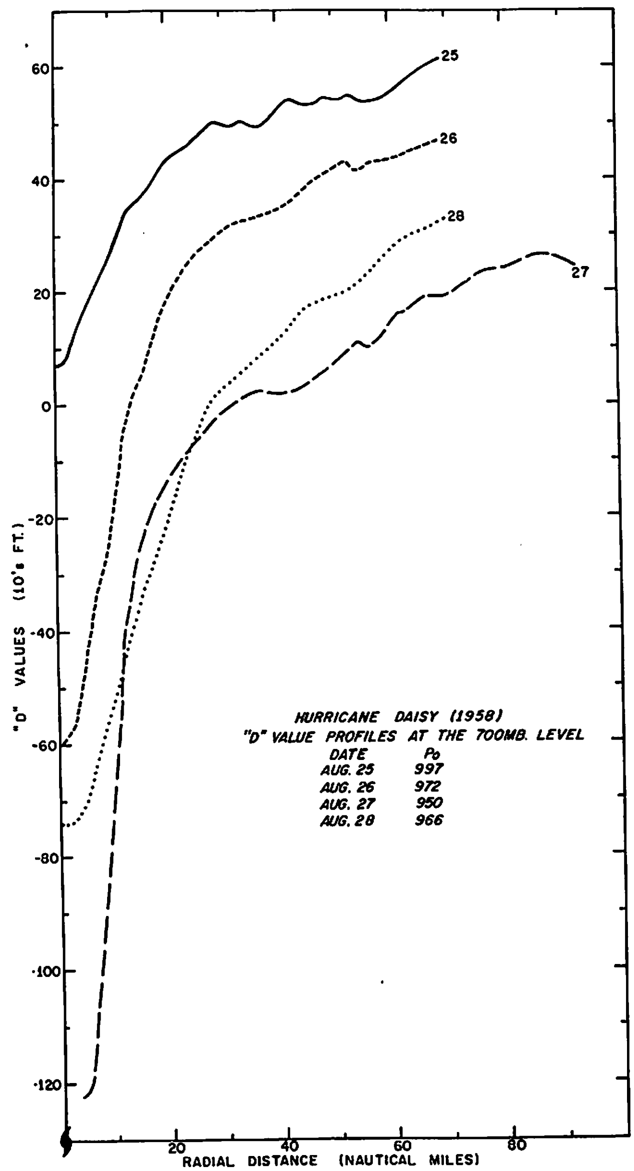

Figure 25. - Profiles of D-values at the 700-mb. level in hurricane Daisy from Aug. 25 to 28, 1958.

winds and pressure gradient would be established in a position closer to the center. Thus, the points of maximum pressure gradient and wind are displaced inward. This process can proceed with continued decrease in p_o. However, as p_o reaches lower and lower values, a situation is approached in which the reduction in central pressure has only a small effect in the distribution of pressure gradient and, consequently, of R_m.

This critical situation was attained in hurricane Daisy quite early in the development stage, and, as observed in figure 25, deepening of the central pressure proceeded with very little change in the position of the maximum pressure gradient, but, naturally, with a large increase in its magnitude.

7. SOME COMMENTS ON HURRICANE GENESIS AND THE EVOLUTION OF THE WIND VORTEX

The most important and difficult question in connection with the observed features on hurricane evolution is how and why they come about and what physical processes guide them. Certainly, more thorough and searching studies are needed in order to assess fully the significance of some of the aspects of the observations, before we even attempt to provide answers to those questions. However, we can offer at this time some comments on certain aspects of hurricane development which are believed to have a bearing on the question of how it happens that hurricanes follow a Daisy or Helene type of evolution. Observations in hurricanes Daisy and Helene and some of the other hurricanes, together with ideas evolved in previous studies, are used as a basis for this discussion. The idea will be explored that the particular type of evolution to be followed by a hurricane is pretty much determined by the sequence of events at the genesis stage in reference to the organization of the eye system.*

From a careful study of the hurricane wind data, one can conclude that the type of vortex depicted by hurricane Daisy on August 27, characterized by a small eye and a sharply concentrated zone of maximum winds located at small radius, is the ultimate type of configuration, or goal, to which the deepening process leads. In the case of hurricane Daisy this type of vortex was arrived at by a growth in place, from an initially small eye system that formed quite early in the development stage. On the other hand,

*To avoid confusion and misunderstanding in terminology, we shall use the term "eye-system" to refer to the eye-wall precipitation band and the eye opening inside. The term "eye" by itself has traditionally been identified with the clear, relatively calm, central area. From the point of view of hurricane dynamics the important feature is the eye-wall band or wall-cloud; that is, the ring of violent convection and strong winds which constitutes the ascending branch of the vertical circulations in the hurricane.

in the hurricanes of the Helene type the observed wind field was evolved in association with a process of gradual diminution and concentration of an initially large eye formation. One might reasonably speculate that if the deepening process in hurricanes Helene and Carla had been allowed to proceed uninterrupted for a longer time, further growth with little or no further reduction in the radius of maximum winds might have taken place. In the case of Carla the intensification stage was obviously interrupted by the approach to, and motion over, a land surface; while in the case of hurricane Helene there were important modifications in the environmental conditions that probably precipitated the onset of the dissipation stage before the maximum potential intensity was obtained (Colón [3]).

The differences between the Daisy and Helene type of evolution seem to have been due simply to the fact that in Daisy the characteristic small eye system was achieved very early in the genesis stage, while in Helene and Carla, it did not form initially but was approached in a slow and gradual way after the system had been in existence for days. In the other extreme, there were cases like storms Frieda, Becky, Fifi, etc., in which a typical eye formation did not materialize and the systems never reached the stage beyond weak storm intensity. There are strong indications that the key to the whole process of evolution lies in the organization of the eye system. It appears also that this organization is largely influenced by convective scale motions (LaSeur [12]).

With this line of reasoning, one can visualize that the formation of the eye-system may not be a passive result of the process of development, but, on the contrary, plays a more active and determining role in the evolution of deep hurricanes. As is well known, the organization of the eye-wall gives rise, in the vertical plane, to two circulation cells with ascent in the wall cloud, descent in the region outside the rain area for one cell, and descent in the eye for the other. The circulation cell in the rain area is positive or energy-producing and supplies the energy for the maintenance; the inner cell in the eye is indirect and driven by the outer one, but the vertical motions imposed by that circulation have an important role in producing the warm temperatures of the eye and play a significant function in the maintenance of the hurricane circulation.

The manner in which the thermodynamic processes in the eye-wall can induce the reduction in surface pressure has been discussed amply in the literature (Riehl [14], Riehl and Malkus [16], Miller [13]). The process can be viewed as an iterative one, in which heat and moisture are added to the air moving inward near the surface by evaporation and eddy conduction. This increases the equivalent potential temperature (θ_e) of the air at the cloud base; moist adiabatic ascent at an increased θ_e brings warming in the vertical column and further reduction in surface pressure (assuming that some upper level, e.g., 100 mb., remains undisturbed). The decrease in surface pressure in turn brings adiabatic cooling of the air near the surface and increase in the temperature differential from sea surface to air. This acts to increase the heat flux from sea to atmosphere, increase θ_e, etc. The reduction in surface pressure near the wall cloud increases the horizontal pressure gradient, and, consequently, strengthens the horizontal field of motion. This increases the roughness of the sea surface which also increases evaporation and sensible heat flux. One of the principal functions of the eye-system lies in providing the organizational framework for a mechanism capable of inducing continued growth of the hurricane circulation. A well-defined and small eye-system provides for a more effective and concentrated action of the thermodynamic engine and a more efficient surface process of surface pressure reduction and kinetic energy generation. It is of interest to notice in figures 24 and 25 that the pressure reduction during the intensification stage of hurricanes Daisy and Helene was largely concentrated in the inner core comprising the eye-wall and eye.

It is our belief that these processes which seem to have prevailed in hurricanes Daisy and Helene may hold true in general in other hurricanes and that the sequence of events at the genesis stage in reference to the organization of the eye-system has a determining effect in the future evolution of the system. In studies conducted in the past, certain properties of the pre-existing perturbation and of the surrounding environment have been identified as being conducive to hurricane development. Among these are the presence of relatively warm waters, a conditionally unstable atmospheric medium, widespread convection and precipitation, a large inflow angle at the surface in the periphery of the low-level perturbation, proper conditions of flow at upper levels that facilitate mass outflow, etc. However, all investigations have led to the disappointing result that while all of these conditions seem to be necessary for intensification, none of them by itself or in combination with others, has proved to be sufficient. Thus hurricane development requires a unique coincidence in time and space of innumerable special conditions, some of which may still be waiting to be discovered. Furthermore, the fact that convective-scale phenomena may at times play a dominant role, brings out the possibility and likelihood that the special set of conditions involve both synoptic and convective scales of motion. One can visualize, then, that in some situations all the special conditions necessary for hurricane generation may be fulfilled at what might be referred to as the ideal or optimum level of effectiveness; the generating process then leads rapidly to the ultimate or goal type of configuration involving a small, well-defined, compact eye-system as occurred in hurricane Daisy. This type of development appears to be more sudden and explosive in nature than the Helene type. In other instances the set of conditions may be somewhat favorable, but not at the optimum level of effectiveness; development would then be slow and gradual and evolve in the manner shown by hurricanes Helene and Carla. Regardless of what physical mechanisms may be in operation, it is believed that the course of events in the initial phase manifested in the formation of the eye-system will determine to large extent the future evolution of the storm and the chances of its becoming a large or small hurricane.

Admittedly the above discussion does not answer the fundamental questions but only attempts to provide a sensible explanation for some phenomena while shifting the unknown to other points. One might ask next, what determines the formation of the eye in the first place? Is it really a determining factor in, or a result of, the process of hurricane generation? How and by what governing mechanisms are the changes in size of an existing eye-system produced? Is the formation of the eye-wall a continuous or a discontinuous process, with convective and synoptic scale phenomena predominating at different stages? All these questions, and others, must be answered in order to obtain a complete understanding of the hurricane problem.

The main aspect of the previous discussion is that emphasis is placed on the early formation of the eye-system. This idea is not entirely new. It was first proposed by Riehl [15]. Other recent discussions stressing the importance of the eye-system on hurricane development were presented by LaSeur [12] and Colón [3]. LaSeur presented a very illuminating discussion of the role of the eye and of convective processes in hurricanes, with documentation for the case of hurricane Judith of 1959.

8. ON THE MATHEMATICAL REPRESENTATION OF THE WIND DISTRIBUTION

The collection of wind profiles under study was examined to see how the profiles fitted into mathematical expressions that have been suggested for the hurricane wind field. For a steady, stationary, and symmetric hurricane vortex, the equation of the horizontal motion in the θ direction (cylindrical coordinates r, θ, z) can be written (Rosenthal [17])

$$v_r \zeta_a = v_r \left(\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} + f \right) = F_\theta - w \frac{\partial v_\theta}{\partial z} \qquad (1)$$

where ζ_a is the absolute vorticity, F_θ represents the frictional forces, and all other terms follow the standard notation. The major difficulty in integrating equation (1) to obtain v_θ as a function of v is that the properties of the radial and vertical motion field, and of the frictional forces are not known with certainty. Riehl and Malkus [16] and Rosenthal [17] carried out numerical integrations of equation (2), or its equivalent, in the inflow layer, by specifying arbitrary distribution of the radial component, neglecting vertical motion and with an empirical treatment of the frictional forces near the surface. The wind profiles obtained in their models are shown in figure 17. Another approach used frequently has been to simplify the equation by ignoring some of the terms. Equation (1) can be rewritten in the form

$$\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} = -f + \frac{F_\theta}{v_r} - \frac{w}{v_r} \frac{\partial v_\theta}{\partial z} \quad . \qquad (2)$$

If in the first approximation the frictional forces and the vertical motion are considered negligible compared to the other terms, the equation is reduced to the expression for zero absolute vorticity, which can be integrated to yield $v_\theta r + \frac{r^2 f}{2}$ = constant. This states the conservation of absolute angular momentum. If the Coriolis parameter is also neglected, we obtain the relation vr = const, the expression for conservation of relative angular momentum. None of these simple expressions has been found to describe adequately the observed wind profiles. A generally adopted procedure has been to express the distribution in the form of

$$v_\theta r^\alpha = \text{constant} \qquad (3)$$

and compute the values of alpha empirically from observed data. From the above discussion one can deduce that alpha is presumably a combined function of the frictional forces, and vertical and radial motions. It follows also that the more the value of alpha approaches 1, the more the combined effect of the terms in the right side of equation (2) approaches zero and the closer the distribution to constant angular momentum. To date, values of alpha of the order of 0.4-0.6 have been reported in the literature (Riehl [14]).

Although equation (3) is an oversimplification of the mathematical problem, it provides a convenient and practically useful form of expressing the wind distribution. Values of alpha were computed for a selection of the wind profiles illustrated in this report by a curve-fitting technique, using least squares. The relative wind profiles were used. Computations were carried out for all cases in which relative winds were available; as a matter of curiosity a few computations were done also for actual wind profiles (table 1).

Values of alpha varied over a large range. The lowest values obtained were 0.23 for the two Carrie profiles. A value of 0.27 was obtained for the Cleo profile. The Daisy profiles gave a value of 0.29 on August 25; there was increase to about 0.5 on August 27 and 28. In general, the Helene type profile yielded values from 0.2 to 0.4 while the Daisy type profiles had values in the range of 0.4 to 0.6. The numerical model of Riehl and Malkus [16] gave a value of 0.52, while that of Rosenthal [17] had a value of 0.59.

In general, in the regions closer to the radius of maximum winds, the wind profile is more steep and if the curve-fitting is limited to that region, a higher value of alpha is obtained. For example, in the profile for hurricane Daisy on August 27 the section from the maximum winds to the 40-mi. radius yields a value of alpha of 0.63, the region from the radius of maximum winds to the 30-mi. radius yields 0.70. Similarly, the inner cores of the Esther and Donna profiles gave values of alpha close to 0.7. A similar, but not as pronounced, tendency was noticed for the profiles of the Helene-Carla type.

9. VARIATIONS IN THE DISSIPATION STAGE

The data recorded by the research aircraft during the dissipation stages of hurricanes have not been as plentiful as for the intensification stage. The existing data indicate that significant filling of the central pressure is invariably accompanied by an increase in the radius of maximum winds, regardless of how the growth process had taken place during the intensification stage. It has also been observed that dissipation is accompanied by a breakdown of the eye-wall system, with the result that the eye representation on radar resembles the disorganized configuration shown occasionally in the formative stage. The wind data obtained during the dissipation stage in hurricane Daisy (fig. 26) show that in addition to an increase in the radius of maximum winds there was a spreading out of the high kinetic energy core, with the result that the wind flow actually increased at some radii. The increase in the radius of maximum winds was also accompanied by a reduction in the anticyclonic shear, as would be expected from the discussion in Section 8.

Another set of data recorded in the dissipation stage is that for hurricane Carrie (fig. 15), which shows also the increase in eye diameter and energy spread outward. In this case the data show actually a slight increase in the maximum winds, but it is difficult to assess the significance of this increase.

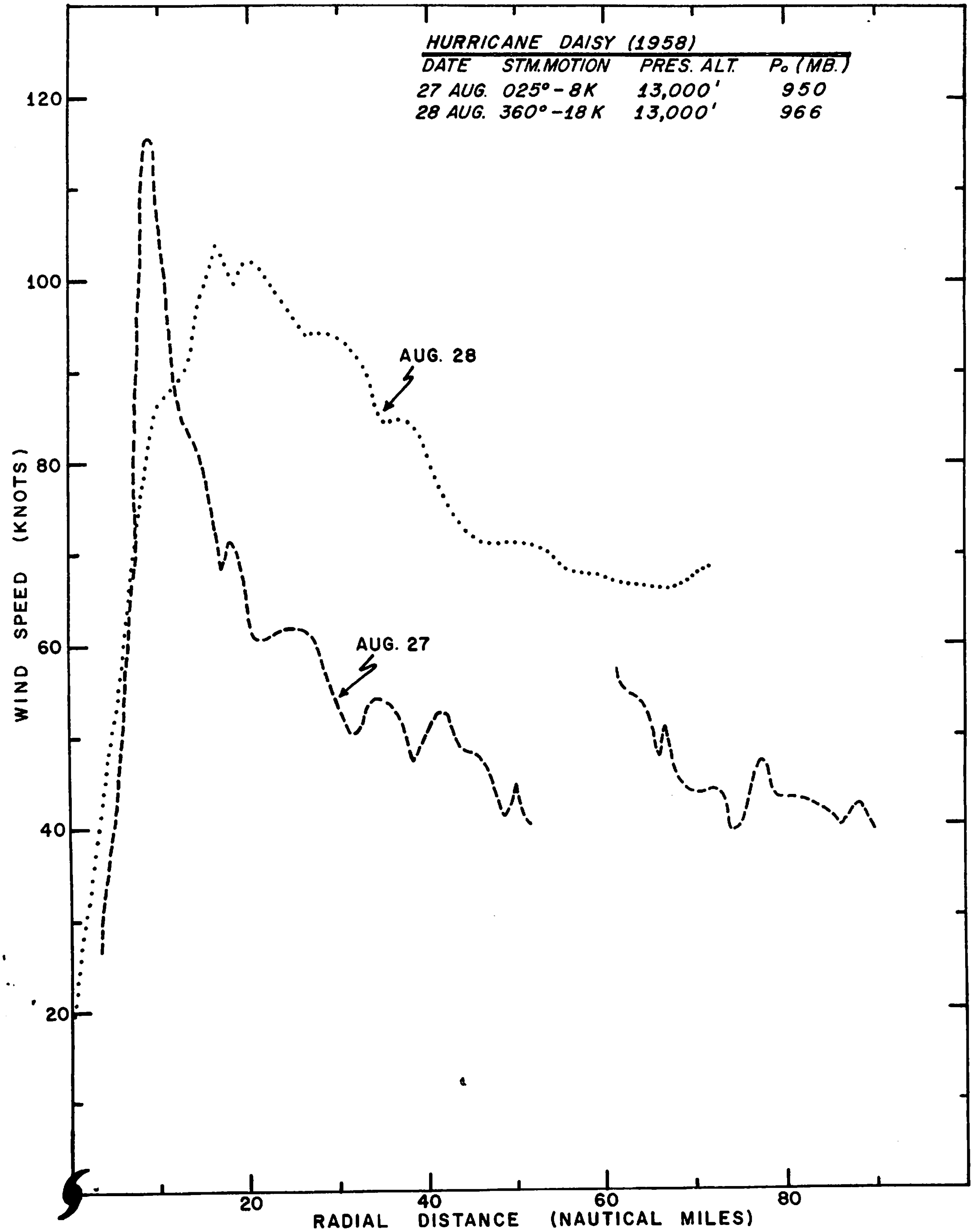

Figure 26. - Wind profiles in hurricane Daisy on Aug. 27 and 28, 1958.

One important fact that has been observed by this writer is that the dissipation does not usually proceed as fast as the intensification and that, except in some cases of motion over land, hurricanes tend to retain their strength for a long period of time. This has important practical considerations in forecasting the effect of dissipating hurricanes in land areas far north in middle latitudes. One important observation in this respect is that the wind strength in the region outside the core may actually increase as the central pressure increases. This also indicates that hurricanes may grow in size in the dissipating stage.

10. CONCLUSIONS

Representative wind profiles obtained in the right semicircle of hurricanes have been studied and analyzed. It was found that hurricanes seem to fit, in greater or lesser degree, into two types of wind vortices. One is illustrated by hurricane Daisy (1958), and is characterized by a small radius of maximum winds, narrow wind peak, and strikingly large values of anticyclonic shear outside the radius of maximum winds. The other type of wind vortex, illustrated by hurricanes Helene (1959), Carla (1961), and Cleo (1958) is characterized by a larger radius of maximum winds, a lack of concentration of speed in the eye-wall, and very gradual decrease of winds outside. By its very nature the Daisy type of wind vortex depicts a small hurricane (areally) while the Helene vortex illustrates an extensive hurricane. It was found that the Daisy type of wind vortex tends to be associated with hurricanes that have rather rapid genesis and are generated in such a manner that the radius of maximum winds is initially small and remains nearly constant during the intensification stage, regardless of the magnitude of the changes in central pressure. The Helene-Carla type seems to have a more gradual development, and is generated by a growth process in which the radius of maximum winds decreases markedly during the intensification stage.

In the sample of cases that attained hurricane intensity, the two types occurred with about equal frequency. Those cases that only attained tropical storm intensity displayed a wind field that resembled the initial stages of the Helene-type. It lacked the characteristic organization with a well defined radius of maximum winds.

An attempt was made to explain the origin of the differences between the Daisy and Helene type of hurricanes by postulating a sequence of events for the genesis stage. These ideas on genesis were evolved from an analysis of the observations in the cases of Daisy, Helene, Carla and other hurricanes. The genesis model is hinged on the organization of the eye-wall and eye, and on the manner and rapidity with which this organization takes place. It is suggested that if conditions are at an ideal level of effectiveness, the process of hurricane growth will tend to the generation of a small eye-system and radius of maximum winds. If this is accomplished initially, development will proceed in the manner of Daisy with little change in eye diameter. If, on the other hand, conditions in the pre-existing perturbation and surrounding atmosphere are somewhat favorable, but not ideal, then the process of development is slow; a large eye with a large radius of maximum winds is generated, which then tends to concentrate inward with intensification. The point of whether the generation of the characteristic eye-wall is produced by, or is a necessary ingredient in, the process of intensification is open to controversy, but the writer is inclined to the view that a true hurricane system with the potential for growth into deep intensities does not exist until the eye system — eye-wall and eye opening — has acquired the characteristic definition. The role of the eye-wall lies in that it provides for the organization of the vertical circulations in the hurricane rain area and permits concentration of the processes leading to the reduction of the surface pressure in a small area where they are more effective.

The generation of the eye-wall is looked upon as being strongly dependent on air motions in the convective scale. Consequently, one may raise the question as to whether the formation of a convective phenomenon of this type at a specific place and time is completely predictable or whether events influenced in some way by chance enter into play.

Regardless of the future elucidation of these aspects of hurricane genesis, some of the facts of observation concerning hurricane evolution discussed here must be taken into account in the study and development of theoretical and numerical hurricane models. Also some of the ideas may be put to fruitful operational use. For example, early determination in the developing system of the organization of the wind field and radius of maximum winds may be used for a sensible forecast concerning the future size of the system. If there is an early eye formation with a small radius of maximum winds and the system is moving in a favorable medium rapid development of deep intensity and generation of a small vortex should be expected. If the wind field initially is such that the eye is wide and disorganized and the radius of maximum wind is large, more gradual development resulting in an extensive hurricane should be predicted. But, once the inner eye-wall band, with the associated zone of maximum winds is organized and has attained a clear-cut arrangement, then, regardless of whether the eye-radius is minimal or not, rapid drop in the central pressure should be expected, unless the system is moving into a clearly unfavorable area (like a land area, extremely cold waters, etc.)

Computations of mathematical representations of the wind profiles with the formula $v_\theta r^\alpha =$ const. yielded values of alpha ranging from 0.2 to 0.6. Vortices of the Daisy type yielded values of alpha from 0.4 to 0.6, and vortices of the Helene type were adequately described by values in the range 0.2 to 0.4. In order to use this expression to calculate the maximum winds given a representative value in the periphery, one would need to know the type of vortex one is dealing with, and also the values of maximum winds.

The information available during the dissipation stage of hurricanes indicates an increase in the radius of maximum winds - or eye diameter - during dissipation, accompanied by an outward growth of the wind vortex.

Table 1. - Values of alpha to satisfy equation (3)

Storm - Date	Value of Alpha: relative wind profile	Value of Alpha: actual wind profile
Daisy (1958):		
25 August	0.29	0.27
26 August	0.44	0.43
27 August	0.48	0.45
28 August	0.52	0.37
Helene (1958):		
25 September	0.42	0.31
26 September	0.39	0.33
Carrie (1957):		
15 September	0.23	0.18
17 September	0.23	0.20
Cleo (1958):		
18 August	0.27	0.18
Janice (1958):		
8 October		0.60
Ione (1955):		
17 September		0.47
Anna (1961):		
21 July		0.37
Esther (1961):		
16 September	0.71 (inner 30-mi. sector)	0.59 (inner 30-mi. sector)
Donna (1960):		
7 September		0.51
Riehl and Malkus model:	0.52	
Rosenthal model:	0.59	
CARLA ?	.1-.2	.1-.2

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