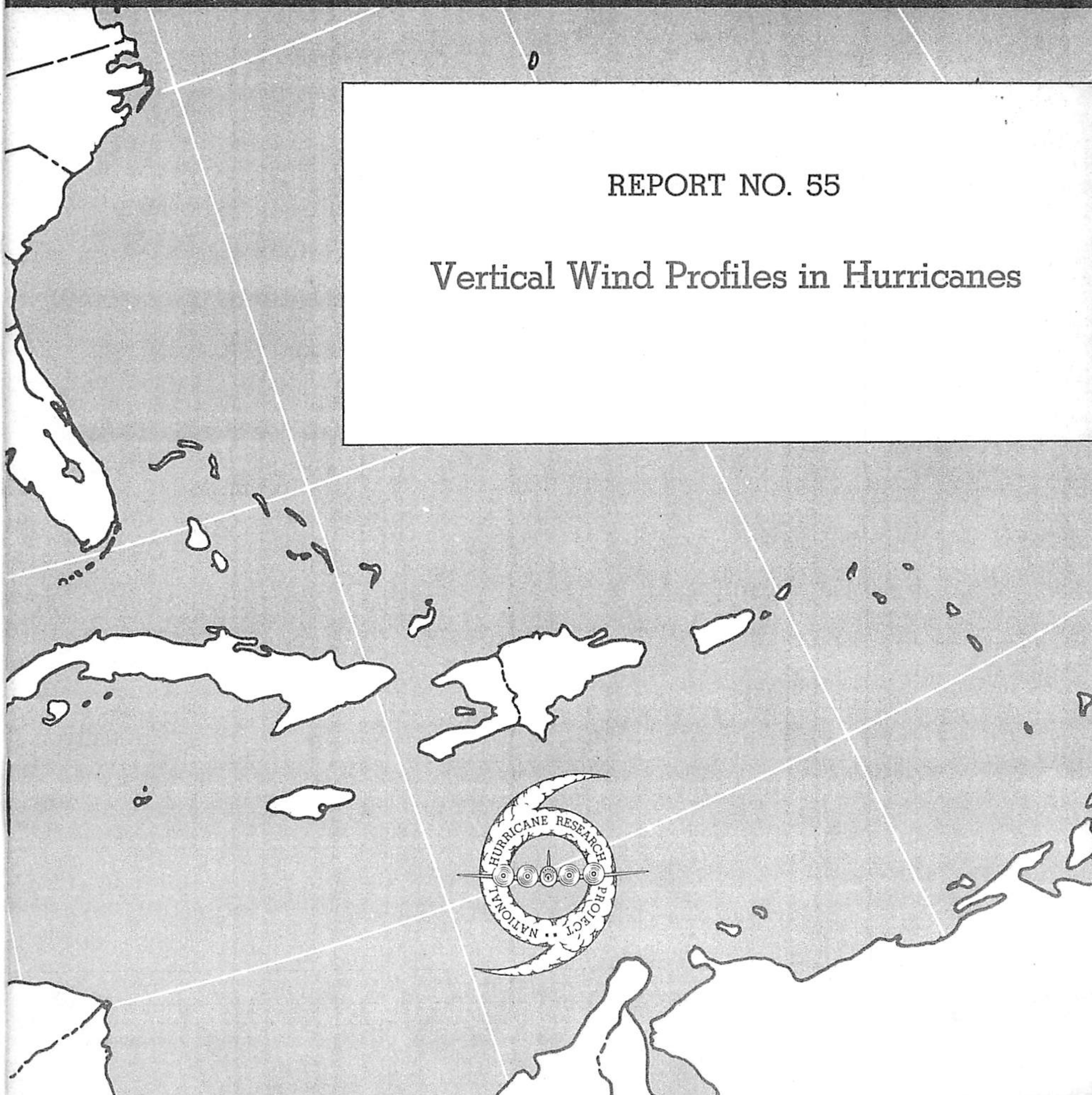
NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 55

Vertical Wind Profiles in Hurricanes



U. S. DEPARTMENT OF COMMERCE
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WEATHER BUREAU
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NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 55

Vertical Wind Profiles in Hurricanes

by
H. F. Hawkins
National Hurricane Research Project, Miami, Fla.

Washington, D. C.
June 1962

NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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VERTICAL WIND PROFILES IN HURRICANES

Harry F. Hawkins, Jr.
National Hurricane Research Project, Miami, Fla.

1. INTRODUCTION

Investigation of the vertical wind structure in hurricanes serves the dual purpose of practical necessity and research. From the practical viewpoint, it is essential that the forecaster be supplied with fairly accurate information as to the intensity and areal extent of damaging winds at low levels (preferably the ground level). Lack of such information must lead either to inadequate hurricane warnings or to overwarning - either of which is unsatisfactory to the public. It is, in a way, a meteorological irony of our time, that the advent of radio and marine broadcasts has so affected shipping procedures that very few ships are now caught in these storms and only rarely is there available any reliable estimate of strong surface winds from these sources. Before the initiation of aircraft reconnaissance, this meant that the forecaster had, on many occasions, to judge and estimate the storm by peripheral data alone. Only when and if the storm made a landfall, was an adequate description of the surface wind field apt to become available.

During most of the period of aircraft reconnaissance (and to some extent even today), flights were carried out at low altitudes - often below cloud base, except where this was unfeasible. In such operations wind speeds could be estimated with considerable accuracy through continuous observations of the state of the sea. Tables and photographs relating characteristic states with wind speed were prepared. Navigational checks and drift readings were used to supplement these estimates. As the demand for more continuous and farther ranging reconnaissance increased, recourse was had to larger and faster planes. Experience indicated that these should be employed at higher levels, for safety reasons 5,000 to 10,000 ft., and to meet meteorological requirements 18,000 to 20,000 ft. In the high-energy core of the hurricane, clouds and rain obscure the sea almost all of the time from these heights. In addition, when viewed from 10,000 ft. or higher, the sea is seen in different perspective so that the brief available glimpses are difficult to evaluate. However, at flight level the winds may be known with from fair to high order accuracy depending on navigational aids utilized and the availability of automatic navigation equipment. The problem is then reduced to making reliable estimates of the sea level wind speeds from the known speeds at flight levels.

The theoretical uses to which knowledge about the vertical wind structure in hurricanes can be put are many and varied. At one time the recognition of the hurricane as a warm core phenomenon led to a belief that the storm disappeared quite rapidly with height. Calculations by Haurwitz [1] indicated clearly that hurricanes of significant intensity maintained their identity through most if not all of the troposphere. Given adequate data on the thermal structure, one can calculate the pressure or contour field at any level if the fied is defined at one level. However, the relation of the winds to contour gradients and the vertical variations in this relationship, the asymmetry in the wind field and its vertical variation, implications of vertical motions as deduced from the vertical wind structure; all of these and more, make determination of the vertical wind structure academically valuable. It is not believed, however, that the vertical shears established and treated in this paper are adequate for the computation of lateral and vertical frictional stresses.

The present paper consolidates and extends the original work reported on by the author at the Joint AGU-AMS Meetings held in Washington, D. C. in May 1958. It is anticipated that the main practical purpose served by this report will be in the estimation of low-level winds over the ocean when flight level winds are available - in moderate, mature hurricanes.

2. DATA

At present the only reliable means by which the vertical wind relationship can be established is through utilization of the unique NHRP collection of data. These data have been gathered by aircraft (usually three) making multi-level traverses through the core of the hurricane along preselected flight tracks. In addition, the flights are planned to achieve approximate simultaneity so that radial profiles are nearly synoptic in time. Since not all flights were planned with these particular criteria in mind, only a limited amount of the NHRP data are suitable for these particular purposes.

Figure 1 is illustrative of the spatial and time separation which was considered acceptable. Data were gathered at three levels: 6,400, 15,600, and 35,000 ft. pressure altitude.* Adjacent radial passes did not lie directly one above the other but it can be readily seen that the spatial separations were not great. The two TB-50's at the lower levels cruised at approximately the same power settings but at different speeds because of the difference in altitude. At the upper level, the B-47 (jet) traveled much faster. This means that, of necessity, the time separation of data gathered at the different levels varied throughout the data collection period. If the storm is in a reasonably steady-state condition , objections to the time difference may be minimized. However, due to the convective and violent nature of the hurricane, one must treat such assumptions with extreme caution and accept the data with reservations.

Nature and characteristics of the wind data.

Having satisfied reasonable requirements as to space and time differences acceptable in the data to be utilized, it was proper to examine the nature or characteristics of these data. The wind observations were produced aboard the aircraft by a small computer linked to the APN/82 Doppler Navigation System. The following statements may be offered concerning the winds thus obtained [2,3].

1. Wind observations were available as often as one every 2 seconds.

2. The Doppler antenna balanced return echoes to a null reading by rotation. This continuous hunting introduced small very-short-term fluctuations

*Pressure altitude is referred to the U.S. Standard Atmosphere throughout this paper unless otherwise noted.

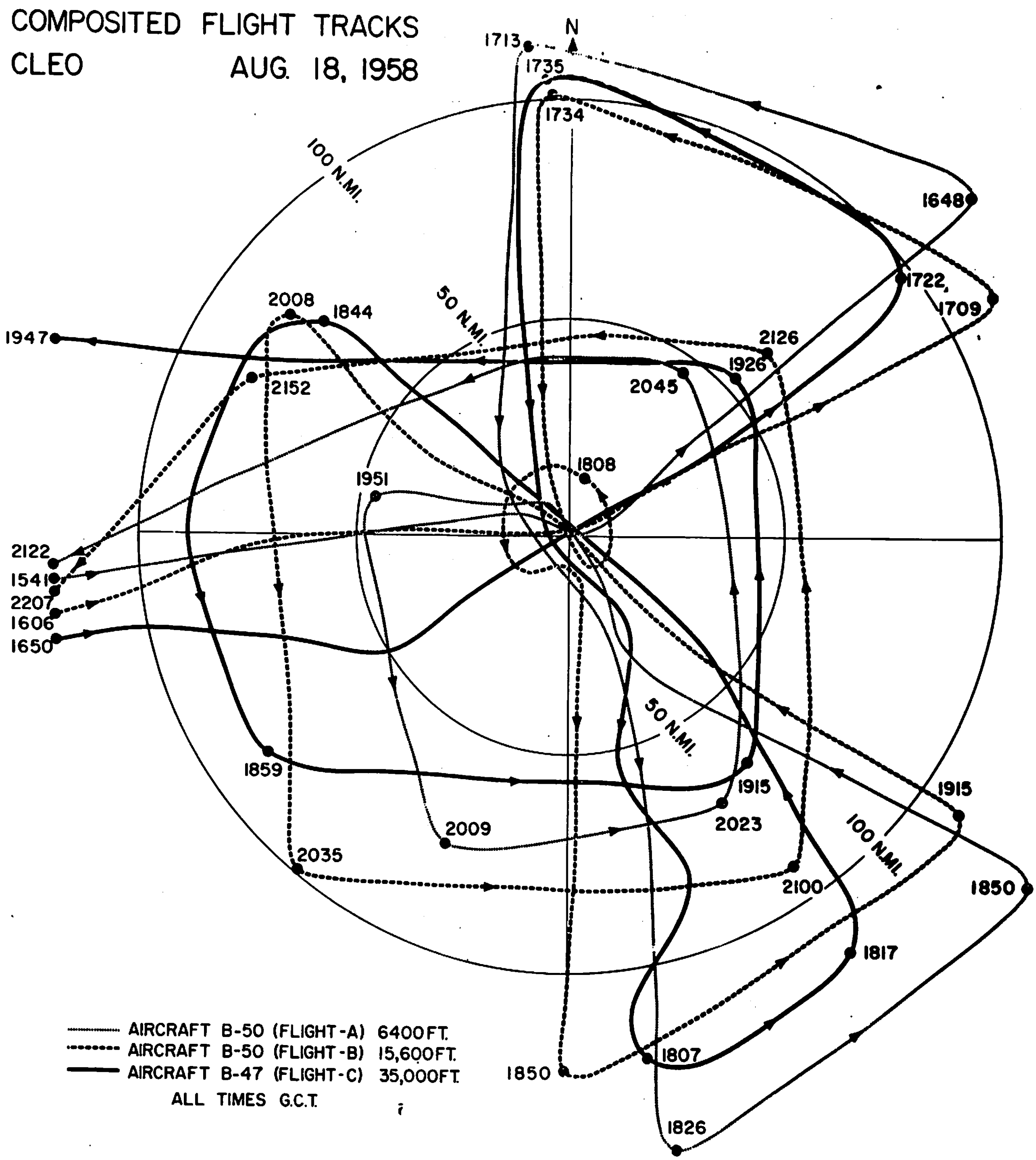

Figure 1. - Space and time separation in the reconnaissance of hurricane Cleo. Wind speed profiles were prepared from each flight level for all of the radial passes. With rare exceptions they were treated as synoptic in time and vertical in space.

in the wind speeds. Such small-scale oscillations in the range of 2 to 10 seconds could not be considered real.

3. The Doppler systems used on the NHRP research planes were especially designed for fast response. Bench tests indicated the maximum response to a change in wind direction was 2.6° per second and this rate of slewing was attained in 4 seconds. For changes in wind speed, a maximum response of 6.6 kt. per second was reached in 3 seconds. While horizontal wind shear and curvature in the free air are by no means negligible, the B-50's flying at 220 kt. travel only 750 ft. in 2 seconds. It is maintained that the aircraft wind data are at least as accurate (after post flight calibration) as rawinsonde winds and that spot values represent a 3-5 second average; i.e. about a 1/4 to 1/2 mile average wind. Examination of hurricane eye penetrations where strong shears are common - from the ring of maximum wind to the much calmer eye - reveals that only very rarely have slew rates (for speed) approached the maximum.

4. When used over open water, Doppler systems suffer a well recognized deficiency, i.e. they measure only relative to the surface beneath, which is presumed to be stationary. Thus, the winds computed by the APN/82 are in error by an amount equal to the net water transport which characterizes a considerable area beneath the plane. The correction, if known, could be made by adding a vector (equal to the net transport) to the computed winds. In near simultaneous flights over the same or adjacent ocean areas this effect should be approximately the same for all three planes (at three different altitudes). The total error introduced should be similar to that made by decreasing the wind speed at each level by a relatively small (compared to hurricane winds) amount.

With the wind speeds recorded once every 2 seconds, detailed features in the profiles were readily available. Figure 2 shows the 2-second observations from the inner eye-wall of hurricane Carrie (solid line). Small-scale fluctuations of 2-3 kt. over intervals of 2 to about 6 seconds were quite common. The dashed line in figure 2 indicates the profile obtained using only every fifth observation, i.e. one observation every 10 seconds (about 2/3 n.mi.). The salient features are still well represented but relatively minor oscillations are still common. These "meso-scale" features may, of course, have been quite real on occasion but if comparison was to be made with winds observed 5 miles away, one-half hour later, and 10,000 feet higher, it was clear that features of this scale had to be eliminated. Smoothing was begun by using running averages of the 10-second observations over 5 n.mi. (measured radially).

An example of the result of such processing is shown in figure 3. Dots show 5-mi. averages of wind speed gathered in a pass at 14,000 ft. (pressure altitude) in Carrie (September 15, 1957) at 2140 GMT. Crosses show the same parameter in a pass made in the same left front quadrant about 2 hours later. The solid curve was considered to be a representative mean profile for this period. That the double peak of speed was a reasonably steady synoptic feature was testified to by similar characteristic shape of the profiles at 19,000 and at 1,500 feet (except the latter penetration was limited to those areas where winds were 65 kt. or less).

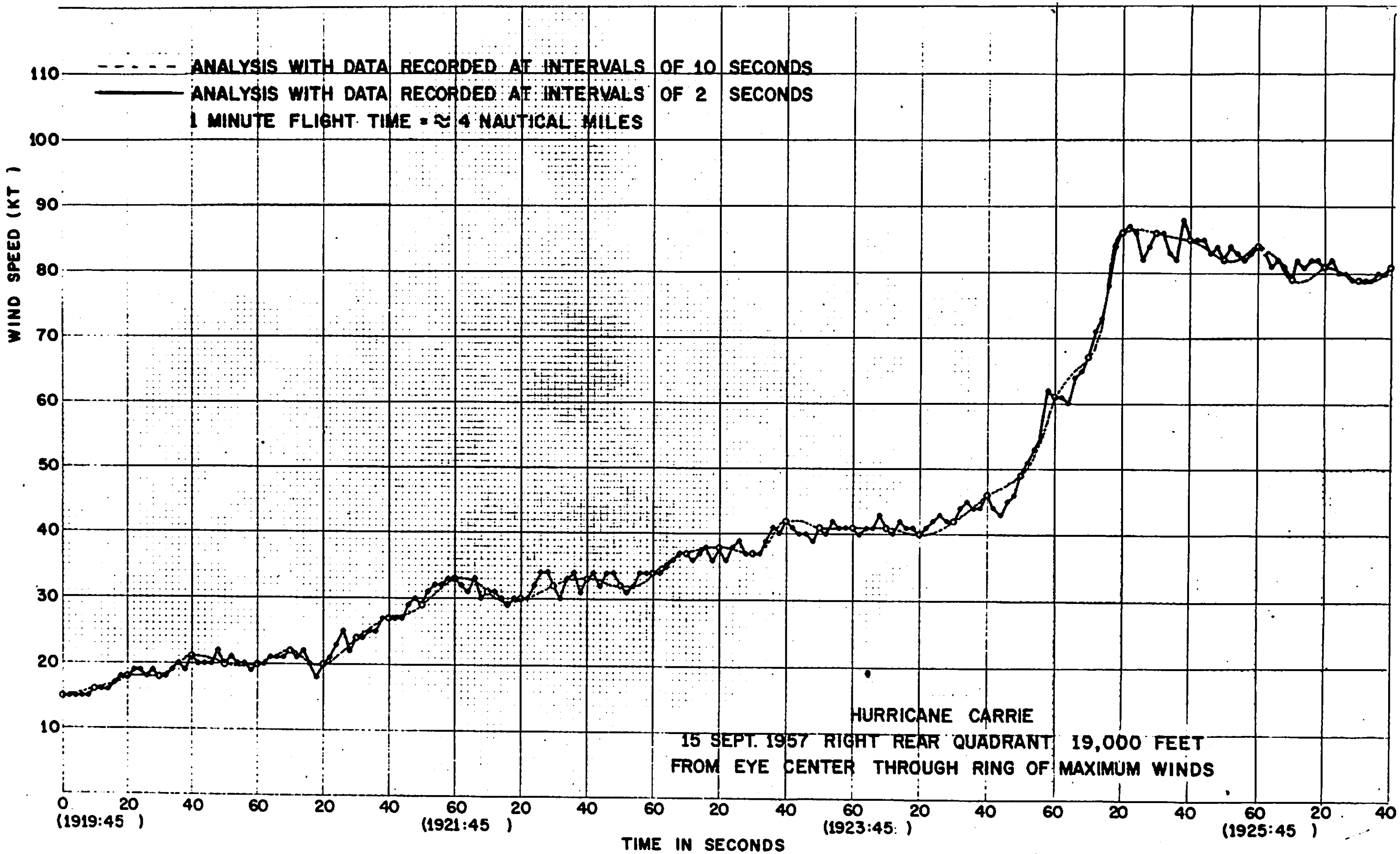

Figure 2. - Variations in wind speed based on observations taken at 2- and 10-second intervals. Note small-scale fluctuations in wind speed in observations taken every 2 seconds (solid line) and residual oscillations when 10-second interval (dashed line) only was retained.

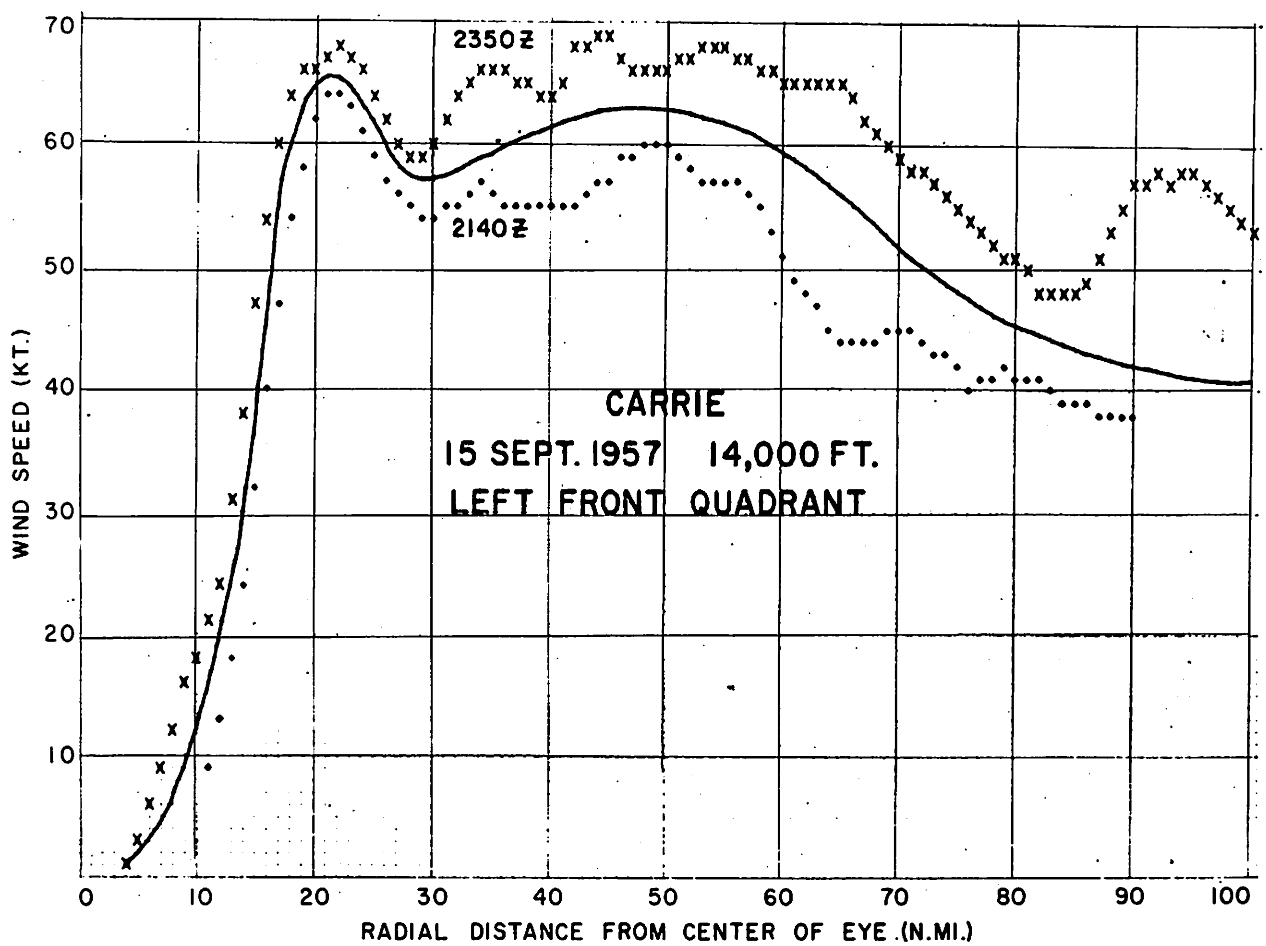

Figure 3. - An extreme example of subjective profile smoothing (solid curve). Ordinarily successive passes from the same quadrant did not produce profiles as dissimilar as those shown.

Vertical data coverage.

Examination of the data available in the vertical showed that coverage from 5,000 to 35,000 ft. was relatively good. Also some data were available down to 1,500 ft. All sets of low-level data were carefully evaluated even if only portions of profiles were available. The main objective here was to establish as firmly as possible the shears from 1,500 ft. to 5,000 and 10,000 ft. It is believed that this relationship was reasonably well determined within the limitations of the data which include the necessary smoothing and steady state assumption. No data from heights less than 1,500 ft. were employed in this study.

Thus, in essence, the shears treated were between the smoothed wind fields at the various levels. The winds have been deliberately smoothed to retain only "synoptic scale" wind variations. It was reasoned that the 1,500-ft. winds so smoothed may well be equivalent to 5-min. average winds observed at sea level. The prevailing level of speed at

1,500 ft. should certainly be greater than that observed at sea level when considered over a comparable radial distance and the actual shear in this area is a matter of great importance. However, available data were not suitable for the solution of this problem. Nevertheless, it seems reasonable to hypothesize that the winds generally obtained at 1,500 ft. are carried down to the earth in gusts due to the turbulence which characterizes the eye-wall and the spiral bands.

Upper-level wind reports were available from 35,000 ft. pressure altitude, i.e. about 240 mb. Consideration of these data for hurricanes Carrie and Cleo clearly demonstrated that at this level much of the closed cyclonic circulation of the storm had disappeared. Therefore, no meaningful relation to the total observed wind was possible. Consequently, only the tangential component of the wind was considered in the data obtained at elevations above 30,000 ft.

Data coverage relative to classes of hurricanes.

It has long been recognized that hurricanes vary greatly one from another. The intensities as measured by maximum wind speed and central pressure cover a wide range from the minimum 64 kt. and about 995 mb. to 150 to 200 kt. and perhaps 890 mb. The vertical extent of the storm is a function of the minimum pressure and the temperature distribution. Observations now available indicate that the deeper more intense storms maintain an inner core of strong cyclonic circulation up beyond 250 mb. Consequently, meaningful average wind shears must ideally be defined for various categories of hurricanes.

In examining currently available data it was clear that the most adequate coverage was provided for a so-called average hurricane. Thus, the bulk of the data treated in this report were gathered in Cleo, August 18, 1958, and in Carrie, September 15 and 17, 1957, with some data from Betsy, August 14, 1956. On these occasions the conditions of nearly identical radial passes and approximate simultaneity were reasonably satisfied. Portions of passes from other storms have been incorporated where the pertinent conditions were satisfied. Since the data were gathered at a rapid rate, each pass at a given level contains hundreds of observations. Thus, in a sense, the quantity of data available was quite large but limited principally to two hurricanes (Cleo and Carrie) which were of approximately the same strength (970 and 975 mb.). Moreover, these storms were both mature hurricanes at relatively high latitudes (near 30°) and were near or in the recurvature stage. This uniformity of the sample was helpful in that the storms were quite comparable but at the same time limits the range over which results may be applicable.

3. PROCEDURE AND RESULTS

One of the incidental difficulties inherent in the comparison of hurricanes is their variation in size. The ring of maximum winds may vary anywhere from about 15 to 50 n.mi. or more in diameter. Consequently, comparison of profiles on a true scale of radial distance is impossible, i.e. the shear inside the eye of one storm cannot be compared with the shear in the turbulent updrafts in the wall cloud of another. To eliminate this difficulty, comparisons are usually standardized and radial distance is normalized in terms of the radius of maximum winds (R_m) . While comparisons are thus rendered more facile there

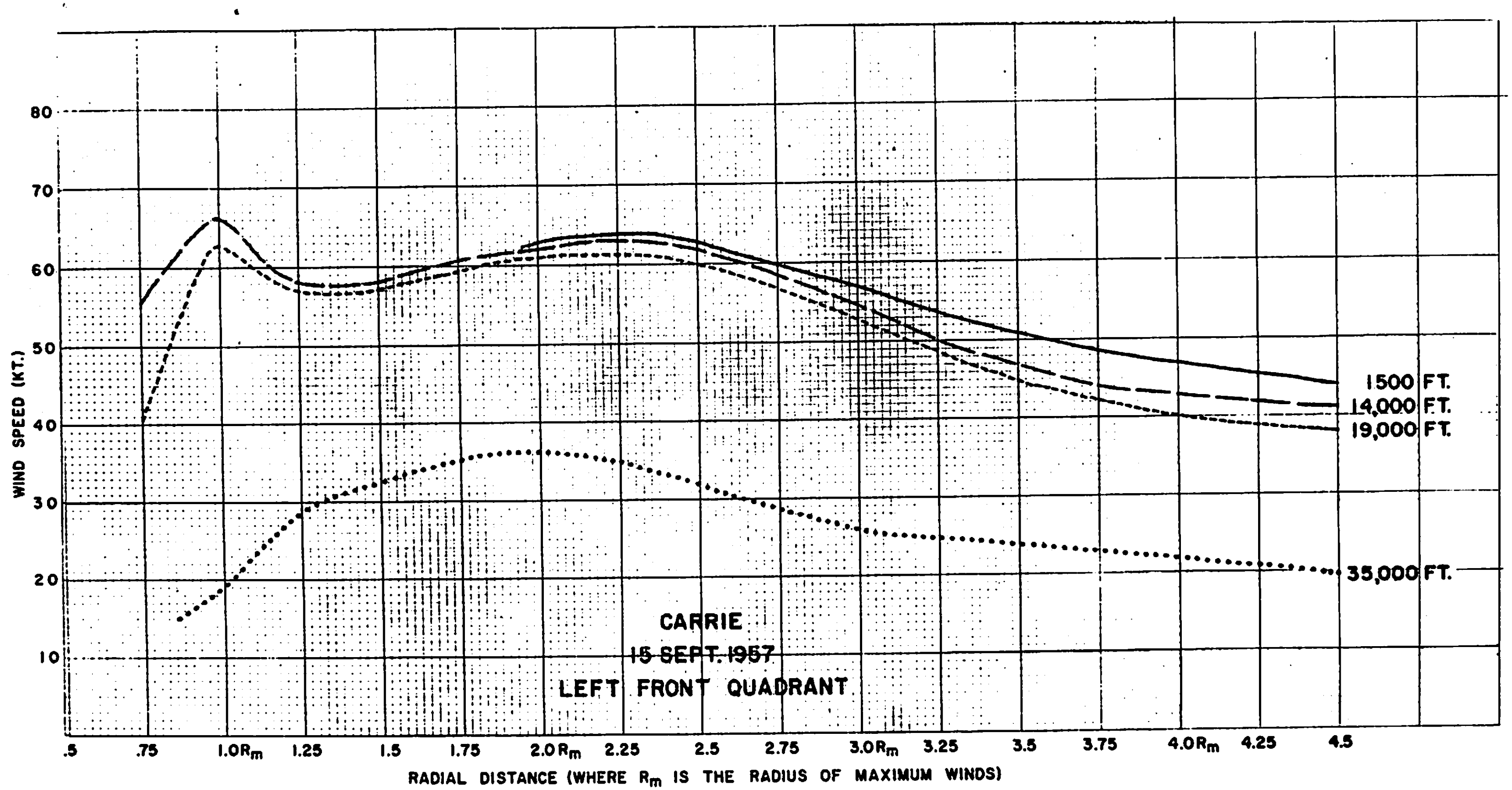

Figure 4. - Smoothed wind speed profiles from four levels in the left front quadrant of Carrie; tangential component only has been retained at 35,000 ft.

seems implicit in this device an assumption that the scale of all processes in a hurricane varies with eye diameter. Undoubtedly some of the phenomena do vary in this manner but it is extremely doubtful that the horizontal scale of say, the convective activity, varies directly with the eye diameter. This being so, one must accept with reservation any relations tentatively put forward at more remote distances from the eye wall. The most meaningful shears may eventually be expressed in terms of eye-wall and spiral bands and relative orientation to such well-defined physical features. Figure 4 shows the smoothed wind profiles from the left-front quadrant of hurricane Carrie (1957) and illustrates the form of the data used to derive the vertical shears.

The winds, previously defined, were plotted at their proper altitude at the correct multiples of the radius of maximum winds. The winds were then expressed in the form of the percentage reduction in wind speed per thousand feet from one elevation to the next higher where data were available. The variation of reduction with elevation and radial distance was analyzed. Since all of the data were from moderately intense, closed vortices, with solid wall clouds, no stratification by quadrant or open vs. closed sector was attempted. By adjustment, interpolation, and cross checking an average relationship was obtained. Since the major use of the nomogram (fig. 5) may be to estimate low-level from flight-level winds, the reciprocal relationship has been retained for presentation here. The percentages were not all expressed in terms of the maximum wind itself since the profiles were by no means identical even when expressed in terms of normalized radial distance.

Figure 5 shows the mean relationship for mature hurricanes of average depth. It may be noted that speeds in the wall cloud (1.0 R_m) weaken very little up to about 25,000 ft. However, above this height they fall off rapidly and at 35,000 ft. are only about 1/3 of their low-level maximum. The maximum winds at upper levels (around 35,000 ft.) are displaced outward (at least in terms of percentage of surface wind) and the total shear is at a minimum at about twice the radius of maximum wind. Wind preservation with height is well marked below 20,000 ft. and out at least to 2.5 R_m.

The effective relation depicted in figure 5 was originally established with the Carrie and assorted supplementary data. Cleo (1958) afforded an opportunity to corroborate and modify the findings. The general agreement was excellent and lent strength to the hypothesis that the relationship was a stable one. The original diagram was modified slightly to include all of the Cleo data.

An illustration of what the "Schematic" relationship implies in a specific example is shown in figure 6, the complete vertical cross-section for hurricane Cleo (1958) [4]. Checks against the nomogram reveal that in almost all regions one can estimate the 1,500 ft. winds within about 10 percent from any given flight level below 25,000 ft.

Probably the poorest defined area in the existing data (for mature average hurricanes) is to be found in the region from 24,000 ft. to 33,000 ft. where few flights have been conducted because of operating limitations of the aircraft employed. For the average mature hurricane this layer is one of considerable interest because most of the shear lies within its confines. Further, in this class of hurricanes the vortex circulation at 35,000 ft. is too weak

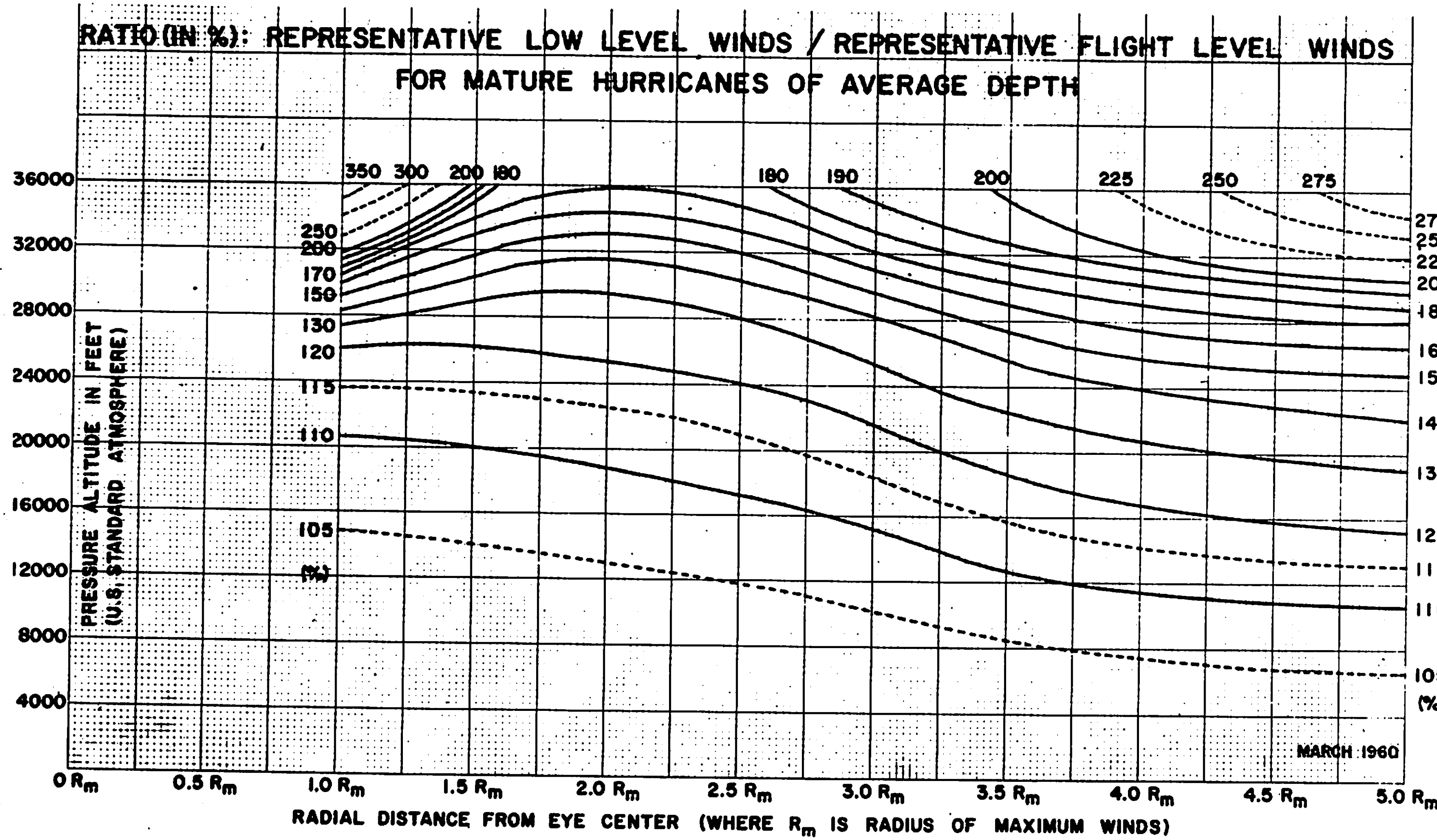

Figure 5. - Nomogram showing (for mature hurricane of average depth) the percentage by which any representative flight-level wind should be increased to estimate low-level winds.

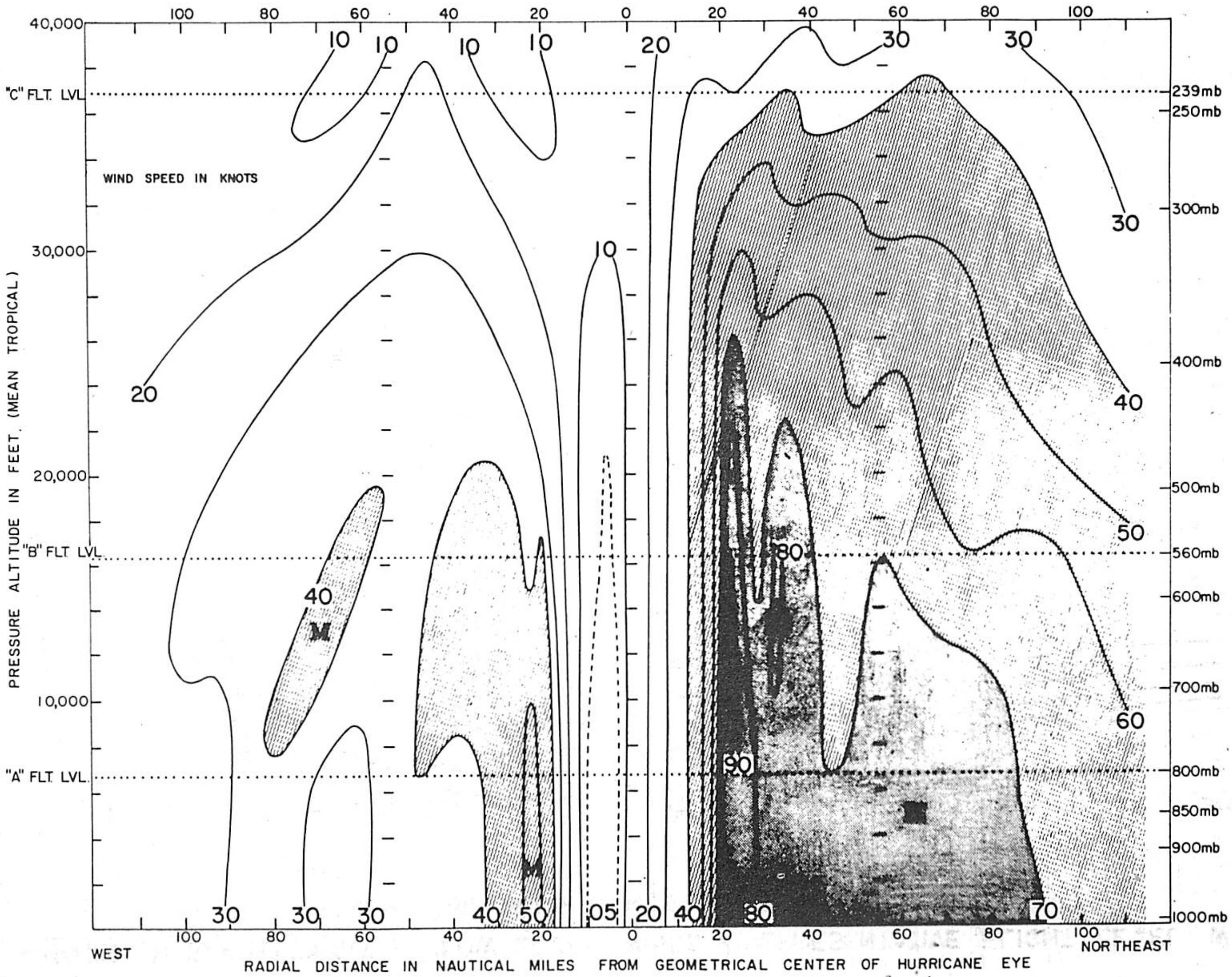

Figure 6. - Vertical cross-section of wind speeds, hurricane Cleo, August 18, 1958. Winds of significant speed did not extend outward any great distance in the left (western) quadrants.

and variable to be utilized effectively as an index of lower-level circulation. It is possible, given more relevant data, that a useful relationship could be developed between the ring of maximum winds at 35,000 ft. and that at 1,500 ft. but in the outer areas of the weak upper-level vortex the circulation is apt to be dominated by the synoptic-scale pattern.

As a consistency check using the best data-set available, the observations gathered in Cleo were subjected to the following test of the shears observed. Figure 7 shows the essence of this work. On the left are the mean D-value (radio altitude minus pressure altitude) profiles from Cleo for the lowest (800 mb.) and highest levels(238 mb.) for which data were available [4]. The profiles have been averaged for all quadrants and inverted (by using the negative of the actual values) for easy comparison with the thickness between these levels (heavy solid line). On the upper right are the average profiles (all quadrants) of the total winds from the same two levels. Solid lines show the smoothed wind at each level and the difference or shear is presented as the solid curve in the lower right graph, i.e., the observed smoothed shear using 10 n. mi. averages. The unsmoothed shear is retained as a dashed line. Using the thickness gradient developed on the left, the "gradient wind shear" was computed from the following considerations:

Let v_θ = the tangential component of the gradient wind

v_g = geostrophic wind

f = Coriolis parameter

r = radius of curvature taken to be the radial distance

$\frac{\partial D}{\partial r}$ = height gradient (on a constant pressure surface) pressure.

Then, $\frac{v_\theta^2}{r} + f\, v_\theta = g \frac{\partial D}{\partial r} = f\, v_g$ and $v_g = \frac{g}{f} \frac{\partial D}{\partial r}$. After differentiation $\frac{\partial v_\theta}{\partial z} =$

$$\frac{\partial v_g}{\partial z} \frac{1}{\sqrt{1 + \frac{4v_g}{rf}}}$$

where $\frac{\partial v_\theta}{\partial z}$ is the "shear" in the gradient wind and $\frac{\partial v_g}{\partial z}$ is the "shear in the geostrophic wind."* The geostrophic shear was calculated from computations of the geostrophic winds at the two levels and v_g for the layer was assumed to be the average of the upper and lower geostrophic winds.

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*Implicit in the use of this equation are the assumptions that the motion is horizontal, non-accelerating, and non-viscous. It provides at best a standard of comparison rather than a rigorous test. However, the equation may be more general than appears at first glance since the variation of v_g with height may be quite similar to the variation of total wind with height and over much of the range of z the variation in trajectory curvature with height may be negligible.

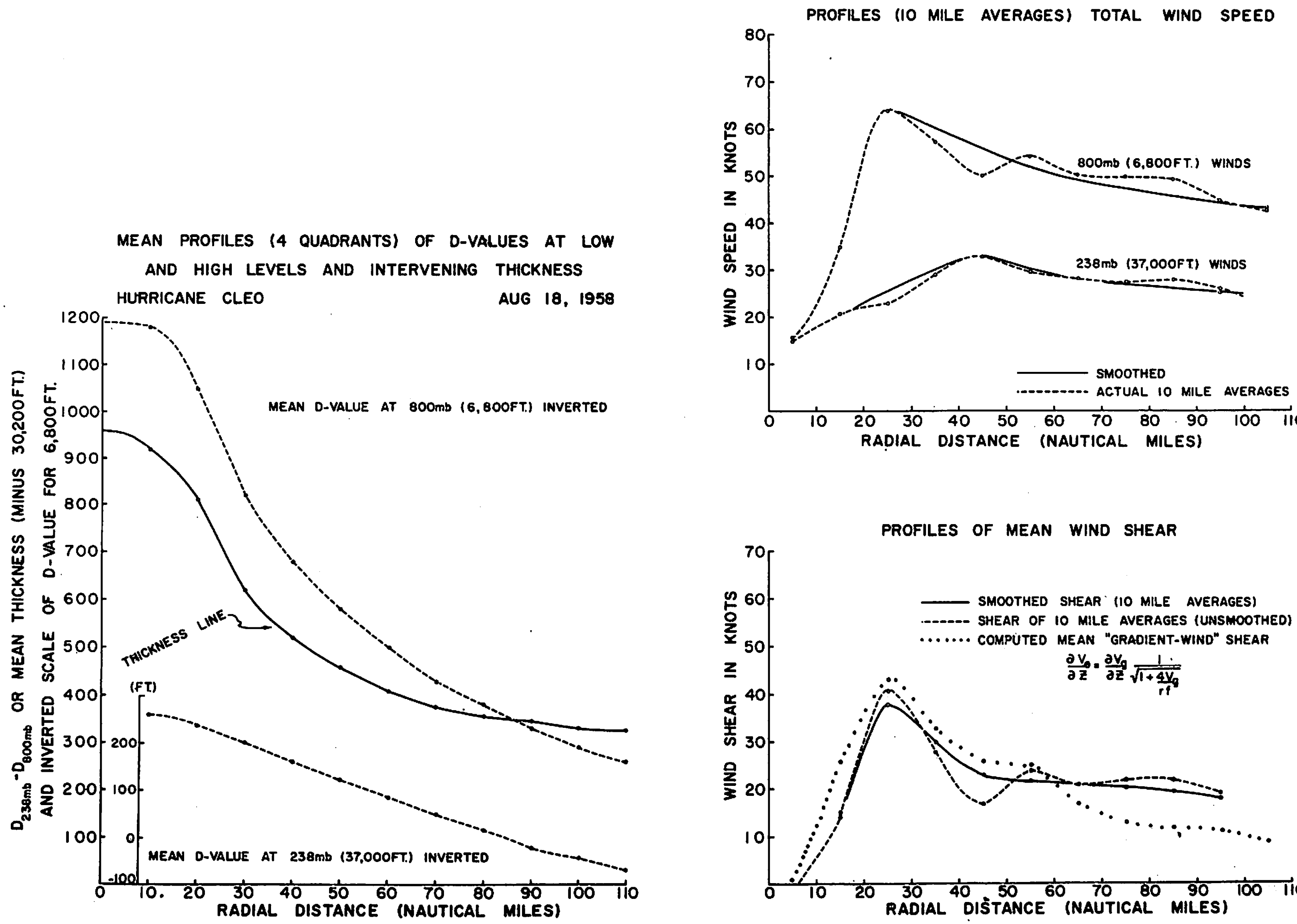

Figure 7. - Comparison of observed and computed shears in Hurricane Cleo, 1958.

It may be noted that the computed "gradient wind shear" agrees quite closely with the observed shear at least out to 60 n.mi. (about 3 R_m). Beyond this point the computed shears were less than those observed while at smaller radii the calculated shears were somewhat greater than observed. It may be worthy of note that at radii less than 60 n.mi., where the observed shears were less than the calculated, there is a suggestion of upward transport of the lower-level, high-speed winds, and possibly a slight imbalance aloft with winds somewhat stronger than gradient.

Checks and comparisons with other research of a similar vein may be of interest but are of limited value because of inherent differences in data and approach. With data fairly well removed from the wall cloud and a necessarily cruder compositing technique, Miller [5] has extended the earlier work of E. Jordan [6] and Hughes [7]. This consisted of hurricane rawins composited by 2°-squares about the axis of storm motion. At distance of 85 n.mi. (assumed to be about 3.5 x the average R_m) and 190 n.mi. (where comparison was made with maximum distance treated in this paper, 5 R_m) the 15,000-ft. and 37,000-ft. wind reductions agreed within 10 percent. At 26,000 ft. the Miller-Jordan-Hughes data indicated a somewhat greater reduction than shown here. Hence, although the data are not strictly comparable, the results are not grossly dissimilar. Jordan and Fortner [8] have presented data using sea level winds made from visual estimates of the state of the sea. They have substantiated the generally unsatisfactory nature of these data and would seem to be in general agreement with the small shears (in the region of the wall-cloud) demonstrated here.

One may also compare the maximum lower-level wind determined from the nomogram with those computed from formulae of the type given by the Weather Bureau Hydrometeorological Section [9] for maximum cyclostrophic winds. The latter expression was chosen for comparison since it presumably represents according to Fletcher [10], "... an average value along a line ..." and is not the peak gust to be observed at sea level which may be "... about half again as strong ...". This expression is of the form $v_{cm} = K_m \sqrt{p_n - p_0}$, where v_{cm} is the maximum cyclostrophic wind speed and p_n and p_0 are the pressures at the storm's outer edge and at the storm center, respectively. Myers [11] showed further that for observed maximum wind speeds in two hurricanes, this coefficient takes on a considerable range of values (7 to 14, where wind speed is in knots and pressure in millibars) depending upon the height of the anemometer and the time interval over which the wind is averaged. The comparison, for the three hurricane days of this study where computations were possible, showed that values of K_m computed from the pressure profiles and maximum low-level winds estimated from observations between 10,000 and 20,000 ft. are within the range of values that Myers [11] had found near the surface.

It should be re-emphasized that the flight winds (for mature hurricanes of average depth) have here been related essentially to 1,500-ft. winds which are probably near the level of maximum wind speed, and that they have also been subjected to radial smoothing. With these considerations in mind one might hazard an estimate that over the ocean, speeds for the fastest mile at ship anemometer level (extreme speed by Weather Bureau definition), may exceed

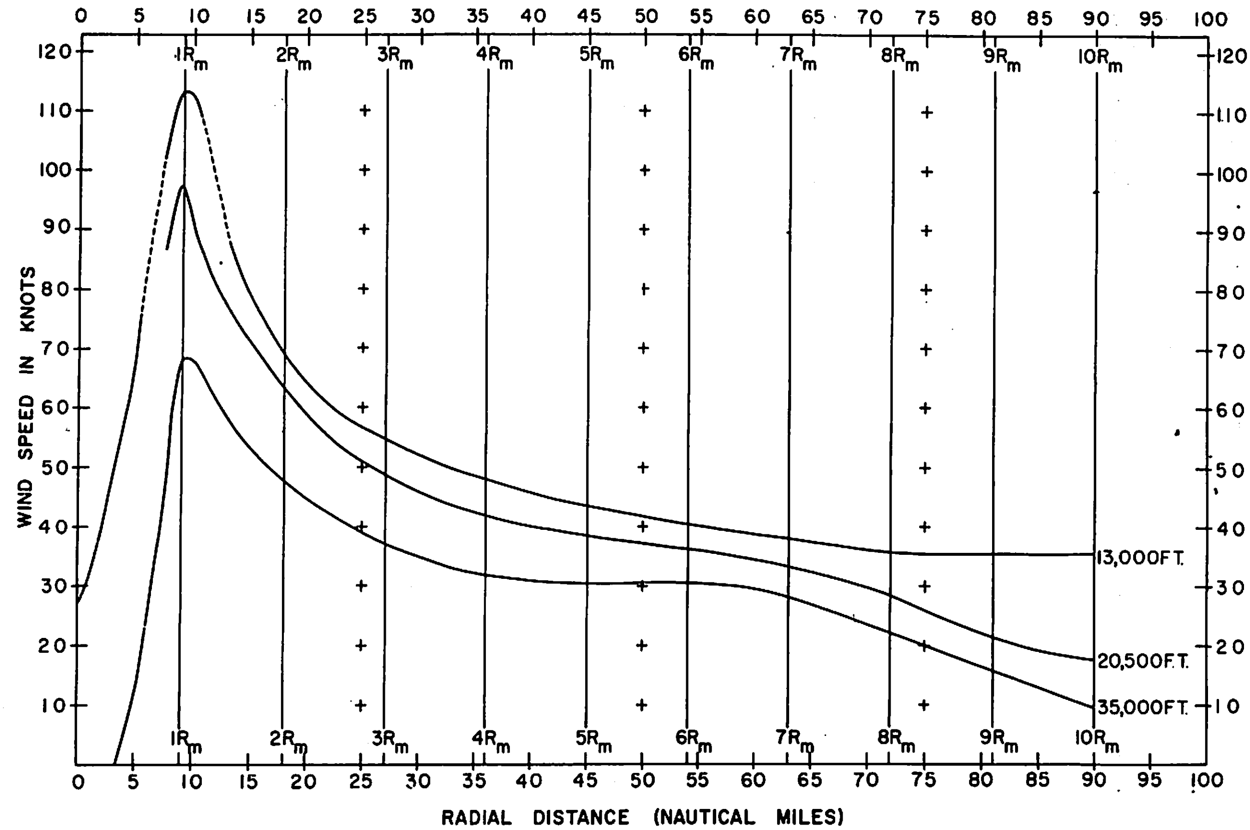

Figure 8. - Wind profiles, right front quadrant of hurricane Daisy (central pressure 948 mb.) Aug. 27, 1958. An example of the preservation of wind speed with height in the wall of an intense hurricane.

the values derived through this flight-wind technique by something like 30 percent. It is recommended that any such approximations be confined to the area of the wall-cloud.

Comparison with hurricanes of greater intensity.

Although insufficient data are at hand to derive a similar nomogram (fig. 5) for intense storms, it may be of value to include a set of profiles for at least one intense hurricane. Figure 8 shows profiles from 13,000, 20,500, and 35,000 ft. pressure altitude from hurricane Daisy, August 27, 1958. Daisy was a small (R_m = 9 n.mi.) fairly deep (948 mb.) hurricane. It will be noted that maximum winds of about 115 kt. were observed at 13,000 ft. At 35,000 ft. these had diminished only to 70 kt. This is a much smaller reduction than the two-thirds decrease which might be anticipated in an average mature hurricane. It is also a graphic example of the preservation of wind with height in the wall-cloud. The speeds decreased only 15 kt. in the layer from 13,000 ft. to 20,500 ft.

Jordan, Hurt, and Lowery [12] demonstrated by RHI photographs that the wall cloud of Daisy on August 27 extended well above the 50,000-ft. level.

When evidence of such strong vertical development is available, it is unreasonable to expect that strong shears persist within the turbulent portion of the wall-cloud.

It is evident that (even if hurricanes can be treated in the average, as attempted in this paper) further categories of hurricanes (by strength, at least) must be studied as data become available before comprehensive treatment can be attained.

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