The Hurricane's Inner Core Region. I. Symmetric and Asymmetric Structure

DENNIS J. SHEA and WILLIAM M. GRAY

Dept. of Atmospheric Science, Colorado State University, Fort Collins 80521

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ABSTRACT

Observational information from 533 radial flight legs executed by the National Hurricane Research Laboratory over a 13-year period (1957-69) is used to present the structural characteristics and the variability of the hurricane's inner core region. Tangential and radial winds, D-values, and adjusted temperatures are composited with respect to the Radius of Maximum Wind (RMW) in order to construct a five-level mean symmetric storm and a five-level mean asymmetric storm. The slope of the RMW with height and the position of the RMW relative to the inner cloud wall are presented. Utilizing these results, an idealized, steady-state schematic model of the flow conditions in the inner hurricane core is presented. Storms are stratified by deepening and filling tendency, intensity and storm speed. Finally, the variations of the RMW with latitude, maximum wind, inner radar radius, central pressure, and other features are discussed.

Many significant features are noted: 1) storm inflow is confined almost exclusively to the lowest layer and occurs at radii larger than the RMW; 2) inside the RMW (i.e., in the eye) outflow is present; 3) the warmest cyclone temperatures result from subsidence and occur just inside the eye-wall cloud edge where the sinking is strongest; 4) the largest D-value and adjusted temperature gradients occur at and just outside the RMW; 5) the largest convergence occurs in the lowest layer at the RMW; 6) the slope of the RMW with height is small and appears to be a function of intensity; 7) the maximum winds occur within the eye wall cloud area; 8) inner core winds are shown to have a natural asymmetry beyond that induced by storm motion; 9) vertical wind shears in deepening storms are much smaller than in filling storms; 10) in intense storms the maximum winds occur closer to the center than in weaker storms; 11) faster moving storms were more intense than slower moving storms; and 12) at high latitudes the maximum winds occur farther away from the storm center than at low latitudes. Other features are shown and discussed.

1. Introduction

This is the first (Paper I) of two papers by the authors on the structure and dynamics of the hurricane's inner core region. This paper discusses the structural characteristics and the variability of the hurricane's inner core region. Paper II (Gray and Shea, 1973a) discusses the dynamic and thermodynamic characteristics. A more complete discussion of all the flight data in project report form has been given by Shea (1972). A data atlas of the flight information in project report form will also shortly become available (Gray and Shea, 1973b).

a. History

The National Hurricane Research Project (NHRP) was established in the middle 1950's at the instigation of Congress following the devastating flooding caused by hurricane Carol in the Connecticut Valley in 1954. Dr. Robert Simpson (present Director of the National Hurricane Center) was the driving force behind the initial organization and functioning of the NHRP as it was then called. The first flights were accomplished in late 1956. Except for the year 1959 (during the changeover from Air Force to civilian aircraft) an almost continuous monitoring of the hurricane by the Weather Bureau's (now NOAA's) Research Flight Facility was accomplished in the decade from 1956 through 1966. From 1966-67 onward the interest of NOAA has steadily shifted to hurricane modification and the typical radial or cloverleaf flight patterns have been modified.

b. Character of flight missions

From 1957 through 1966 the majority of flight missions were flown into the hurricane eye and out again. This was repeated at individual flight levels four to six times with a rather even balance between the storm quadrants. Fig. 1 shows a typical flight pattern. Most of these flights into and out of the hurricane have occurred at radii <100 n mi. Voluminous data are available from the center to 50-60 n mi radius. Beyond this radius the quantity of flight data drops off. A small sample of individual radial

1 Present affiliation: National Center for Atmospheric Research, Boulder, Colo.

8 In 1960 the name was changed to the National Hurricane Research Laboratory (NHRL).
legs\textsuperscript{3} from several flight missions have been superimposed to illustrate this in Fig. 2.

The data have been primarily gathered by propellor aircraft (B-50's from 1956 through 1958, and DC-6's from 1960 to the present). This has restricted operations to below the 500-mb level. Also, due to safety restrictions on low-level flight missions most of the data were taken above 900 mb. In this tropospheric range from 500 to 900 mb there have been approximately 700–800 radial legs flown. Of these lower tropospheric flights the processed reliable data at this time comes to 492 radial legs.

Upper tropospheric sampling was accomplished between the 180- and 260-mb levels by B-47 aircraft in 1957 and 1958 and by a B-57 after 1960. The number of B-58 flights has not been large because of range and instrumental difficulties. For this reason there are only 11 evaluated upper level missions (41 radial legs) used in this study.

Combining upper and lower levels there are 533 radial legs. This study concentrates on the flight data between the 500- and 900-mb levels.

c. Character of the measurements

The development of the Doppler navigation instrument in the mid-1950's and the simultaneous measurement of pressure and absolute altitude (possible over water where terrain features do not interfere) have allowed accurate wind and $D$-value\textsuperscript{4} measurements down to the cumulus scales of motion.

Doppler wind measurements are much more reliable in high wind conditions because the error-noise-to-true-signal ratio is much smaller than in weak wind conditions. The general validity of these Doppler determined winds has been demonstrated on many occasions when navigation errors after many hours of flight proved to be but a few nautical miles.

The vortex temperature measurements have shown a very strong reliability in the statistical average. It is possible to obtain an independent check on the observed inward radial temperature gradients by measurement of the pressure level thickness changes when simultaneous double level missions were flown. When this was done the average calculated temperature gradients from the thickness changes and the average directly measured temperature gradients proved to be quite close (see Appendix for more discussion on temperature measurements).

d. Processing of the data

Only in the last few years has this complete set of processed and checked flight data become available. The data reducing, cross checking, navigation corrections, hydrostatic consistency checks, etc., that had to be made have required a rather lengthy and painstaking evaluation procedure. This large data sample is now available for close scrutiny.

2. Purposes of study

Perhaps the most outstanding characteristic of hurricanes is the large variability of conditions in the inner core\textsuperscript{5} area. Not only is one storm different from another (e.g., intensity, asymmetries, storm motion, etc.), but day-to-day and even hour-to-hour changes in the individual storm's inner core are frequently substantial. Fig. 3 presents a small sample of observed

\textsuperscript{3} A radial leg is the portion of the plane's flight pattern during which the plane was flying directly into or out of the storm center. For example, the flight pattern shown in Fig. 1 has six radial legs.

\textsuperscript{4} The $D$-value is the difference between the absolute altitude and the pressure altitude.

\textsuperscript{5} The term inner core refers to the inner 50 nmi of the hurricane. This region includes 1) the area of high winds, clouds, and intense vertical motions and 2) the calmer, clearer area inside (i.e., the eye).
Fig. 3. Sample of observed tangential wind profiles.

tangential wind profiles. The variable character of these profiles is immediately seen. Some profiles exhibit sharp peaks, whereas others show a slow increase to the maximum wind and then a flat profile.

Obviously, results drawn from individual storm case studies [e.g., Staff NHRP (1958), Jordan et al. (1960), Colón and Staff NHRP (1961), Riehl and Malkus (1961), Miller (1962), LaSeur and Hawkins (1963), Colón (1964), Sheets (1967a, b, 1968), Hawkins and Rubsam (1968a, b, c) and Bell and Tsui (1973)] may not necessarily be representative of the majority of storms. Generalizations of typical hurricane dynamics from individual storm data can be misleading. Yet, except for the hurricane modeling of Ooyama (1969) and Rosenthal (1970, 1971a, b), most of our hurricane concepts have come from individual storm evaluations.

This study will utilize the large amount of aircraft observations collected by the National Hurricane Project to present the structural characteristics and the variability of the hurricane's inner core region. This portion of the storm is of special interest because of its potential destructiveness and its concentration of cyclone dynamics.

3. Data collection

a. Data

Discussion of the instruments and aircraft employed to obtain the meteorological data used in this study have been made by Hilleary and Christensen (1957), Hawkins et al. (1962), Gray (1962, 1965a, b, 1966, 1967), Gentry (1964), Reber and Friedman (1964) and Friedman et al. (1969). For detailed descriptions of the instruments and the character of the data collection the reader is referred to these reports.

After a flight into a storm has been completed, the raw data are composited with respect to the moving storm center by computer. The data are further processed and the computer prints out the plane's distance from the storm center, the actual tangential wind (\(V_{\theta}\)), the actual radial wind (\(V_{r}\), positive outward), the relative tangential wind (\(V_{\theta r}\)), the relative radial wind (\(V_{r r}\)), the D-value (\(D\)), and the adjusted temperature (\(T\)) at that radius. The actual winds do not consider the effects of storm motion whereas the relative winds have had the storm motion subtracted from the data. The adjusted temperature is the observed temperature adjusted to a constant pressure surface using typical hurricane lapse rates.

This study does not treat humidity measurements. Nevertheless, an estimate of the effect a virtual temperature correction would have on the observed temperature and temperature gradients has been made and is discussed in Section 5.

The data are unique in that we have simultaneous wind, temperature and pressure measurements down to the cumulus scale. Over land, where terrain features obscure D-value measurements, this is not possible. The simultaneous pressure and wind measurements allow examination of radial wind and pressure balances. Where double-level flights were made, an examination of the cylindrical thermal wind balance can be made (see Paper II).

b. Data errors

In general, the final processed data are quite reliable. Two non-instrumental factors can contribute to errors in the wind reports, however. These are positioning of the aircraft relative to the storm center and water motion under the aircraft.

The positioning of the aircraft is quite important. Hawkins and Rubsam (op. cit.) have discussed the sensitivity of the radial winds to the aircraft's position to the storm center. They note that even small
changes in position can result in significant changes in the radial winds. Thus, along individual radial legs the radial winds are believed to be only marginally acceptable. If these positioning errors are random, however, a large data sample will tend to average them out. The mean radial wind data should then be meaningful.

The AN/APN-82 Doppler navigation system is used to determine the motion of the aircraft relative to the ocean. The wind speed is obtained from the vector difference between the true airspeed and the aircraft motion relative to the ocean. Because the aircraft measurements are made over the ocean which moves under wind stress, the Doppler winds have been suspected of underestimating the true wind speeds by 5–10% (Grocott, 1963; Gray, 1967) and upward to 20% by Black et al. (1967). The observational evidence (presented in Paper II) supports the former estimates of only 6–7% water motion correction.

A few researchers (e.g., Colón, 1964) have asked how individual parameters (temperature, D-values, radial winds) might vary as data are gathered by inward (IN) plane penetration as opposed to outward (OUT) plane penetration of the inner core area. In order to investigate this, each radial leg was stratified according to whether the plane was flying IN or OUT. In the statistical average no systematic differences are noted in any of the parameter profiles. The temperature and D-value gradients for the IN and OUT legs are remarkably similar. The radial wind profiles differ but not in any consistent fashion (Shea, 1972).

In other uses of the DC-6 aircraft some researchers have noted that in flying through cumulus clouds with heavy liquid water concentrations that the vortex temperature sometimes measures values 1–2°C too low. This is presumably due to evaporation cooling. As discussed more extensively in the Appendix, this effect (although possibly present in some of the hurricane flights), was not explicitly detected by us. As the temperature portrayals of this paper are statistical averages of temperature gradients on a scale larger than the individual cumulus, the possible influences of this liquid water effect on the measured temperature gradient are not believed to be significant.

c. Data available

All the fully processed and checked reconnaissance data from the hurricane flights of 1957–69 have been gathered. This included data from 21 hurricanes, on 41 storm days. The number of radial flight legs was 533. [See the project reports by Shea (1972) for more specific information on the pressure levels at which the data was collected, the maximum winds at flight levels, the central pressures, radar eye radius, radius of maximum winds, etc., for the storms used in this study.]

Fig. 4. Distribution of radial leg data in the vertical for the five-, three- and two-level mean storms. The number in parentheses is the number of radial legs in each layer average. The pressure level is the level which the data best represents.

The data were collected on days when storms were deepening and filling and while the storms were in a quasi-steady state. The combined data sample is believed to be large enough to assume steady-state conditions.

Other data collected included the time interval during which the data were obtained, the ground track of the aircraft, the octant in which the aircraft was flying both with respect to geographic north and storm motion, and whether the plane was flying toward or away from the storm center.

Although the wind, pressure and temperature data were recorded every few hundred meters, it was decided that the very small scale data fluctuations should be smoothed. This was accomplished by printing out information from 5 to 50 n mi from the storm center using a 2.5 n mi overlapping data interval. This interval offers enough horizontal resolution for the purposes of this study.

d. Distribution of data

Fig. 4 shows the manner in which the data were combined in the vertical. The number of radial legs at each level and the pressure level which the data best represents is indicated. A five-level mean asymmetric storm was determined by dividing the information in the horizontal in azimuthal octants. Since several of the octants contained only a few radial legs, individual octant data for each level were combined with the data in each adjacent octant in order to increase the data sample. This overlapping technique slightly underestimated the degree of asymmetry but made the data more representative.
4. Compositing methods

The data compositing was accomplished in two ways:

Method I consisted of compositing data and dynamic calculations (see Paper II) with respect to the Radius of Maximum Wind (RMW). This method is illustrated in Fig. 5 using tangential wind profiles from five different storms.

Method II consisted of compositing all the data and dynamic calculations with respect to the absolute radius. This method is illustrated in Fig. 6.

Method I has the advantage of allowing the dynamics in the region outside the RMW to be separated from the region inside the RMW. This is necessary because the two regions are dynamically quite different. At and outside the RMW convergence and high winds are present. Inside the RMW high vorticity values, divergence and subsidence are present. In general, compositing method I has more physical relevance for understanding the hurricane's inner core dynamics. The data presentations which follow were made by use of Method I only. A more detailed analysis of the results using Method II are discussed in the CSU project report by Shea (1972). The dynamic calculations presented in Paper II which involve the radius are, of course, always made before compositing with respect to the RMW.

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Footnote:

*The expressions "inside the RMW" and "outside the RMW" will be used throughout this study. The former expression refers to radii less than the RMW (e.g., RMW - 5 n mi, RMW - 10 n mi, etc.). The latter expression refers to radii larger than the RMW (e.g., RMW + 5 n mi, RMW + 10 n mi, etc.).
5. The structure of the mean symmetric storm

a. Structure with respect to the radius of maximum wind

The structure of the mean symmetric storm obtained by compositing parameters with respect to RMW (Method I) will now be discussed. Data from at least 20 radial legs were required for a point to be plotted.

1) Tangential winds

Radial profiles of the mean tangential wind for lower (900 mb) and mid-tropospheric (525 mb) levels are shown in Figs. 7 and 8. The similarity of the wind profiles in the lower half of the troposphere should be noted (see Fig. 9). All exhibit sharp peaks at the RMW and show large anticyclonic shears outside the RMW. A vertical cross section of the tangential

![Fig. 9: Tangential wind profiles for the mean symmetric storm averaged with respect to the radius of maximum wind (Method I).](image)

![Fig. 10: Vertical cross section of tangential wind for the mean symmetric storm (Method I).](image)

![Fig. 11: Mean tangential wind profile and standard deviation (σ) for the 900–500 mb layer in the mean symmetric storm (Method I).](image)

![Fig. 12: D-values for lower four levels of the mean symmetric storm. The mean D-value profile for the 900–500 mb layer is shown by the dashed line (Method I).](image)
Fig. 13. Adjusted temperature profiles for the five levels of the mean symmetric storm. The mean adjusted temperature profile for the 900–500 mb layer is shown by the dashed line (Method 1).

winds (Fig. 10) shows that the winds decrease with height, but the decrease is much smaller than one would expect from the steady-state cylindrical thermal wind relationship. This is in agreement with the earlier findings of Gray (1962). The mean wind profile and the standard deviation for the four-level average of the 900–500 mb layer is shown in Fig. 11.

2) Radial winds

Radial wind profiles are also shown in Figs. 7 and 8. The lowest layer exhibits inflow from the outer regions into the area around the RMW. The magnitude of this inflow is largest at distances far from the RMW and decreases sharply as the RMW is approached. Inside the RMW outflow is present. Thus, in the lowest layer at and outside the radius of maximum winds we have the strong convergence one might expect in a layer near the top (~900 mb) but apparently just within the surface frictional boundary layer. By contrast, the three middle levels (750, 650 and 525 mb) show very little overall inflow or outflow around the RMW. No radial winds are presented for the 240-mb level due to the small amount of radial wind data available.

3) D-values

D-values for the four lowest layers of the mean symmetric storm are presented in Fig. 12. D-value data were not available in sufficient quantity at the upper tropospheric level to give a reliable profile. The largest D-value gradients are found at and just outside the radius of maximum wind. At radii inside the RMW the D-gradients are much less.

4) Adjusted temperature

Fig. 13 shows the profiles of the adjusted temperatures for the five levels. Clearly, the warmest temperatures occur well inside the RMW, whereas the largest temperature gradients occur at the radius of maximum wind. For the three middle layers these temperature gradients around the RMW average approximately 1.5°C (5 n mi)^{-1}.

The departure of individual mean temperatures from the mean temperature at the RMW for each of the four lower levels is shown in Fig. 14. The largest temperature deviations inside the RMW occur at 525 mb. These deviations become smaller with de-
creasing elevation. This shows that the subsidence is much more effective in warming the middle levels than the lower levels.

5) Virtual temperature correction

Because of some uncertainties in the humidity instrumentation this parameter was not treated. Thus, virtual temperature corrections were not made to the raw temperature data. In these conditions precise temperature comparison can only be made in an environment with a constant relative humidity. At radii well inside and outside the RMW this is not valid because relative humidities are generally less than at the RMW. Estimates of the effect a virtual temperature correction would have on the measured radial temperature gradients have been made for assumed relative humidities of 25% and 50% less than at the RMW. This is shown in Fig. 15.

The effect that the virtual temperature correction would have on the observed temperature gradients
Fig. 16. Variation of the RMW with elevation for storms with simultaneous lower and upper tropospheric data (left) and storms with two or more simultaneous flights in lower troposphere only (right).

(i.e., baroclinicity) is shown in Table 1. This table presents observed radial temperature gradients and the changes in the radial temperature gradients due to various assumed relative humidity changes. The ±5 and ±10 n mi radial gradients are centered at the RMW. Several case studies (e.g., Colón and Staff

Fig. 17. Radius of maximum wind (RMW) vs inner radar eye radius (IRR). Points falling on the 45° line are those where the RMW and IRR coincide. The other line indicates the best fit curve.
NHRP, 1961; La Sear and Hawkins, 1963) indicate that relative humidities in the inner 50 n mi at, and outside the RMW are between 80 and 90%. Inside the eye the relative humidities at low levels are quite high (80-95%) but decrease with elevation and may be as low as 40-60% in the subsidence part of the eye at middle levels as shown by Jordan (1957, 1961) and Simpson (1952). The assumed relative humidity values of Table 1 indicate that the virtual temperature correction would have only a small effect on the measured temperature gradients.

6) SLOPE OF THE RADIUS OF MAXIMUM WIND WITH ELEVATION

The left portion of Fig. 16 shows the slope of the RMW with elevation for storms with simultaneous

Table 1. Changes in observed 10 and 20 n mi radial temperature gradients (centered at the RMW) due to virtual temperature corrections for various relative humidity reductions.

<table>
<thead>
<tr>
<th>Pressure (mb)</th>
<th>Observed adjusted temperature gradient straddling RMW</th>
<th>25% less inside eye</th>
<th>50% less inside eye</th>
<th>50% less outside eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>1.0/1.2</td>
<td>0.2/0.0</td>
<td>0.7/1.5</td>
<td>0.7/1.2</td>
</tr>
<tr>
<td>750</td>
<td>1.9/2.8</td>
<td>0.1/0.6</td>
<td>0.4/1.2</td>
<td>0.4/0.7</td>
</tr>
<tr>
<td>650</td>
<td>2.4/3.4</td>
<td>0.2/0.5</td>
<td>0.5/1.0</td>
<td>0.5/0.5</td>
</tr>
<tr>
<td>525</td>
<td>2.2/3.6</td>
<td>0.0/0.2</td>
<td>0.1/0.6</td>
<td>0.1/0.4</td>
</tr>
</tbody>
</table>

* First entry °C per 10 n mi, second °C per 20 n mi.

Fig. 18. Difference between the RMW and the inner radar eye radius vs maximum wind speed. The best fit curve is indicated by the heavy line.

Fig. 19. Portrayal of the mean flow conditions in the hurricane's inner core region. The horizontal and vertical arrows represent the radial and vertical velocities, respectively. The mean D-value and temperature profiles are the result of combining all the data for the 900-, 750-, 650- and 525-mb levels.
lower and upper tropospheric data. The right side of this figure shows the slope of the RMW with elevation for those storms which have two or more lower tropospheric levels. Only the weaker storms exhibit a slope of the RMW with height; more intense storms do not. The vertical slope of the RMW is probably related to the intensity of cumulus convection. The more active eye-wall convection in intense storms is more effective in transporting horizontal momentum to upper levels. The cumuli possess very little slope and the maximum winds at upper levels occur more directly above those at lower levels.

The fact that the slope of the RMW with height is small and apparently a function of intensity does not support the rather large eye-wall slope hypothesized by Palmén (1956).

7) Position of the inner radar eye radius relative to the radius of maximum wind

Fig. 17 shows the position of the RMW, relative to the inner radar eye radius (IRR, assumed synonymous with the inner cloud wall). In the overwhelming majority of cases, the RMW occurs within the cloud area. In the mean the IRR occurs at radii of 5–6 n mi inside the RMW.

Positioning errors could account for some of the difference but it seems likely that these errors would be random in such a large data sample. The larger discrepancies seen in Fig. 17 occurred in storms where the maximum wind was up to 31 n mi away from the storm center.

Fig. 18 shows the difference between the RMW and
the IRR versus the maximum wind speed for individual radial legs. Positive values along the ordinate indicate that the maximum wind is at a radius greater than the radius of the inner eye-wall cloud. Clearly, the more intense the wind the better is the agreement between the RMW and the IRR. Presumably, this is a result of the stronger subsidence in the more intense storms. This strong subsidence would tend to evaporate the inner portion of the eye-wall cloud.

b. Schematic

Based on the results and observations just presented and some previous research efforts, an idealized schematic model of the flow conditions in the inner hurricane core is presented in Fig. 19. In this model the lowest layer exhibits inflow outside the RMW and outflow inside this radius. This inflow-outflow pattern causes strong convergence and ascending vertical motions at the RMW. The majority of this ascending air is advected away from the storm. Some of the ascending air, however, is not caught up in the upper outflow, but is advected or turbulently diffused inward at middle and upper levels (as noted by Simpson and Starrett, 1955) and sinks within the eye. In the lowest layer the subsiding air is advected outward from the eye into the region of ascending motion. This type of recycling flow pattern does not permit a “stagnant”
eye; rather it seems that the eye is “dynamic” in the sense that air is continually moving through it.

6. **Structure of the mean asymmetric storm with respect to actual radius**

The structure of the mean asymmetric storm is exhibited in a few plan views. These plan views present the mean data with respect to the RMW for distances of 20 n mi inside the RMW to 30 n mi outside the RMW.

a. **Parameter plan views**

1) **Actual tangential winds**

The actual tangential winds (tangential winds relative to instantaneously fixed cyclone center) for the 900-, 525- and 240-mb levels are shown in Figs. 20–22. The winds for the 750- and 650-mb levels were similar to the other lower levels. There is a large degree of asymmetry. At all levels the highest wind speeds are to the right of the storm motion and the weakest speeds to the left. This is, of course, partly due to the superposition of the storm speed upon the wind field. At larger radii, Hughes (1952), Riehl (1954), Miller (1958), Izawa (1964) and Black and Anthes (1971) also show large asymmetries in the winds.

2) **Actual radial winds**

The actual radial winds (radial winds relative to instantaneously fixed cyclone center) for the lowest four levels are shown in Figs. 23–26. The 900-mb level shows the largest inflow both in area and in magnitude.
Most of the inward motion takes place in the rear and right quadrants. The 750-, 650- and 525-mb levels show approximately equal areas of inflow in the rear and outflow to the front of the storm. Most of the inflow and outflow cancels when the storm motion is subtracted from the data.

3) RELATIVE TANGENTIAL WINDS

The relative tangential winds (tangential winds relative to the moving cyclone center) for levels of 900, 525 and 240 mb are shown in Figs. 27–29. As might have been expected, the relative tangential winds are more symmetric than the actual tangential winds. There still is, however, a maximum to the right of the storm motion. Many individual case studies have also shown this feature.

This asymmetry in hurricane tangential wind (even after the storm motion has been subtracted out) has been discussed for rawinsonde data at larger radii by Sherman (1956). He noted that the difference in wind speed between winds to the right of the storm and those to the left is sometimes two or three times the storm velocity.

4) RELATIVE RADIAL WINDS

The relative radial winds (radial winds relative to the moving cyclone center) for the lower four levels is shown in Figs. 30–33. At 900 mb inflow is present.
compared to the very symmetric $D$-value pattern has been noted before in the literature by Gray (1962) and LaSueur and Hawkins (op. cit.). Their studies reported sub-gradient winds to the left- and super-gradient winds to the right of the storm motion. Analysis of the present data shows the same results.

6) Adjusted temperature

The adjusted temperatures are shown in Figs. 36–40. The inward temperature gradients increase with height in the lower half of the troposphere. At 525 mb the average radial temperature gradient is 5–6°C per 45 n mi. At 250 mb the radial temperature gradients are on the order of 3°C per 45 n mi. The upper warm area at 250 mb in the direction of storm motion is probably due to subsidence and may be initiating the forward warming and pressure falls required in the storm's motion.

b. Storm wind asymmetry

Quantitative estimates of the asymmetries in the actual and relative tangential winds were determined for selected flight missions that had at least four approximately equally spaced radial legs. The equation used was

$$\text{asymmetry} = \frac{(V_{\text{max}},r) - (V_{\text{min}},r)}{(\bar{V}),r}, \tag{1}$$

where $(V_{\text{max}},r)$ is the maximum wind at any radius, $(V_{\text{min}},r)$ the minimum wind at any radius, and $(\bar{V}),r$ the mean wind at the radius. Eq. (1) will yield asymmetries which are somewhat smaller than actually occur because it is unlikely that the aircraft will measure the absolute maximum and absolute minimum winds at a particular radius.

The resulting composited (Method I) asymmetries are shown in Fig. 41. The largest asymmetries for both wind types are inside the RMW. This is probably due to position errors and to the higher degree of wind variability inside the RMW. Outside the RMW the asymmetries are less.

7. Storm stratifications

The highly variable character of the hurricane's inner core area has been noted. In order to further investigate this variability, storms have been stratified by their deepening and filling tendencies and other characteristics.

The structural characteristics of the storms relative to these stratifications (although not completely independent of each other) were made using the lower two levels of the three-level storm model (i.e., 900–700 mb and 700–500 mb). The five-level model was not used because, after stratification, the data samples were not large enough. The data sample for the 260–
Figs. 36–40. Plan views of temperature (°C; Method I). The arrow indicates the direction of storm movement. Distance from the RMW is in nautical miles.
180 mb layer was also too small for this type of analysis.

### a. Deepening and filling storms

This classification was quite subjective and due to the many short-period tendency changes some inaccuracies may be present. Storms were classified as deepening or filling depending on whether their central pressure showed a marked pressure change \( \geq 15 \text{ mb} \) from one day to the next. In some cases the storms did not quite satisfy this criteria at the time of observation but they showed a definite tendency toward deepening or filling over a longer period. Steady-state storms were not treated since it was felt that the resulting averages would resemble those of the mean storm.

A definite latitude bias is exhibited in this stratification. Most of the deepening storms occurred at low and middle latitudes, whereas the majority of filling storms occurred at high latitudes. The filling at higher latitudes is largely due to the colder water and reduced cumulus activity.

With these criticisms in mind, wind profiles for the lower two layers in the deepening and filling storms

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**Figure 41.** Asymmetry in the actual and relative tangential winds (Method I).

**Figure 42.** Tangential wind profiles for deepening storms (Method I).

**Figure 43.** Tangential wind profiles for filling storms (Method I).

**Figure 44.** Variation of the RMW with latitude for all lower tropospheric data. The best fit curve is indicated by the heavy line.
are presented in Figs. 42 and 43. Note the difference in vertical shears. Deepening storms have almost identical lower and middle profiles. In contrast, the filling storms, although they exhibit similar profiles, have much larger vertical shears. (It might be possible to make operational predictive use of this observation.) This is probably due to a lessening of cumulus convection in filling storms. The higher momentum from low levels is not being distributed in the vertical and the thermal wind equation at the RMW should be more in balance (see Paper II).

b. Variation of RMW with latitude

Fig. 44 presents the variation of the RMW with latitude for lower tropospheric data. Although there is large variability at individual latitudes, there is a pronounced tendency toward larger RMW's at high latitudes. Colón (1963) has noted that weakening storms are "invariably" accompanied by a widening of the eye. The present data agrees well with his conclusion.

c. Relationship of RMW with maximum winds

In order to determine if a correlation exists between the RMW and the maximum winds, Fig. 45 was prepared. Although there is large variability at individual radii a definite pattern exists: higher wind speeds occur at radii closer to the storm center. It is felt that in intense storms the low-level inflow penetrates closer to the center. Angular momentum considerations would require higher speeds.

Fig. 46 shows the number of occurrences and frequency of the RMW's for all radial legs in the lower half of the troposphere. The mean maximum wind for each radii is shown at the top of each radii band. In most instances, the radius of maximum wind is inside 30 n mi. As noted above, the highest wind speeds occur at radii close to the storm center.

![Fig. 45. Variation of the maximum wind with RMW for lower tropospheric data. The best fit curve is indicated by the heavy line.](image)

![Fig. 46. Frequency distribution of the occurrence of the maximum wind at various radii.](image)

![Fig. 47. Variation of the maximum wind with central pressure for all lower tropospheric data. The best fit curve is indicated by the heavy line.](image)
d. Maximum wind vs central pressure

Fig. 47 presents a scatter diagram of maximum wind speed vs central pressure. As expected in the statistical average, surface pressure is inversely correlated with wind speed. There is, however, a large variability in maximum winds at various central pressures. Clearly, central pressure gives only a rough approximation to storm intensity.

8. Summary

A number of relevant features are apparent from this investigation:

1) The large variability of individual storms from the mean is the most striking general feature of this study.
2) The slope of the RMW with elevation is shown to be small and a function of storm intensity. Except for weak storms the RMW in the upper troposphere is almost directly above the RMW in the lower troposphere. In the lower half of the troposphere the RMW varies little with elevation, regardless of storm intensity.
3) The difference between the inner radar eye radius (IRR) and the radius of maximum wind (RMW) shows that the IRR occurs at radii 5–6 n mi inside the RMW. In the most intense storms the differences between the IRR and the RMW is very small, whereas in weak storms the difference is large. Presumably this is due to the more concentrated and stronger subsidence which occurs in intense storms. This causes evaporation along the edge of the cloud eye wall.
4) The D-values of the mean symmetric storm exhibit a very symmetric pattern, whereas the wind field shows a larger degree of asymmetry. Analysis of the data used in this study shows that the winds to the right of the storm motion are generally super-gradient, whereas the winds to the left are sub-gradient. This agrees with earlier findings by Gray (1962) and LaSeur and Hawkins (1963). The advective terms of the total derivative would account for most of this difference between the right and left quadrants.
5) Composites of the tangential wind asymmetries in flight missions with approximately equally spaced radial legs verify that there is a natural wind asymmetry in the inner hurricane’s core beyond that induced by motion. This amounts to roughly 25–35% of the wind speed.
6) Deepening storms have smaller vertical wind shears than filling storms. Presumably the cumuli are more active during the deepening stage and distribute the high momentum at lower levels throughout the lower half of the troposphere. This observation may have operational potential.
7) The hurricane’s inward temperature increase of 2–7°C occurs quite close to its center. At the RMW the inward temperature increase is only about half of what it is in the eye. The eye-wall warming cannot be explained by an inward diffusion of heat from the eye wall clouds.

The reader is encouraged to consult the project CSU report by Shea (1972) for more detailed discussion of this flight data. Other features are discussed in Paper II.

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APPENDIX

Reliability of Data

The temperature and D-value data used in this study are considered to be quite reliable—in the statistical average. In order to check this assertion, area-weighted radial vortex temperature gradients were compared with temperature gradients calculated from flight D-value thickness gradients through use of the hydrostatic equation, i.e.,

$$
\Delta T_{\text{obs}} = \frac{\int_{0}^{\text{RMW}+30 \text{n mi}} \frac{\partial T}{\partial r} \, dr}{R \ln \left( \frac{P_1}{P_2} \right)} \Delta D_{\text{obs}},
$$

$$
\Delta T_{\text{obs}} = \frac{[\Delta T_{\text{upper}} + \Delta T_{\text{lower}}]}{2},
$$

where:

- $\Delta T_{\text{obs}}$ calculated radial temperature gradient
- $\Delta D_{\text{obs}}$ observed radial thickness gradient between levels 1 and 2
- $P_1, P_2$ upper and lower pressure levels
- $g$ acceleration of gravity
- $R$ gas constant
- $\Delta T_{\text{obs}}$ mean observed radial temperature gradient
- $\Delta T_{\text{upper}}$ observed radial temperature gradient at the upper pressure level
- $\Delta T_{\text{lower}}$ observed radial temperature gradient at the lower pressure level.

The calculations were performed on all the double-level flights which occurred exclusively in the lower half of the troposphere. The composited (Method 1)
results are presented in Fig. 48. It is obvious that, in the mean, the calculated and observed radial temperature gradients are quite similar.

Some researchers have observed that the DC-6 vortex temperature measurements may, when the aircraft is encountering heavy liquid water, occasionally read 1–2°C too low. We have carefully watched for this effect in our temperature evaluations and do not believe this possible influence to be a significant factor in altering the temperature gradients that have been portrayed. This is because of:

1) The close statistical agreement between the pressure thickness values independently determined by the D-value and temperature gradients as discussed above.

2) The lack of any significant difference in the temperature gradients measured by the aircraft penetrations into the eye wall and those measured going out of the eye (see report by Shea, 1972).

3) The flights in and out of the storm center often do not encounter an eye-wall cloud with heavy liquid water. The in-and-out radial leg penetrations were often executed between individual Cb’s and, as such, encountered no or only small amounts of liquid water. In these cases there would be little or no liquid water correction.

Even if the liquid water influence were present, its average contribution over nearly 500 radial legs investigated would be significantly smaller than the temperature gradients measured. We do not feel that this possible liquid water influence is sufficient to significantly alter the measured temperature gradients here portrayed.

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