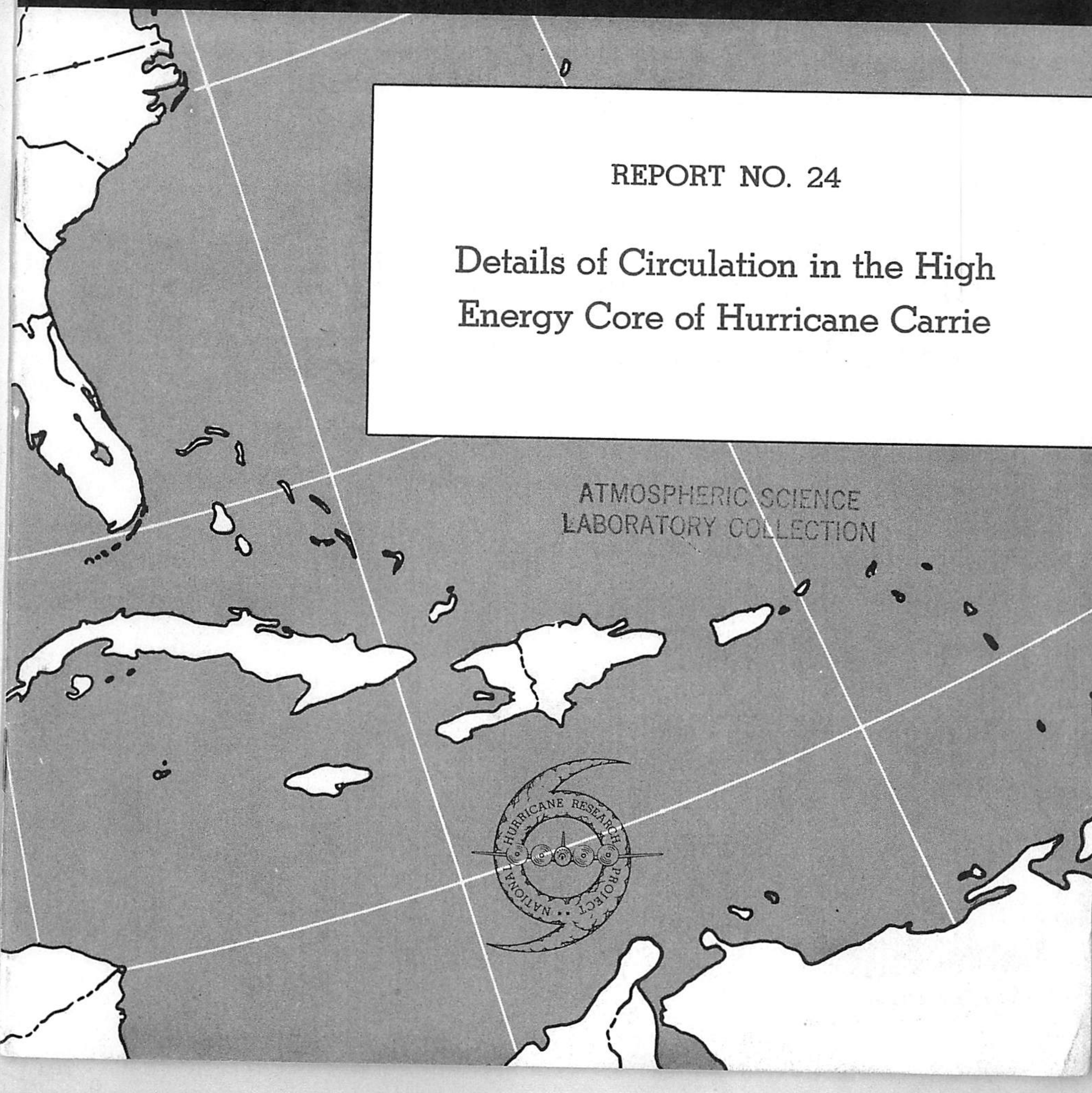
ONAL HURRICANE RESEARCH PROJECT

REPORT NO. 24

Details of Circulation in the High Energy Core of Hurricane Carrie



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

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Details of Circulation in the High Energy Core of Hurricane Carrie

by

Staff, National Hurricane Research Project, West Palm Beach, Fla.

Washington, D. C.
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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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DETAILS OF CIRCULATION IN THE HIGH ENERGY CORE OF HURRICANE CARRIE

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1. INTRODUCTION

During the past two decades considerable information on the thermodynamic properties and circulation of hurricanes has been acquired gradually from sounding balloons and from reconnaissance aircraft. Various summaries of these data (e.g., E. Jordan [3] and B. I. Miller [5]) have proved useful in studying energy processes in the hurricane (e. g., Palmén and Riehl [7]). Until recently, however, there have never been enough observations made within a short period of time to describe synoptically the details of hurricane circulation at any level. Moreover, there has been little or no sounding information from the general areas of the storm vortex where the greater portion of the kinetic energy is concentrated.

One of the primary objectives of the National Hurricane Research Project has been to obtain observations from the storm core on a space and time scale which would permit the circulations in this area to be described synoptically, and further quantitative studies of the energetics of the hurricane heat engine to be made. As of this writing the research aircraft of NHRP have flown 32 missions into tropical storms of various sizes and stages of maturity. On seven of these occasions, two planes were in the storm at the same time, collecting data at two or more levels, and on two occasions three aircraft entered the storm simultaneously and collected information at levels ranging from 1500 feet to 35,000 feet. For a description of the instrumentation of the research aircraft see NHRP Report No. 11 by Hilleary and Christensen [1]. The most complete description of a single hurricane was obtained during flights into hurricane Carrie on September 15 and 17, 1957. The findings presented here are based entirely on data from these flights. However, most features of circulation represented by the Carrie data have been reflected in the data from other hurricane missions (e.g., LaSeur [4]), though generally in less detail. Nevertheless, any conclusions based upon these descriptive materials must necessarily remain tentative until additional complete data samples can be obtained to determine just how well these circulations found in Carrie represent those of hurricanes in general. It is intended that the material presented here serve only to describe the circulation of Carrie and to summarize the implications which may be drawn therefrom. A more specific treatment of dynamical and thermodynamic aspects of these data will be the subject of subsequent reports.

2. GENERAL CHARACTERISTICS OF HURRICANE CARRIE

Hurricane Carrie [6] was one of the longest lived hurricanes of record. When the first reconnaissance flight into the storm was made on September 7, 1957, some thousand miles east of the Lesser Antilles, it already had

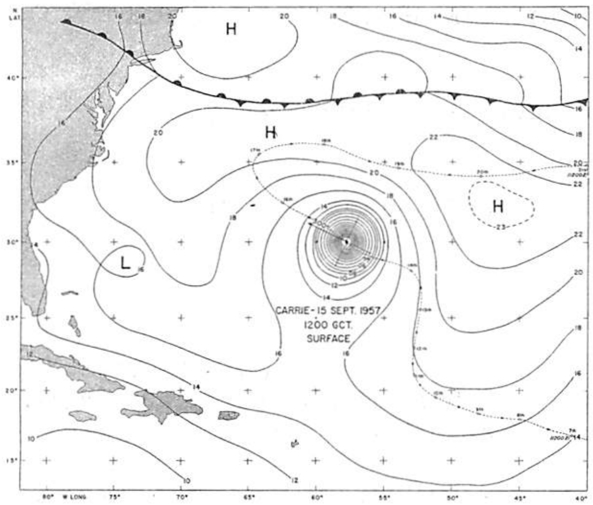

Figure 1. - Sea level pressure map. Hurricane Carrie, September 15, 1957.

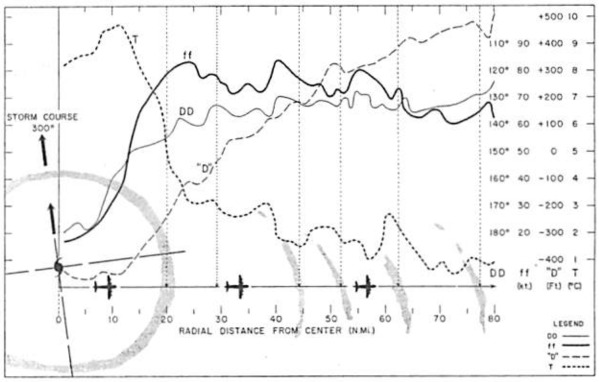

Figure 2. - Profiles of wind, temperature and D-value from the storm center north-northeastward. September 15, 1957.

hurricane-force winds. Before recurving northward along the 52d meridian, its central pressure was reported as low as 945 mb. Subsequently it filled and after September 12 its central pressure was never lower than 960 mb. On September 14 Carrie was deflected once again to a west-northwestward course until it finally recurved eastward late on September 16. During the flight of September 15 the storm was moving on a course of 300° at approximately 12 knots, and on September 17 after recurvature its course was 70° at approximately 12 knots. The central pressure on both days was 960-965 mb., the storm was fully mature, and had an eye whose diameter was 40 miles on the 15th and 50-60 miles on the 17th. The storm area contained numerous spiral rainbands on the 15th, but on the 17th there were virtually no bands present. On both days, however, the eye was well formed with walls rising on all sides to about 38,000 feet. Figure 1 is a surface analysis for the western Atlantic on September 15 showing the track of the hurricane.

3. RADIAL PROFILES OF WIND, TEMPERATURE, AND PRESSURE

The most complete coverage of observations was obtained from reconnaissances at 14,000 and 11,000 feet. Flights were planned to provide a succession of diametrical traverses through the center of the storm so that one or more radial profiles would be available from all quadrants. Figure 2 is a typical radial profile of data for 14,000 feet. The abscissa represents the radial track flown by the aircraft. In order that the variation of elements recorded may be associated with the principal hydrometeors traversed by the aircraft, the eye wall and the several rainband segments encountered by the aircraft have been schematically superimposed.

In general this profile exhibits the kinetic and thermal properties to be expected in an intense warm core circulation. Of curious interest, however, and perhaps the most striking feature of these data, is the striated character of the temperature and wind speed profiles. As the plane left the eye center, the wind increased rapidly to more than 70 knots before the clouds of the eye wall were penetrated, then on to a maximum of 83 knots about 25 miles from the center. Beyond this, a succession of wind maxima and minima were observed as the plane proceeded outward through the vortex. After a second 83-knot maximum at a radius of 42 miles, still a third maximum was encountered at 55 miles, and a fourth at 78 miles from the center. These four maxima occurred while the aircraft was traversing five major rainbands (including the eye wall) and one minor band. The vertical located about 29 miles from center is the position where the aircraft crossed the axis of a dissipating rainband in which there were active convective elements to either side of the track. The location of these wind maxima apparently do not occupy unique positions relative to the rainy areas identified by radar.

The temperature profile reveals similar (though not corresponding) fluctuations rather than a steady decrease outward from the storm core. While in general there is a trend toward more pronounced temperature falls through the rainey sections, the salient maxima and minima do not occupy unique positions relative to the rainband areas identified by radar. Moreover, there is little evidence that the variations observed could have been due primarily to wet-bulb effects.

The profile of D-values[1] reveals a rise of 950 feet in a horizontal distance of 80 miles from the center. Here also there are apparently systematic variations in slope of the profile. However, variations of this profile seem to be associated specifically with the rainband segments and were observed generally on the high pressure side of the radar echo similar to those previously reported by Simpson and Starrett [8].

In attempting to associate spatially the observed striations with the spiral rainband segments identified by radar, one must remember that the radar echoes represent rain areas and do not identify uniquely the regions of maximum convection. J. Malkus[2] has recently pointed out that rainband convection tends to be displaced horizontally from regions of maximum rain identified by radar, and that this displacement varies with height, due to wind shear and other factors. She proposes the model in figure 3 for relative distribution of convection and rain in the spiral bands of the hurricane.

Finally, figure 2 shows, perhaps more graphically than usual, how very concentrated are the primary changes in thermal and kinematic properties about the eye. Most of the wind and temperature change at this elevation occurs within a radius of 10-25 miles from the center.

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[1] D-value as used here refers to the difference between the observed height and standard (atmosphere) height of the pressure surface along which the aircraft flew.

[2] Personal communication to Director, NHRP.

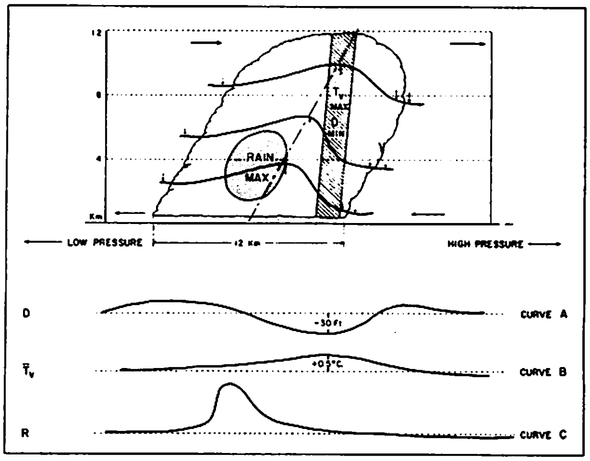

Figure 3. - Model of radial section through an active convective rainband (J. Malkus). The convective Chimney may slope by about 45° radially outward if inflow occurs at low levels and outflow higher aloft. Thus the axis of maximum updraft and maximum buoyancy may have a 45° slant from vertical and the active convection bubbles would follow this slanting path. If they should succeed each other sufficiently rapidly the mean draft structure and buoyancy structure would follow the solid wavy lines. Thus a vertical column having maximum mean virtual temperature (and minimum D) would be produced, indicated by the shaded column. The maximum liquid water and drop size, on the other hand would be as designated in curve C, because maximum liquid water must occur in the middle cloud region and thus be displaced toward low pressure from the max. $\overline{T}_v$ and min. D. Cloud physics studies have shown that maximum water contents are mainly at lower levels and thus in a slanting cloud column would be displaced radially inward.

4. DATA COMPOSITING FOR SYNOPTIC ANALYSIS

A cursory examination of data from various radial tracks flown through hurricanes reveals significant asymmetries from quadrant to quadrant. These tend to limit the use which can be made of a single profile of data in studying the dynamics of the vortex. For example, radial components of motion relative to the center might well indicate net mass inflow in the right rear quadrant and pronounced net outflow in the left front quadrant. Therefore, to study the dynamical properties of the vortex as a whole, it is necessary to have data from each quadrant which can be analyzed synoptically. Ordinarily it takes an airplane 3-4 hours to collect data for this purpose. This means that individual observations must be adjusted in space to account for the travel of the storm during the period of data collection. In addition, some cognizance must be taken of changes due to non-steadiness of circulations during the period. The latter is more difficult, and no suitable means has been found to deal with it. The former is not difficult, and is discussed here mainly because of the problem which arises in defining and specifying the hurricane center about which data must be composited for quasi-synoptic analyses.

The compositing or repositioning of observations collected from the vortex of a moving hurricane over a 3- or 4-hour period, ordinarily involves the computation of a virtual latitude and longitude for each data point. This relocates the point geographically about the mean position of the hurricane so that all observations are at the same azimuth and distance from the storm center as they were at the time the data were recorded. This is done with an electronic computer which calculates the adjusted position as a function of time, in terms of initial position of data and the successive positions of the hurricane center. It was soon apparent that relatively small differences in identification and tracking of the center could make the difference between a homogeneous appearance of data or serious discontinuities — the important question being, how shall the center of the hurricane be identified? A hurricane can be located in terms of a (1) pressure center, (2) circulation or wind center, (3) temperature center, (4) geometric center of the radar eye, or (5) geometric center of the ring of maximum kinetic energy.

The eye wall can be considered in effect as a substantial surface. Inside the eye, horizontal circulations, pressure, and temperature gradients are not a direct consequence of the circulation dynamics in the rain area. Rather they are a product of — and to a considerable extent a manifestation in eddy form of — the subsidence and other vertical motions in the eye and of convective scale motions surrounding the eye. They are perhaps the least conservative of hurricane properties. Intuitively one is led to the concept that the effective center of the hurricane, as an atmospheric heat engine, is the geometric center of maximum kinetic energy. This more conservative center can not always be specified with ease from data customarily available. However, the geometric center of the radar eye wall, or region of maximum convergence, is a closely related center and is more readily and continuously observable. The convention finally adopted and used in compositing data for the analyses which follow is to identify the hurricane center as the geometric center of the radar eye. This means of compositing has consistently produced the most uniform tracks and homogeneous data groupings. It suffers the obvious deficiency that not all hurricanes have closed or circular eyes. Moreover the problem of time variations in circulations still remains unsolved. Nevertheless in the samples collected to date, it has not been necessary to do more than minor smoothing of data to obtain the kind of analyses presented here.

5. CIRCULATIONS AT 14,000 FEET

Enough radial passes were made at 14,000 feet to permit reasonable analyses of wind, temperature, and pressure for all quadrants of the storm. These are shown in figs. 4-8.

Figure 4 is an analysis of isotachs at 14,000 feet on September 15. This indicates that the striations of wind speed observed in the radial profile of figure 2 are not local in nature, but, rather have continuity from quadrant to quadrant. While it is not contended that the data, copious as they were in this and succeeding analyses, eliminate subjectivity and the need for interpretation, these analyses have been completed without appreciable smoothing or violation of individual data points.

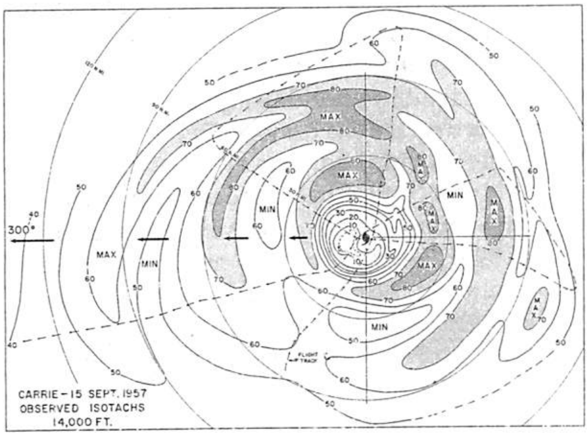

Figure 4. - Wind speed field (knots) at 14,000 ft. for Hurricane Carrie, September 15, 1957.

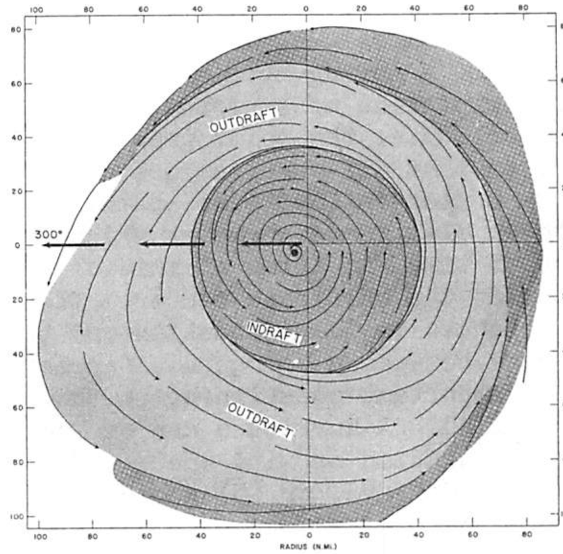

Figure 5. - Streamlines at 14,000 ft. for Hurricane Carrie, September 15, 1957.

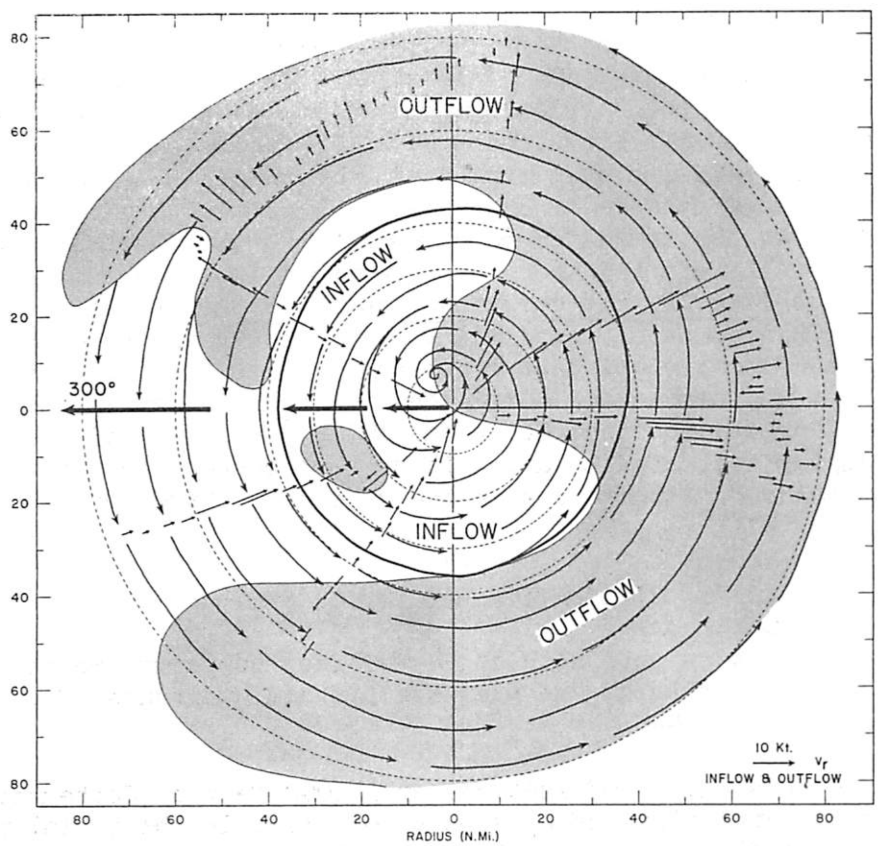

Figure 6. - Relative streamlines (motion of the storm center subtracted from the observed winds) at 14,000 ft. for hurricane Carrie, September 15, 1957. Individual arrows indicate radial components of the relative winds (length of arrows scaled to represent speed).

Figure 5 is a streamline analysis which corresponds to the isotach pattern in figure 4. The most interesting feature of this analysis is the circular asymptote of streamline divergence at a radius of approximately 40 miles from the storm center, a cyclonic outdraft extending toward higher pressure and cyclonic indraft toward low pressure. If one subtracts from the observed winds the vector of storm travel, the circulation residue relative to the storm center is much more symmetrical. This is quite evident from the relative streamlines in figure 6. Upon first inspection, the circulation here would appear to be almost pure rotation. However, an analysis of radial components of the wind reveals a horseshoe pattern of radial outflow surrounding the center, with equally pronounced radial inflow near and immediately ahead of the storm center. The radial outflow at these levels was indicated in the mean data of Miller [5], although the mean data failed to indicate the selective region of inflow. Again, the circular asymptote of streamline divergence appears at a radius of approximately 40 miles with gradual cyclonic indraft toward lower pressure.

If there is indeed pronounced inflow to the very core of the hurricane through the forward quadrants and outflow through the rear quadrants, then the storm core must experience a ventilation action in which colder environmental air is mixed with warm rising currents of the storm, a factor recently identified by Riehl[3] as one which tends to reduce the efficiency of the hurricane heat engine and throttles the release of kinetic energy. The amount of ventilation occurring is illustrated by the vectors of relative radial motion computed from spot measurements of wind by the research aircraft and superimposed on the streamline analysis of figure 6.

The presence of cyclonic indraft in the storm core is of special interest for several reasons. If it may be assumed that (1) the circulation pattern is characteristic, and (2) the circulation remains reasonably steady, then a constant level balloon released in the eye of the storm at this level would move to and remain near the storm center and could serve as a positioning device for the moving storm (e.g., see hurricane beacon [9]).

Figure 7 is an analysis of isotherms at 14,000 feet. Here the analyst envisages circular continuity of a striated character of the temperature field similar to those of the wind field. However, because of the more frequent, though systematic, radial fluctuations in temperature there is more subjectivity in this analysis than was the case for the isotach analysis of figure 4.

Figure 8, a contour analysis based upon D values, indicates that while there is greater symmetry in the pressure fields at the core than there is in either wind speed or temperature, there are numerous local disturbances to the pressure field, probably associated with pronounced convective activity in certain segments of the spiral rainbands and hence of a transitory nature. Of considerable interest to the problem of kinetic energy production is the cross-contour motion indicated by the radial components of the observed wind. These individual observations, superimposed on the contour analysis, indicate

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[3]Unpublished notes, March 1958.

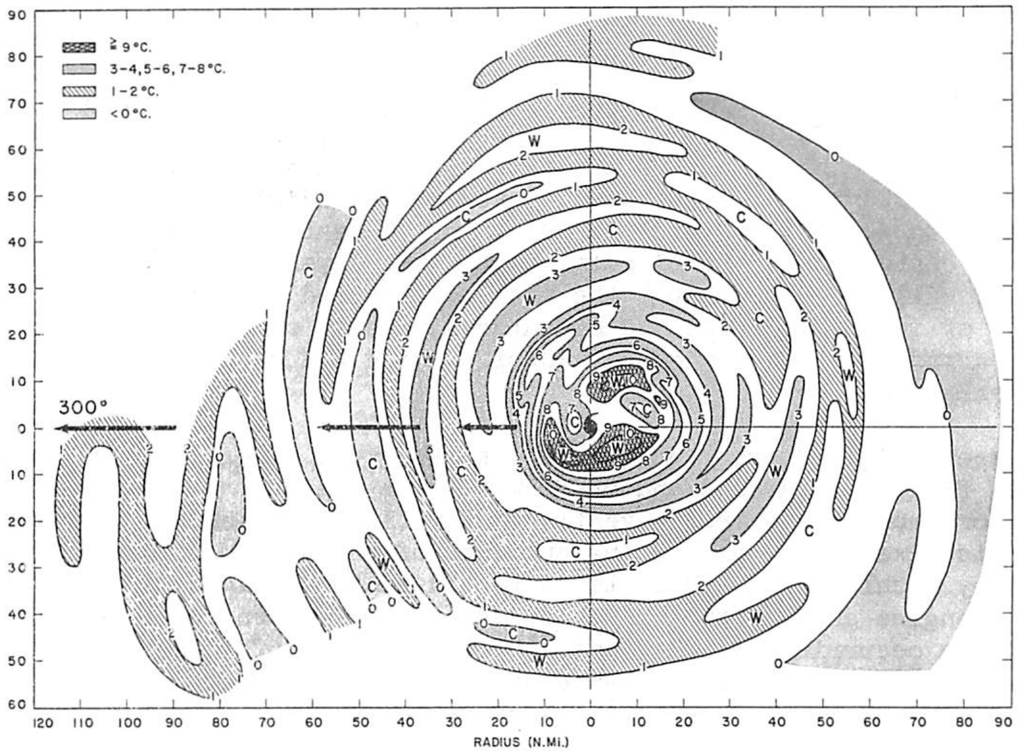

Figure 7. - Temperature distribution at 14,000 ft. for Hurricane Carrie, September 15, 1957.

that, instantaneously, there is net outflow towards higher pressure, a kinetic-energy-absorbing process.

6. CIRCULATIONS AT 35,000 FEET

Indications are that the striations of wind speed observed at 14,000 feet tend to prevail throughout the lower and middle troposphere. Figure 9 indicates that remnants of these striations remain even at 35,000 feet where the B-47 research plane flew near the top of the cirrostratus outflow of the storm while these data were being collected. Here the circulation is predominantly a cyclonic outdraft except over a small area near the center where there is a cyclonic indraft. This pattern is essentially preserved in the relative motion field. On the other hand, temperature at 35,000 feet, analyzed in figure 10, reveals no evidence of the striations which were prominent at 14,000 feet. Here the considerable temperature gradient in the eye itself appears to stem from subsidence.

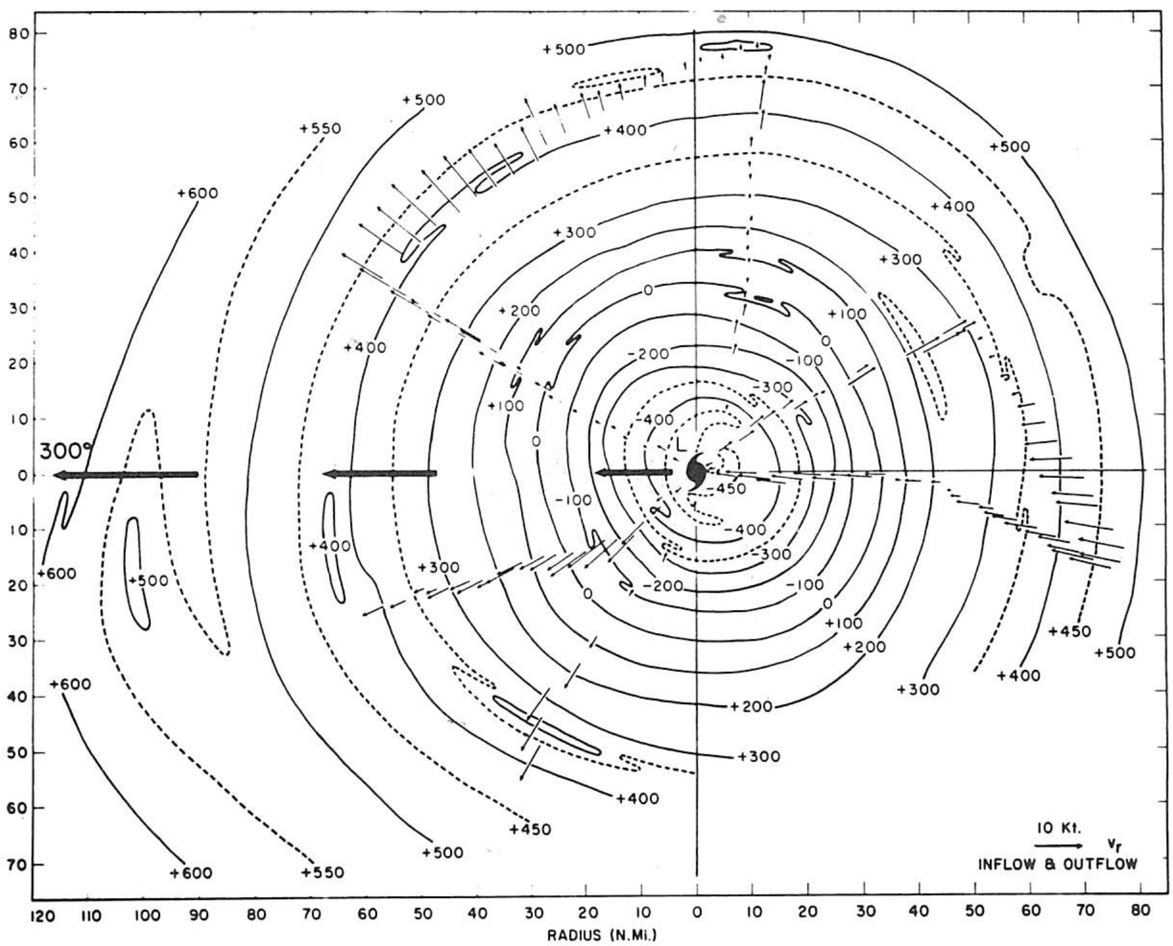

Figure 8. - Contour chart (D-values) at 14,000 ft. pressure altitude for Hurricane Carrie, September 15, 1957. Individual arrows represent radial components of the observed winds (length of arrow scaled to represent speed).

7. COMPARISON OF CIRCULATIONS BEFORE AND AFTER RECURVATURE

Hurricane Carrie remained approximately the same in overall size and intensity, and there was little change in central pressure between the reconnaisance of September 15 before recurvature and that on the 17th after recurvature. Moreover, the total kinetic energy both in the middle troposphere and the high troposphere remained essentially unchanged. There were, however, two noticeable differences. First, the radius of maximum wind had materially increased on the 17th, and second, there was a minimum of organized convection in the form of spiral rainbands on the 17th. While striations of temperature and wind were observed on the 17th as on the 15th, they were greatly dampened on the 17th and in some quadrants almost absent. This would suggest that

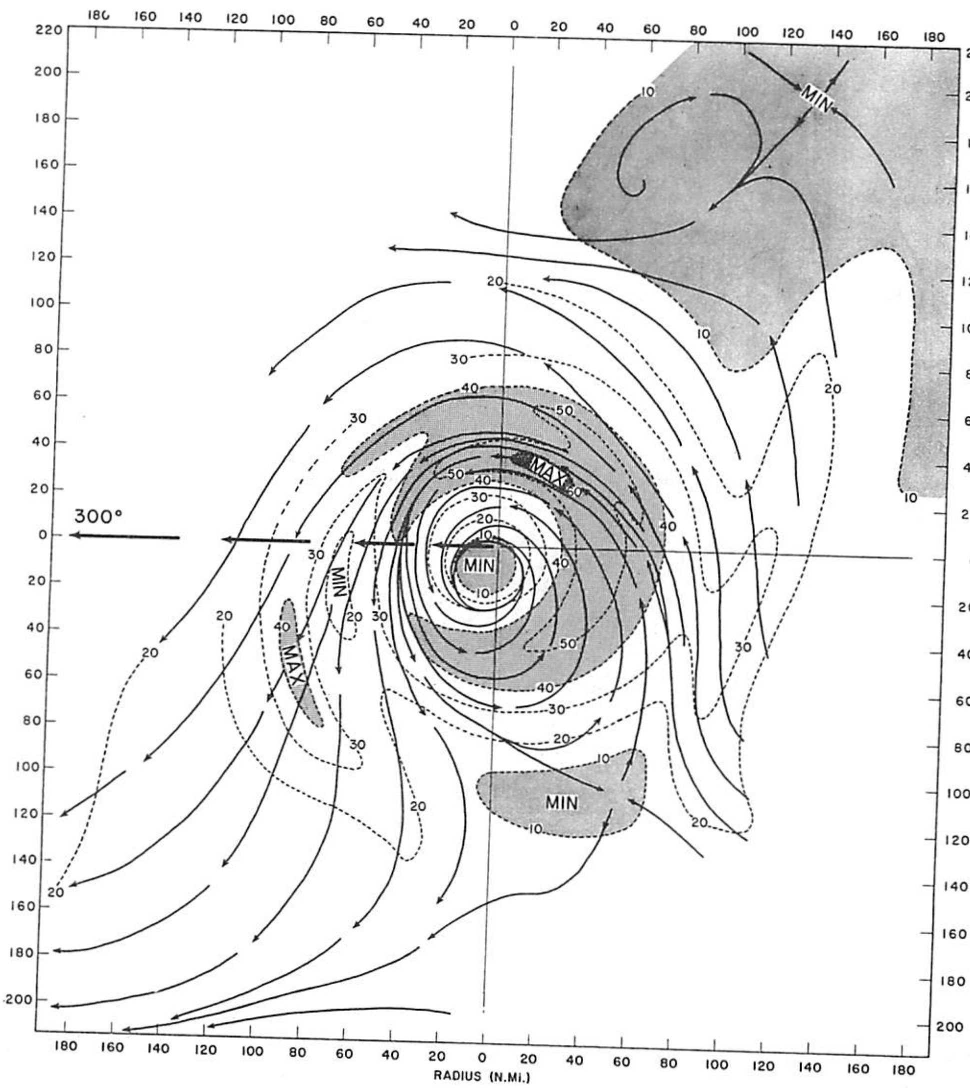

Figure 9. - Streamlines and isotachs (knots) of the observed wind field at 35,000 ft. for Hurricane Carrie, September 15, 1957. Winds measured by B-47 reconnaissance aircraft.

while the striations may not be the local result of convection in a rainband segment, they most likely are associated systematically with the rainband system as a whole, their prominence depending therefore on the degree of development of the spiral rainbands.

Figure 11 shows the isotach pattern at 11,000 feet on September 17, and figure 12 shows the corresponding streamlines. In figure 11 the salient features of figure 4, including the outdraft spiral of wind speed maxima, are preserved. Also, in figure 12 the asymptote of divergence, a prime feature on the 15th (fig. 5), is again present and similarly located.

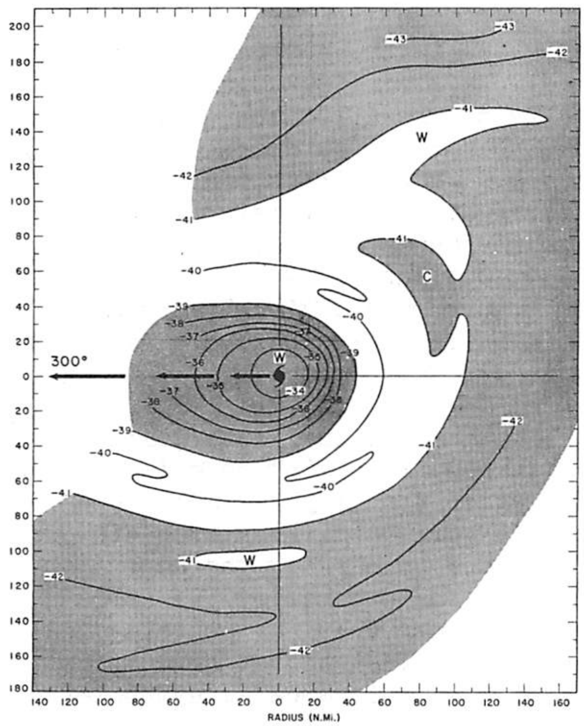

Figure 10. - Temperature field at 35,000 ft., September 15, 1957, as measured by research aircraft.

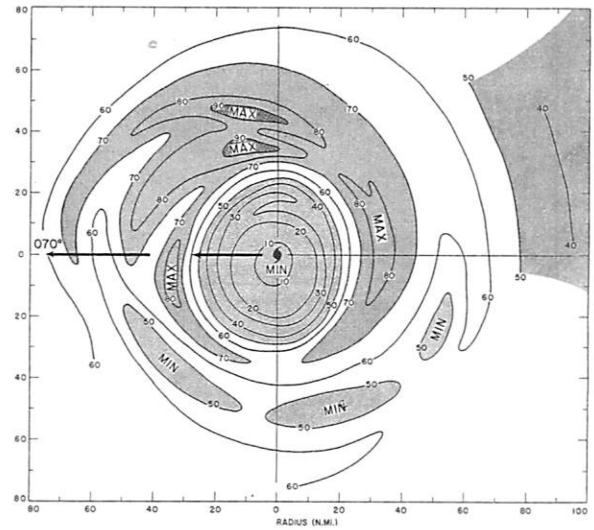

Figure 11. - Wind speed field at 11,000 ft., for Hurricane Carrie, September 17, 1957.

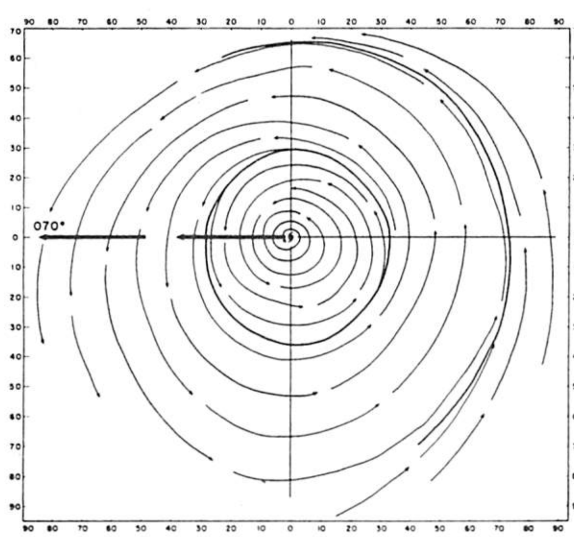

Figure 12. - Streamlines for 11,000 ft. for Hurricane Carrie, September 17, 1957.

8. SIGNIFICANCE AND SOURCE OF WIND SPEED STRIATIONS

It is reasonable to assume that the striations observed either stem directly from imbalances which develop in the vortex and are therefore of relatively short duration, or comprise a characteristic part of a circulation complex and thus may tend to persist. While not enough information has been collected to decide between these two possibilities on the basis of steadiness of circulations, it is significant that striated patterns have been observed in every hurricane investigated by the research aircraft supporting the NHRP, and the patterns observed have had continuity and have persisted over the period of hours in which the research aircraft were in the storm. Certainly the wind speed patterns are more persistent than the spiral rainband segments which continually change intensity and form.

In any event observational data make it clear that the striations of

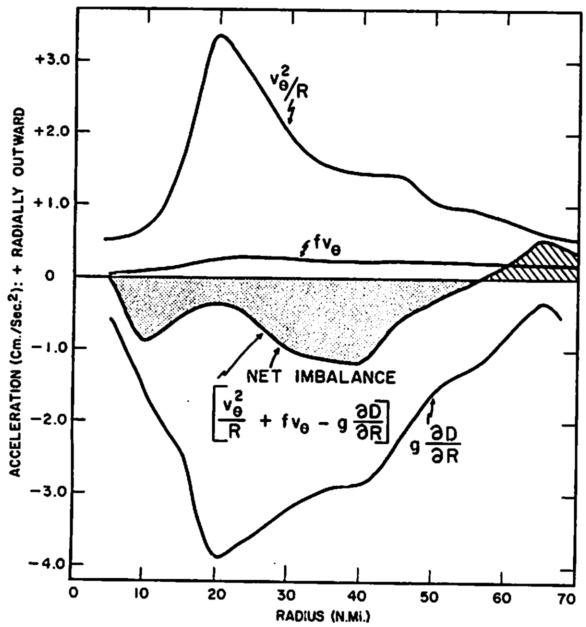

Figure 13. - Resultant mean forces causing horizontal acceleration of the tangential wind at 14,000 ft. in Hurricane Carrie, September 15, 1957. The pressure gradient, Coriolis and centrifugal forces are means for successive concentric circles, and are based upon analyzed rather than individually observed values. Acceleration is considered positive outward.

wind speed in the hurricane vortex are not simply a manifestation of the squally outflow from convective cells or rainbands of the storm, as in thunderstorms where air is dragged down to the surface by heavy rain and causes large increases in surface wind as it spreads out laterally. The striations in the hurricane obviously are as prominent in mid-troposphere as they are nearer the surface.

Until additional data samples can be obtained, including more detailed information from layers near the surface, it will be difficult to draw conclusions concerning the source or ultimate significance of the striations, whether they may be relegated as noisy manifestations, or must be treated with deference as symptomatic elements of a circulation complex.

9. ACCELERATIONS IN THE HURRICANE VORTEX

Figures 6 and 8 reveal that net outflow toward higher pressure was present in the middle troposphere on September 15. Radial components vary from quadrant to quadrant with mainly inflow in the forward sectors, but with outflow laterally and to the rear of the storm center. In view of the extensive information available at 14,000 feet, it has been practicable to examine by quadrants and for the vortex as a whole the balance of forces which sustain the gradient wind. By considering only tangential components V_θ of the wind, the gradient wind relation may be expressed as follows:

$$\frac{V_\theta^2}{R} + fV_\theta = g\frac{\partial D}{\partial R}$$

in which R is the radial distance from the storm center positive outward. Figure 13, based upon the analysis of circulation at 14,000 feet, shows the mean cyclostrophic, Coriolis, and pressure gradient forces acting in the hurricane vortex at this level together with the net imbalance of these forces available to overcome frictional decelerations and tending to produce acceleration of the wind. The mean values are based upon averages of tangential wind speeds and pressure gradients from twelve equi-spaced points on each of 13 concentric circles about the storm center. Circles were spaced 5 nautical

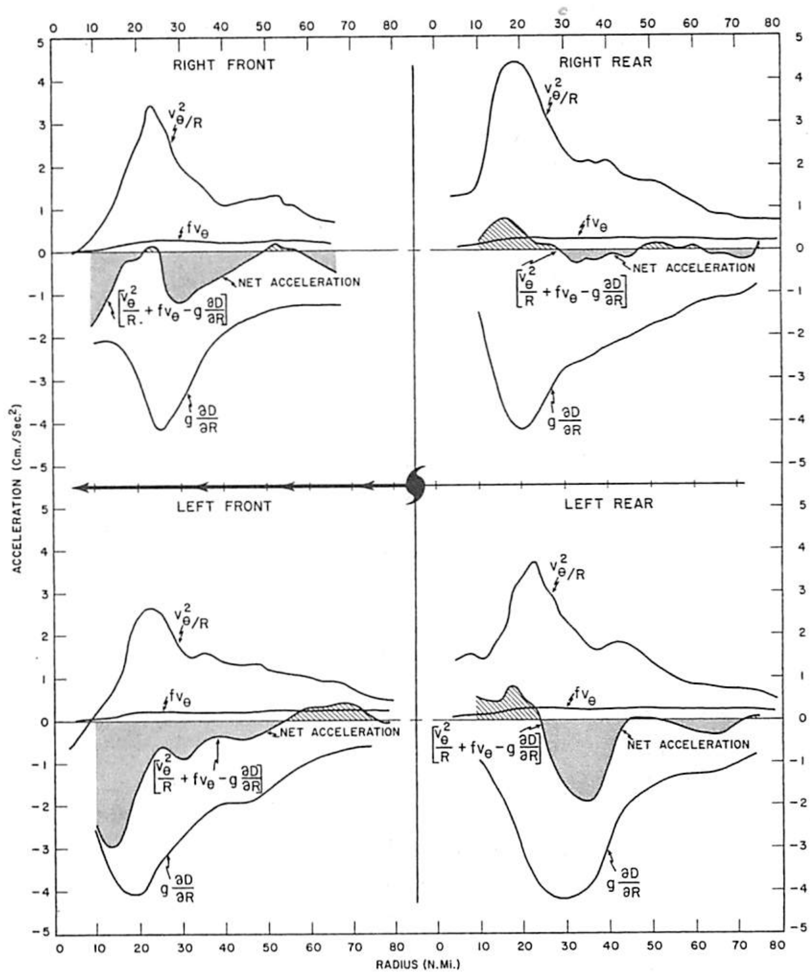

Figure 14. - Resultant forces tending to cause horizontal acceleration at 14,000 ft. in each quadrant of Carrie, September 15, 1957. These computations are based upon radial profiles of recorded data in each quadrant, rather than upon analyzed values as in figure 13. Acceleration is positive outward.

miles apart. The acceleration potential is at a minimum at the eye wall and near the circular asymptote of divergence in figure 6. It is at a maximum in the eye and at a radius of 35 to 40 nautical miles from the center (on the low pressure side of the asymptote of divergence).

Figure 14 shows the imbalance of forces tending to cause acceleration of the gradient wind in each storm quadrant at 14,000 feet. These data are for radial profiles flown by the aircraft rather than from analyzed values as in figure 13. For purposes of computation, running averages of V_θ were obtained for distances of 5 nautical miles; likewise the D-value profiles were smoothed to provide conservative estimates of pressure gradient forces useful for this computation. The net potential acceleration of the gradient wind is essentially the same here as represented by the mean in figure 13 with the exception that marked acceleration toward the storm center is indicated in the forward quadrants near and in the eye, while in the rear quadrants potential acceleration in the eye is away from the center. Minimal acceleration is indicated in the vicinity of the circular asymptote of divergence (fig. 5). It is also interesting that in the right rear quadrant, acceleration is much smaller than in any other quadrant.

10. CONCLUSIONS

Insofar as these data from hurricane Carrie are representative of a mature hurricane circulation – and there is no reason to suspect that they are not – they show that a number of circulation features in the high energy core of the hurricane differ from those which have been deduced by extrapolation and from scattered observations previously available. The most prominent of these is a striated distribution of wind speed, temperature, and pressure, which seems to have a systematic character. While the hurricane is a warm core storm and its kinetic energy necessarily must decrease with height, the striated pattern of wind speed appears to be conserved with height through the low and middle troposphere, and maximum winds near the surface in the hurricane tend to be conserved into the upper troposphere. The most intense gradients of the temperature, wind, and pressure are concentrated in a narrow band about the center extending from about 8 miles inside the eye wall outward through the wall cloud. Outflow in the middle troposphere works against the pressure forces and dissipates part of the kinetic energy produced in the hurricane. Finally, a computation of forces tending to accelerate the wind at 14,000 feet is qualitatively in analytical agreement with the observed wind circulation including the ventilation of the hurricane by currents which accelerate into the core in advance of the center and out of the core through the rear quadrants.

ACKNOWLEDGMENTS

The entire staff of the Research Operations Base of the National Hurricane Research Project participated either in processing or analyzing the data for the research flights into hurricane Carrie or in preparing this paper for publication. The authors also wish to acknowledge the stimulating discussions of the data which they had with Prof. Herbert Riehl, Prof. Jule Charney, and Dr. Joanne S. Malkus.

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