NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 69

A Study of Hurricane Rainbands

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

NATIONAL HURRICANE RESEARCH PROJECT

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by

R. Cecil Gentry

National Hurricane Research Project, Miami, Fla.

Washington, D. C.
March 1964

NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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A STUDY OF HURRICANE RAINBANDS

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ABSTRACT

The structure and variability of the spiral rainbands of hurricanes are described using data from more than 75 rainbands selected from tropical cyclones that occurred between 1957 and 1962.

Temperature gradients within the bands are as much as 2.5°C. per 2 n. mi. and are frequently greater than 1.5°C. per 10 n. mi. The anomaly of the mean temperature in the bands varies directly with the intensity of the storm, directly with altitude at least to above the 16,000-ft. level, and inversely with radius in the area within about 50 n. mi. of the eye wall.

Winds along the bands vary greatly and apparently in association with microscale features of the band. Gradients in wind speed frequently exceed 10 kt. per 5 n. mi. and sometimes exceed 20 kt. per 5 n. mi. These gradients in wind speed are not as great as those along radii near the center of the storm, but are far greater than previously indicated for variations along the bands.

Relatively extensive exchange of air takes place both in the outer bands and in the eye walls, and between the various bands and their immediate environments. This is indicated by the large gradients of the component of the wind normal to the bands both within the bands and in the air 1 to 5 mi. on either side of the bands. There is evidence that a small portion of the air that ascends from near the surface to the upper troposphere may accomplish the ascent with very little mixing with ambient air, but most of the air that reaches as high as 35,000 ft. has been thoroughly mixed with other air at the various elevations between that level and the surface. This mixing affects the temperature distribution within the hurricane as well as the energetics of the storm.

Variations of the equivalent potential temperature in the bands are appreciable both with radius and with height but the change with height is relatively small in the eye wall. These variations can be accounted for by a combination of the following: (1) transfer of sensible and latent heat from the ocean to the air spiralling inward near the surface: (2) mixing; (3) release of latent heat of fusion in the upper troposphere; (4) melting of ice particles in the middle troposphere; and (5) other diabatic effects. The distribution of the equivalent potential temperature is used as a basis for deductions concerning the vertical component of the circulation through the storm and to help verify various hypotheses which have been advanced by earlier investigators.

The asymmetrical distribution of rainbands in hurricanes and the variability of the asymmetries are illustrated by the data from four hurricane days. The importance of these asymmetries to development of numerical models of hurricanes is discussed.

The vertical motions and temperature anomalies within the bands in the high energy portions of the storms are significantly correlated and to such a degree that the coexistence of ascending warm currents and descending cold currents in the bands can produce almost as much kinetic energy by conversion from potential energy as previous budget studies by other investigators have indicated to be generated from all sources in the average hurricane. Evidence is presented to show the importance of rainbands to the energetics of the tropical cyclone.

1. INTRODUCTION

The first radar images of tropical cyclones revealed a spiral rainband structure that was soon identified as being typical of such storms. Since this phenomenon was first reported by Maynard [28] and Wexler [51], many studies of it have been made by such investigators as Ligda [24], Kessler and Atlas [18], Fujita [10], Senn and Hiser [39], Senn, Hiser, and Stevens [42], Riehl and Malkus [37], Ackerman [1, 3], Atlas et al. [4], and others. A radar picture of a hurricane and its bands is shown in figure 1. This is a picture of an unusually intense, mature hurricane (Donna of 1960), but the spiral band structure is typical of nearly all the tropical cyclones that are not in either the early formative or advanced dissipating stages.

The apparent organization of the principal cloud systems into an organized spiral band pattern and the implication that most of the latent heat released in a hurricane is made available through these channels, rather than either symmetrically around the center or in randomly distributed convective towers, has stimulated the interest of many research meteorologists. There have, therefore, been many attempts to describe rainbands and to explain their origin. None of these explanations has been completely satisfying and the descriptions have been mainly restricted either to listing the events associated with passage of a band that could be observed at the ground or to describing what can be observed on the radarscope. The latter, furthermore, has been mostly restricted to the geometry and kinematics of the echoes and deductions about the distribution of water through the bands. Little information has been introduced to portray the structure of the atmosphere in the band, the variation of temperature and wind within the band, or to show the role of the bands in the production of kinetic energy and other aspects of storm structure and the maintenance of kinetic energy within the high energy portions of tropical cyclones.

The first description of the surface weather associated with passage of a rainband was furnished by Wexler [51]. He analyzed radar pictures and surface weather reports from a hurricane that traversed Florida in 1945, and reported that passage of a rainband over a point was accompanied by squalls, heavy rain, shift in wind direction, increase in wind speed, a large temperature fall, and a temporary dip and recovery in the pressure. These same events have been reported to a greater or lesser extent by many of the later

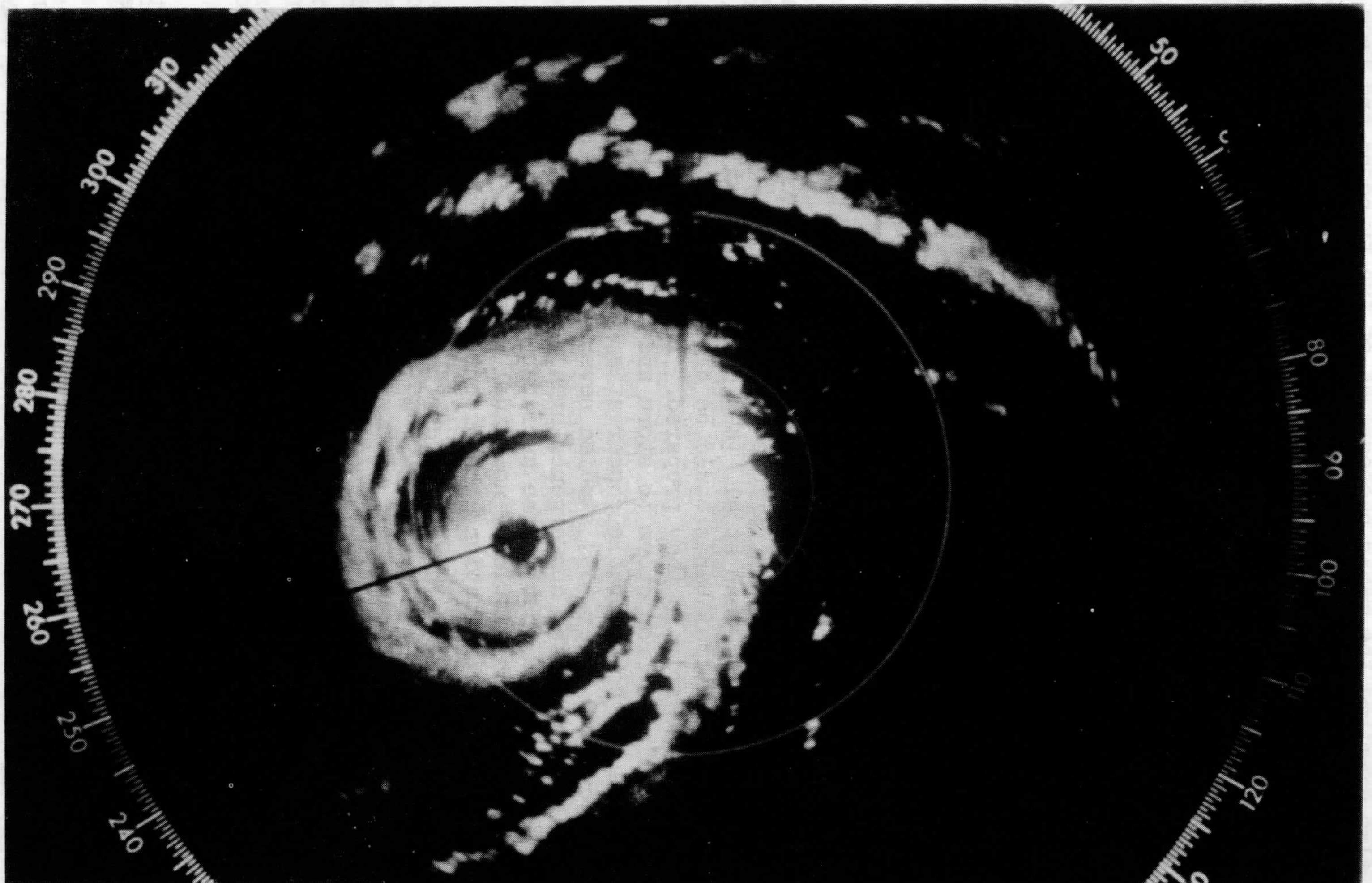

Figure 1. - Hurricane Donna and its rainbands as seen on radarscope at Miami, Fla., September 10, 1960.

investigators, except that the temperature change has not always been a noticeable drop.

Wexler also examined the radar photographs of two typhoons and from these pictures and those of the hurricane in 1945 reported several deductions concerning the geometry and kinematics of the storms. He wrote: (1) bands near the storm center were frequently arranged in parallel rows and were quite distinct; (2) there was great variation in the width of the bands and in the distance between them; (3) bands spiralled inward toward the center; (4) bands were regions where water drops were concentrated and hence contained sizable upward currents; (5) the bands were essentially streamlines of horizontal motion; and (6) the bands were relatively symmetrical with respect to the storm center when the latter was over the ocean but became asymmetrical after the storm passed over land.

We now know that winds near the earth's surface blow across the bands toward lower pressures (Ligda [24] and Senn et al. [40]); those in the middle and upper troposphere blow across the bands toward higher pressures (Colón et al. [8], and Staff, National Hurricane Research Project [48]; and the bands may not be symmetrical about the storm center even when the storm is over the ocean, but otherwise the same general observations and deductions have been made about later tropical cyclones.

The geometry and the kinematics of the bands and the echoes have also been studied by Ligda [24], Senn and various co-workers [39, 40, 41, 42, 43], Fujita [10], and Jordan [16]. Senn et al. [40] developed a set of spiral overlays and found that most rainbands could be closely approximated in shape by one of the three spirals they prepared. Although the shape of the spiral varied within limits from storm to storm and to a lesser extent within a storm, there was considerable conservatism in the shape of any particular band. Senn and Hiser [39] studied several storms and concluded that the bands originated in the convergence area near the eye wall and moved outward. Ligda [24] reported that in the hurricane of August 1949 which passed over Florida there was little or no actual rotation of the bands around the eye, but that precipitation echoes continually formed at the outer end of the bands and moved through and disappeared at the inner end. Fujita [10] found a band in which echoes propagated at different rates, such that one portion of the band became more elongated with time while, simultaneously, an adjacent portion became shortened with the rate of expansion and shrinking varying up to 6 kt. in absolute value.

Various investigators have tracked individual echoes to measure the rate of movement in the hope of getting an estimate of wind speed and direction (Ligda [24], Jordan [16], Senn, Hiser, and Nelson [41], and Senn, Hiser, Stevens, and Low, [43]). Varying results were obtained since different techniques were used. In some cases the echoes appeared to move with about the speed of the wind or slightly faster and in other cases the echoes moved more slowly than the best estimate of the wind. It has, however, been impractical to determine satisfactorily the relationship between rate of echo movement and wind speed because on very few occasions have satisfactory radar pictures and upper air wind measurements been obtained simultaneously.

Many of the investigators already named have commented on the relatively short duration of both echoes and bands. Most of the bands are difficult to identify as separate entities after 1 or 2 hr., and the intermediate sized echoes can be traced on the average for only about 35 min. (See Senn et al. [40], and Ligda [24]).

Most investigators have emphasized that the inner bands appear to be rather uniform even though several commented on the cellular structure of the outer bands. There have been few if any hints in the literature that the wind, temperature, and other parameters might vary appreciably along the bands as well as across the bands. Wexler [51] in his pioneer paper had reported that the bands far removed from the center had cellular or granular structure and that this structure probably denoted individual showers. This feature is also obvious in the radar photograph in figure 1. Ligda [24] reported that for the 1949 storm there was a distinct difference in the inner and outer bands and that the former presented a diffuse, uniform appearance while the latter appeared to be composed of convective elements. Atlas et al. [4] also affirmed that the major well-developed bands were all composed of diffuse and uniform echoes except that each usually had a sharp convective type echo at the upwind end of the band. In some cases another convective type echo would appear downwind from this original echo. All of these observations were reported with the implication that the inner bands would be rather uniform and that the main gradients in meteorological parameters should be normal to the bands. Jordan, Hurt, and Lowry [17], however, presented pictures of hurricane Daisy of 1958, in which there were bright, sharp-edged individual echoes (that is, the convective type) extending into the area that the other investigators had labeled the area of the inner bands. One can deduce from their observations that the characteristic appearance of the echoes in this inner area was at least partly the function of the distance from the radar to the echo and of the power and sensitivity of the radar. These observations are of special interest because some of the data collected for the present investigation strongly suggest that the inner bands are also cellular in nature.

Published reports therefore tell us much about the weather at the surface associated with rainbands, about the geometry and kinematics of the bands, and to some extent about the liquid water distribution through the bands. They are entirely inadequate, however, for describing variations of temperature, wind, and pressure through the bands and for answering many of the pertinent questions about the bands. This lack of detailed and accurate knowledge may account in part for the failure of anyone to present a generally acceptable theory to account for the origin and maintenance of the bands even though many hypotheses concerning the bands have been advanced.

Fletcher [9] was the first to offer a suggestion as to the origin of the bands. He reported that hurricanes which originated in the intertropical convergence zone were composed of a number of individual cloud lines similar to those commonly observed in the intertropical convergence zone. He hypothesized that the latter lines had " 'coiled into' the center of the storms."

Wexler [51] expanded and generalized this hypothesis to include the storms that developed outside the area of the intertropical convergence zone. He thought that the bands originated when either the cloud streets frequently observed in the trade wind area or the cloud bands in the intertropical convergence zone were drawn into an intensifying circular convergent vortex, and those with suitable wavelength developed and others were suppressed. The original cloud streets were believed to be caused by the right combination of vertical wind shear and thermal instability.

Ligda [24] suggested that the inner hurricane bands were essentially a friction-gradient level phenomenon and that the outer bands were a squall-line type of disturbance. He argued that the inner bands resulted from raindrops falling from a stratus overcast through roll stratocumulus and presented considerable evidence to show that raindrops falling through the rising air on one side of the roll stratocumulus would grow much faster than those falling through descending air on the other side. Since the larger drops reflect much more radar energy, it was thought that this process could give the band appearance commonly observed on radarscopes. The stratocumulus roll clouds were to form as a result of wind shear and thermal instability in the air mass. The bands would remain approximately stationary relative to the storm center because they should be aligned perpendicular to the wind shear and would therefore be approximately parallel to the mean wind in the lower and middle troposphere.

Tepper [49] reviewed what had been reported about rainbands, concluded that they were similar to squall lines, and thought they resulted from a gravity wave propagation. In a stationary storm this mechanism should produce circular bands, but with a moving storm it should produce spiral bands.

Atlas et al. [4] hypothesized that the convective cell at the upwind end of the rainband initiated it. They thought that if such a cell were imbedded in a circular vortex, the precipitation plume in spreading downstream would trace out a spiral along which the falling snow particles would melt and create a stable and possibly an isothermal layer. The maintenance of this cooling from above would give rise to instability below the base of the 0°C. isotherm which in turn would provide a mechanism by which fracto- and stratocumulus roll type clouds were generated. They wrote concerning hurricane Esther of 1961. "The generating convective cloud at the upwind end of the band appeared to propagate up-band thus maintaining a virtually continuous plume for one or more hours, the typical band lifetime. Also a second convective tower may occasionally develop downwind and at the leading edge of the band to release another plume which blends with the first."

A review of the work of previous investigators thus reveals that a lot of surmising has been done, and a lot of tentative conclusions have been drawn without sufficient data for verification. No detailed and complete description of the rainband has been furnished. In addition to the unanswered questions about the structure and origin of the rainband some of the theoretical work in recent years has suggested additional questions.

The importance of the hurricane problem as a whole and the success with numerical models in other fields of meteorology have encouraged numerous investigators to attempt to develop a numerical model of a hurricane.

Although it should be much simpler to develop a symmetrical rather than an asymmetrical model, it is recognized that rainbands certainly introduce asymmetries. Data are needed to determine whether accounting for these asymmetries is important.

Theoretical investigations have raised questions about the manner and location of energy transformations within hurricanes that can be answered by more complete knowledge of the rainband. Evidence presented by Riehl [36] and by Riehl and Malkus [37] indicates that much of the energy used to drive the tropical cyclone is released in the eye wall. These investigators have also argued that the amount of sensible and latent heat transferred from the ocean surface to the air flowing near the sea surface from the outer boundary of the storm circulation in to the vicinity of the eye wall puts an upper limit on the intensity of the storm. Since rainfall records indicate that rainfall is also heavy in the bands of the hurricane other than the eye wall, it seems desirable to consider whether these other bands contribute materially to the generation of kinetic energy within the hurricane.

Riehl and Malkus [37] have also discussed the problem of getting air from the lower inflow levels to the outflow layer in the upper troposphere in such a manner as to permit accounting both for the observed equivalent potential temperature lapse rate and the generation of sufficient kinetic energy for the hurricane. Most collections of data giving vertical distribution of temperatures in hurricanes show a minimum of equivalent potential temperature in the middle troposphere. It has been hypothesized by many investigators (Riehl [36]) that air in the upper outflow layer ascended from lower levels and principally within the eye wall. If this ascending air is not mixed with other air while rising from the surface to the upper troposphere, then soundings taken in that region should show an isothermal equivalent potential temperature. To account for the assumed vertical component of the hurricane's circulation and also the observed temperature and moisture distribution, Riehl and Malkus hypothesized that most of the air reaching the outflow layer ascended through buoyant updrafts of rather limited area and number rather than by gradual ascent over a large portion of the storm. Presumably many of the data collected in the middle troposphere might then be from areas where little ascent was taking place and where the equivalent potential temperatures need not be constant with height. Observations are needed to verify if such a hypothesis is consistent with the structure of tropical cyclones. These buoyant updrafts of assumed undiluted ascending air should lie within the bands (including the eye wall); for, as Simpson [44] has noted, bands are the channels through which most of the latent heat of condensation, a primary energy source for the hurricane, is released. If, however, the inner rainbands are all diffuse and uniform as reported by many investigators, it can be questioned whether the Riehl-Malkus hypothesis is correct.

There are therefore, many unanswered questions about the hurricane rainband such as:

(1) Are there warm buoyant columns of relatively limited extent through which the air ascends from the lower inflow layer to the upper outflow layer without mixing with the ambient air? Are all of these columns concentrated in the eye wall, or are they distributed throughout the rainbands of the hurricanes?

(2) Where is the kinetic energy generated that feeds the hurricane system? Does all of it come from the conversion of potential energy in the eye wall region, or is it also generated in other sections of the storm? Are the rainbands important cogs in the conversion of other forms of energy into kinetic? If so, of what importance is this to various theoretical studies?

(3) Since it will probably be simpler to develop a symmetrical numerical model of a hurricane than an asymmetrical one, can the theoretical meteorologists working on the problem be assured that the rainbands are approximately symmetrical with respect to the center of the storm? Or, if the rainbands are asymmetrical, do those bands outside of the inner more symmetrical portion of the storm make any significant contributions to the energetics of the storm?

(4) What causes the rainbands to form and by what mechanism are they maintained? If rainbands are important to the mechanism of the storm, and if their maintenance is dependent on some instability that might be modified, does this offer an opportunity for experiments at hurricane modification?

Data to answer all the questions listed cannot be obtained with resources available. To answer some of them would require a knowledge of the variations of several of the meteorological parameters throughout the volume of the hurricane at frequent intervals over a long period and for a representative sample of hurricanes. With the aid of existing data networks and the use of the research aircraft of the Weather Bureau it was possible, however, to collect and assemble data to answer some of the questions.

Special flights were planned during the 1962 hurricane season to collect data on rainbands. Three research planes were to fly longitudinal traverses of rainbands as well as closed patterns around portions of several bands at three different levels, respectively, in the lower, middle, and upper troposphere. These flights were to be as nearly simultaneous in time and horizontal spacing as possible. From these data we expected to be able to describe the variation of the various parameters along the bands and to calculate both the advection and generation of kinetic energy in the relatively small areas involved. Some of the band segments were to be about 20 mi. long and others about 50 mi. It was impossible to keep the planes aligned exactly in the vertical throughout the flights because they operated at different speeds. The data collection was further complicated by the capriciousness of Nature who furnished a subnormal hurricane season in 1962 and the foibles of the aircraft which were seldom all operable during the rare hours when a suitable storm was within range. Nevertheless several of the planned patterns including the longitudinal traverses were executed by one or more of the aircraft. Computations made, using data from some of the closed box-type patterns, gave results consistent with those to be reported later. It was soon found, however, from data collected on the longitudinal traverses that the various meteorological parameters varied about as much along the bands and with time as they had been known to vary normal to the band. The life of many of the cells in the bands and even of some of the bands was less than the time it took to fly the complete closed box patterns. These factors raised serious doubts as to the representativeness of results obtained from computations based on the data collected for just a few cases; that is, it soon appeared to be a statistical problem. In particular, since variations of the magnitude being sought by the computations occurred frequently within 2 to 5 mi. of flight along a band, there was no point in considering data as being synoptic which were collected from 2 different levels but with the planes separated either in space by 10 to 15 mi. or in time by 10 to 20 min. Such data could not be used with confidence to compute divergence from data collected along a closed curve, nor to compute vertical motions. Since we had planned to use the correlation between temperature and vertical velocity to help compute the generation of kinetic energy in a volume (Palmén [32]), it was necessary to have many cases to avoid obtaining nonrepresentative results due to nonsynopticity of the data.

We decided therefore to combine the data available in the archives and the data collected during the special flights during the 1962 seasons. These data would be used to determine the 3-dimensional distribution of temperature, pressure, and wind in the bands in order to furnish as complete, quantitative and representative a description of the hurricane rainband as practical since such a description was needed in order to answer many of the questions which had been raised about the bands. It was also needed as a necessary preliminary step for several theoretical investigations and for preparation of any generally acceptable explanation of the origin and maintenance of the bands. In addition it was believed that these data could be used to help determine the mechanism by which air ascends from the lower inflow layer to the upper outflow layer, to ascertain whether the rainbands were important to the energy transformation processes within the hurricane, and to determine whether the kinetic energy was released symmetrically with respect to the center of the storm and in what areas significant amounts of kinetic energy were generated.

2. COLLECTING THE DATA

The Air Weather Service of the U. S. Air Force operated two B-50's and one B-47 in support of the National Hurricane Research Project from 1956 through 1958. During the 1960-62 seasons the U. S. Weather Bureau had two DC-6 and one B-57 aircraft instrumented for use in research flying into hurricanes. Many of the research flights utilized box, clover leaf, or cross type flight patterns, each of which was approximately symmetrical relative to the center of the storm. Since the spiral rainbands are usually approximately perpendicular to storm radii, and since most of the flight patterns in the earlier years included radial passes through the intense portions of the storm, there were many traverses of hurricane rainbands made along lines approximately normal to the bands. To get more information about the bands, special flight patterns were used in hurricane Ella, 1962. These patterns included longitudinal traverses of several bands. In a few cases in the earlier years the aircraft crossed the rainbands at a relatively small angle, thus approximating a short longitudinal traverse of the band.

All of the aircraft were equipped with APN-82 automatic navigation equipment which included Doppler radar for measuring the ground speed and the

ASN-6 analog computer. The latter computed flight level winds, latitude, and longitude in flight from input of initial position, true air speed, ground speed, compass heading, magnetic variation, and drift angle. There were several temperature probes, but the one used to collect the data for this investigation was the AMQ-8 (vortex) thermometer. The data were recorded automatically on punch cards in the earlier aircraft and on magnetic tape in the later aircraft. The recording interval varied from 1 to 10 seconds, but for most of the cases to be presented, the data were recorded at least as often as 3 times per mile, and during the 1962 flights were recorded every second (about 16 times per mile).

Each of the earlier aircraft was equipped with essentially the same radar, a 3-cm. search radar with an antenna that detected echoes throughout the layer from flight level to the surface of the earth. Each of the DC-6 aircraft was equipped with a 10-cm. search radar of the APS-20 type. The former radar were much more subject to attenuation than the latter, but did show more detail at the shorter ranges. Pictures were taken of the radar scope at variable intervals, but in all cases where the data were used the pictures were taken at least 2 times per mile of flight.

Time-lapse pictures of the clouds were obtained on nearly all the flights. In most cases a picture was exposed at least as often as every 2 sec.

3. ACCURACY OF DATA

The data used were principally the temperatures, winds, pressures, and D-values for flight level, and position of the observation relative to the rainband and to the storm center. It was also important to know as precisely as possible when the airborne sensors entered and departed from clouds and heavy concentrations of liquid water. The instrumentation of the research aircraft and accuracy of the data have been discussed by Hilleary and Christensen [14]; and by Hawkins, Christensen, Pearce, and Staff, National Hurricane Research Project [13]. In the following paragraphs pertinent information concerning the instruments used to collect the data for this investigation will be reviewed and some possible effects on the results will be discussed.

Temperatures

Vortex thermometers (AMQ-8) were used to obtain all the upper-air temperatures utilized in the investigation except for those from a few rawinsonde soundings. Several other temperature probes were mounted on the aircraft, but comparison of readings showed that the vortex probe was as satisfactory for the present investigation as any of the others. It was much more convenient to use because no dynamic correction had to be applied to the recorded temperatures. While its response time was longer than some of the other probes (about 10 sec.) it was sufficiently fast to measure changes on the smallest scale desired for the present study. Temperature data recorded by the vortex probe were compared with data from the much faster responding temperature sensors on board the aircraft. The vortex data did not reveal many of the variations which extended over less than 1/4 mi., but indicated the correct sign of the temperature gradient for longer-period variations which includes all those summarized in this investigation. There was a tendency, however, for a slight underestimation of the magnitude of the total temperature change across a convective element.

The vortex thermometer electronics system was calibrated one or more times during each flight. A "calibrate" switch on the front of the instrument control box was used to substitute a fixed resistor for the sensor. When this switch was activated the indicated temperature came to a certain fixed value when the system was functioning properly.

Each vortex thermometer was checked for the effect of any air speed errors after installation on an aircraft by plotting temperature versus speed for a number of runs over a fixed flight path in clear air. No consistent air speed effect was found for any of the systems, and all values fell within the limits of the manufacturer's rating. The manufacturer claimed that the cooling effect at the center of the vortex chamber compensated within $\pm$ 0.5°C. for dynamic heating in the air speed range of 0.2 to 0.65 Mach. These values spanned the speed range of all the research flights used.

Research aircraft carrying a vortex thermometer have followed a rising radiosonde to get a further calibration of the instrument. No error with altitude and no significant departure from the radiosonde-measured temperature have been found.

The most persistent question asked about air temperatures measured from high speed aircraft is whether they are affected when the plane passes through liquid water. A parcel of air going through the vortex thermometer system is first compressed as it approaches the airplane, expanded going through the vortex chamber, and slightly compressed again right at the sensing element. The thermometer has been tested in wind tunnels and on whirling arms where it was exposed to all types of moisture conditions (Ruskin and Schecter [38]). In none of the tests have any errors due to moisture been detectable. Radiation error from the sun was undetectable with airspeed above 25 to 50 kt. A determination of the possible wetting of the thermometer element was made on the whirling arm by coating the sensor with a water soluble dye. No discoloration of the dye occurred after it passed through either natural precipitation or artificial spray.

No wet bulb effect on the temperatures was identified on any of the rainband flights, even though there have been indications on other research flights. In many cases the measured temperature increased as the airplane passed from clouds into relatively dry air, and this is just the opposite to what the wet bulb effect would cause. This point will be discussed further in Section 4 when some of the data are presented.

The temperatures in the middle levels of the hurricane eye walls were usually lower than undiluted ascent from the surface would provide. Since these are the levels where water concentrations are high, it is natural to suspect the thermometer. Several of the flights at these levels did, however, measure temperatures as high as should be expected from the measurements made at levels above the liquid water concentrations. Further discussion of this problem is included in Section 11.

The wind tunnel tests of the vortex probe under icing conditions (Ruskin and Schecter [38]) indicated that the recorded temperatures might be too high due to the change of state on impact at probe entry. The tests showed no change, however, until ice started blocking the air flow. Nearly all the cases summarized in the present investigation for the lower and middle troposphere had temperatures higher than 0°C., so data from these levels should not have been affected. No evidence is readily available as to whether much ice accumulated on the vortex probe of the aircraft flying at about 35,000 ft. or higher. Ordinarily, little liquid water would be encountered at the higher elevations and the ice accumulation should be minor. Some data collected by the research aircraft in 1961 and 1962 indicated, however, that at times the ice accumulation might be significant. There is the possibility, therefore, that the temperatures recorded for the upper troposphere are too high by an unknown amount.

There will probably always remain a question as to the accuracy of the temperature measurements until some absolute standard of comparison is developed. With knowledge presently available, however, it is concluded that the temperatures measured by the vortex thermometer are as good as can be presently obtained from high speed aircraft for the general purposes of the present investigation and are probably adequate.

Winds

The winds used in this investigation were those measured by the APN-82 system which includes the Doppler radar and the ASN-6 analog computer. The same type instrumentation was used in all the aircraft, and many of the same components were transferred from the B-50 and B-47 aircraft used through 1958, to the DC-6 and B-57 aircraft used in later years. The systems were all modified (by the same man) to have a faster response time than was usual for the APN-82 system. All the systems were carefully calibrated at the beginning of each hurricane season and at later times when need was indicated, and the wind data were examined after each flight for any errors in calibration which would become evident when the aircraft made turns. Since the ASN-6 computed the winds from ground speed, air speed, drift angle, and compass heading, and since some of these vary greatly around turns in the track, calibration errors should cause apparent changes in the recorded winds at such points even when the winds remain constant. A system was established early in the data processing effort at the National Hurricane Research Project to use this characteristic of the wind measuring system to check and to further calibrate the data before they were released to the researcher.

Tests made of the APN-82 wind measuring system indicate that the error in wind direction should be 5° or less for wind speeds typical of hurricane circulations. The response time of the system is such that the measured wind direction and speed can change at a maximum rate of 2.6° and 6.6 kt. per second. In either case, 4 or 5 sec. are required for the maximum response rate to be attained. The lag of this instrument caused the variability of the measured winds (Sections 4, 6, and 8) to be less than the variability of the actual winds.

The ground speed is one of the inputs for obtaining the wind solution, and it is measured by the Doppler radar. To get this measurement, one has to assume a speed for the reference surface; and, in this case, it was assumed that the surface of the ocean was stationary. Obviously, this assumption was not completely justified for hurricane conditions, and it has never been determined just how much effect this error may have on the computed winds. The Doppler radar used in the APN-82, however, has a characteristic which, according to the manufacturer, causes it to lock-on to the strongest return signal. Presumably the signal from the moving spray would be less than that of the relatively stationary water in the upper layers of the ocean, and this effect would be minor. Most of the data collected during the past several years show wind speeds of the right order of magnitude when compared with independent data. It, therefore, seems likely that the Doppler has not often used the return signal either from the spray or from water drops in clouds. None of the cases where it was suspected that this happened have been included. How fast the upper layers of the ocean in the hurricanes were moving was not determined. The flight-level winds were computed on the assumption that the speed of this water did not materially differ from zero. Experiments recently reported by Grocott [12] suggest that this is not a good assumption and that a correction should be applied to the ground speed of about 10 percent of the surface wind at wind speeds of near hurricane force. The conclusions drawn in the present investigation should not be much affected even if the assumed zero movement of the water surface is incorrect. This is because all of the conclusions have been based on gradients of speed and, in most cases on gradients as measured over a relatively short distance. Certainly, even if the upper layers of the ocean are moving, oceanographers would lead us to believe that any such movement is the integrated effect of a long fetch rather than the effect of the microscale structure of the wind field. Hence, it is not believed that significant errors in the measured gradients of the wind over distances of 5 to 10 n. mi. were caused by gradients in the speed of the surface reference plane. If later investigations show that such errors were significant, some of the conclusions will be affected.

Pressures and D-values

The pressure data used from the earlier aircraft were computed from the pressure altitude measurements made by Kolsman sensitive altimeters. These were rated accurate to 1.5 percent by the manufacturer. Later laboratory calibrations of the specific instruments indicated 2 percent to be a more realistic value. Hysteresis and friction effects added further uncertainties, but the altimeters were subjected to frequent regular vibration to help minimize these effects. After all corrections had been applied, pressure altitude was estimated accurate to 40 ft. The aircraft in the later years were equipped with sensitive aneroid barometers and calibrations of this instruments indicated that they should be at least as accurate as those used on the earlier aircraft. Furthermore, these newer barometers did not have nearly as large frictional and hysteresis effects.

The D-values were computed from the difference between the corrected radar altitude and pressure altitude. The absolute altitude was measured by a SCR-718 altimeter. In the earlier aircraft these data were recorded by photographing the trace that appeared on a small oscilloscope. It was difficult to read these data with precision and the D-values for the flights made by the earlier aircraft were not used in any of the summaries. The values were smoothed to eliminate small-scale irregularities before being plotted on the illustrations presented in other sections and were included only to indicate the general slope of the pressure surfaces along the flight path. In the later aircraft the signal from the altimeter was digitized by an analog computer on board the aircraft and was recorded each second along with the other data. The absolute accuracy of these measurements was believed to be as good or better than those of the pressure.

In all of the summaries prepared from the D-values, only the gradients were used which should not be affected by small errors in the measurement of the pressure or radar altitude. They would be affected, however, by differences in the lags of the two measuring systems. There was evidence that lag in the aneroid barometer might be affecting the data. In any case either the lag in the instrument, other deficiencies in the instrumentation, or very small-scale oscillations in the atmospheric pressure caused oscillations in the D-values extending over less than 1/4 mi. of flight. To eliminate these small-scale variations the D-values were smoothed using a running mean of 3 observations (3 sec.) centered on the time of observation. These smoothed values are the data plotted in the illustrations and used in the summaries.

There are other possible sources of error in the D-values. The radar altimeter might measure elevation from the crest of an ocean wave at one time and from the trough of a wave at another. With the wave heights frequently encountered in hurricanes, this difference could be significant. Furthermore, in turbulence the plane's flight attitude is frequently changed and the radar beam might not be reflected from the water immediately beneath the plane. The beam of the SCR-718 is rather broad however and should cover several waves. Likewise unless the attitude of the aircraft is changed more than is usually the case in turbulence, a portion of the beam should still be pointed toward the nearest surface of the ocean and should give a stronger signal than that portion of the beam intersecting the surface at an oblique angle. In any case no evidence was found that these possible effects influenced the data unless they were causing part of the high frequency oscillations described in the preceding paragraph.

Positioning the data relative to rainband and storm

Time lapse photographs of the radar scopes and of the clouds were used in locating the observational points relative to the rainbands and the center of the tropical cyclone. Since these photographs were taken several times per mile, the amount of information should have been entirely adequate for the purpose. There were, however, two problems that had to be solved. The first one involved time synchronization of the radar and cloud pictures with the other data, and the second involved black-out on the radar scope by the transmitted radar signal of weather echoes from the first few miles around the airplane.

It was necessary to get a positive time synchronization between the photographs and the recordings of the other data. A clock or some other time indicator was included in the radar photographs and in some of the cloud photographs. In addition most of the cloud photographs were taken at regular intervals so the lapse of time could be calculated by the number of frames exposed. The time synchronization for the radar photographs could be obtained with an accuracy of about 5 sec. (time needed to travel about 1/3 mi.) at each turn in the flight track. The time synchronization for the cloud photographs could be obtained with equal or greater accuracy each time a turn occurred while the airplane was in clear air and there were clouds in the field of view of the camera. The technique was not effective inside clouds however, because it was not practical to determine from the cloud pictures when the aircraft was turning. Once synchronization was achieved it could be extrapolated forward or backward in time by counting picture frames and multiplying by the interval between exposures. In many cases there were counter numbers in the radar photographs which corresponded to counter numbers recorded along with the other data. These numbers gave positive time synchronization.

The black-out of all weather echoes for the first few miles around the aircraft by the transmitted radar signal meant that good image of the bands could be obtained when approaching or leaving them, and of the more distant portions of the band while the aircraft was inside the band. This meant that some extrapolation either in time or space had to be made of band boundaries on the radar pictures. No great problem was encountered because of this factor for the data from the earlier years except that small inaccuracies in placing the boundary of the bands relative to the other observations may have been introduced. It did cause some problems in locating the aircraft relative to the rainbands in 1962. It was found desirable, therefore, to use liquid-water-content measurements and changes in indicated air speed (both of which were recorded digitally and simultaneously with the other parameters) to verify when the aircraft was in the bands. By using all of the information available, it is believed that the boundaries of the various bands were located relative to the other data within about 1/2 mi. In some cases it was possible to use the cloud photographs or the liquid-water-content measurements to locate the boundary within about 100 m. Achieving this accuracy, of course, was dependent on the boundary of the band being a narrow well-defined line. This was true for most of the bands for which normal traverses are illustrated in Section 4. In some cases, however, the boundary of the band was quite diffuse and the uncertainty in selecting it might be of the order of 1 or 2 mi.

The location of the band relative to the center of the storm could nearly always be determined within a few miles which was sufficient for all purposes for which these data were used.

4. THE DATA

The most detailed data available for study of rainbands are those collected on flights made into hurricane Ella on October 17 and 19, 1962, at about 13,800 ft. and 3,250 ft., but observations from many traverses of rainbands made in 1957 and 1958 have also been utilized. The data were collected principally from flights either normal to the rainbands or during longitudinal traverses of the bands. In this section the types of data collected on each kind of traverse will be illustrated with examples which show typical variations and values of the various parameters. Most of the summaries, however, will be presented in later sections.

Longitudinal traverses

Four of the flights into hurricane Ella included longitudinal traverses of bands for about 50 mi. The data collected during these flights were used in preparing figures 2 to 7, some of which represent conditions inside bands and some between bands. The data in figures 2, 3, and 6 represent conditions on longitudinal traverses of the bands. In figure 5 the first portions of the profiles are for conditions within the band, and the remainder are for conditions adjacent to the band. The boundary of the band is marked on the profiles by the broken vertical lines. The data in figure 4 are from a leg during which the aircraft was flown along the side of and near the band. The data in figure 7 represent conditions on a flight leg between two bands. It is presented as a control. Thus from hurricane Ella, data examples are available at two different levels for conditions inside bands, just outside bands, and between bands.

Ella was intensifying on the 17th, but was poorly organized compared to many hurricanes. The eye was variable in size and was about 100 n. mi. in diameter. The eye wall was poorly formed. The bands investigated were relatively close to the eye wall even though they were 60 to 100 n. mi. away from the storm's center. By the 19th Ella was somewhat better organized but still had a larger than average eye whose wall was not as prominent as in many mature hurricanes. The storm was still intensifying, but reached its maximum intensity a few hours after the flights.

The flight crews used radar to locate the bands relative to the aircraft. Unfortunately, as was mentioned in Section 3, the characteristics of the radar were such that weather echoes from the first few miles around the airplane were obscured on the radarscope by the transmitted pulse. It was difficult, therefore, for the navigator to be sure of the precise location of that portion of the band nearest the aircraft once the plane had entered the band. Post flight analysis of all the traverses was made to verify during which periods the collected data represented either conditions in the band, near the band, or between bands. Liquid-water-content and indicated-air-speed measurements, in addition to pictures of the radarscope, were used for this analysis. The water and speed data were recorded digitally every second simultaneously with the temperatures, winds, and the other parameters, so positive time synchronization was available.

Liquid-water-content measurements made by the research aircraft in hurricanes in 1957 and 1958 have been analyzed in great detail by Ackerman [1, 3]. She found that in most cases the water content values encountered were fairly steady in amount and less than 0.3 g. m.$^{-3}$ except in rainbands when the amounts were larger and much more variable [3]. The water-content measurements during the Ella flights were made with a heated-wire liquid-water-content meter. Although this instrument probably seriously underestimates the water content of clouds in hurricane rainbands, it has a very fast response and should clearly show the difference between the amount and variability of the liquid water in the stratus clouds near and between bands, and the convective-type clouds in the bands (Ackerman, [1, 2]). The water content measurements for the traverse for figure 4 and for that portion of figure 5 that was not in the band were very steady from second to second and less than 0.25 gm. m.$^{-3}$

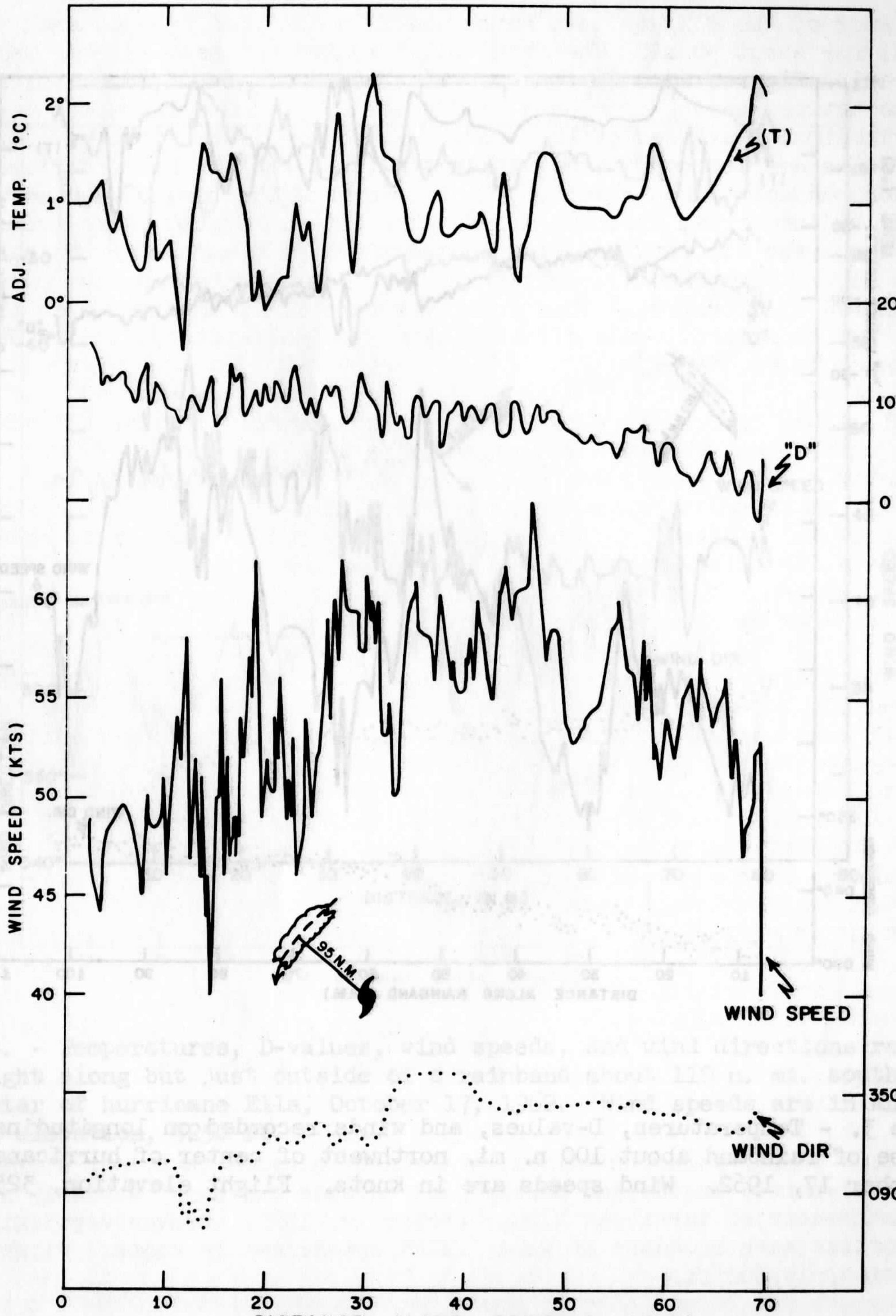

Figure 2. - Temperatures, D-values, and winds recorded on longitudinal traverse of rainband about 95 n. mi. northwest of center of hurricane Ella, October 17, 1962. Wind speeds are in knots. Flight elevation, 13,800 ft.

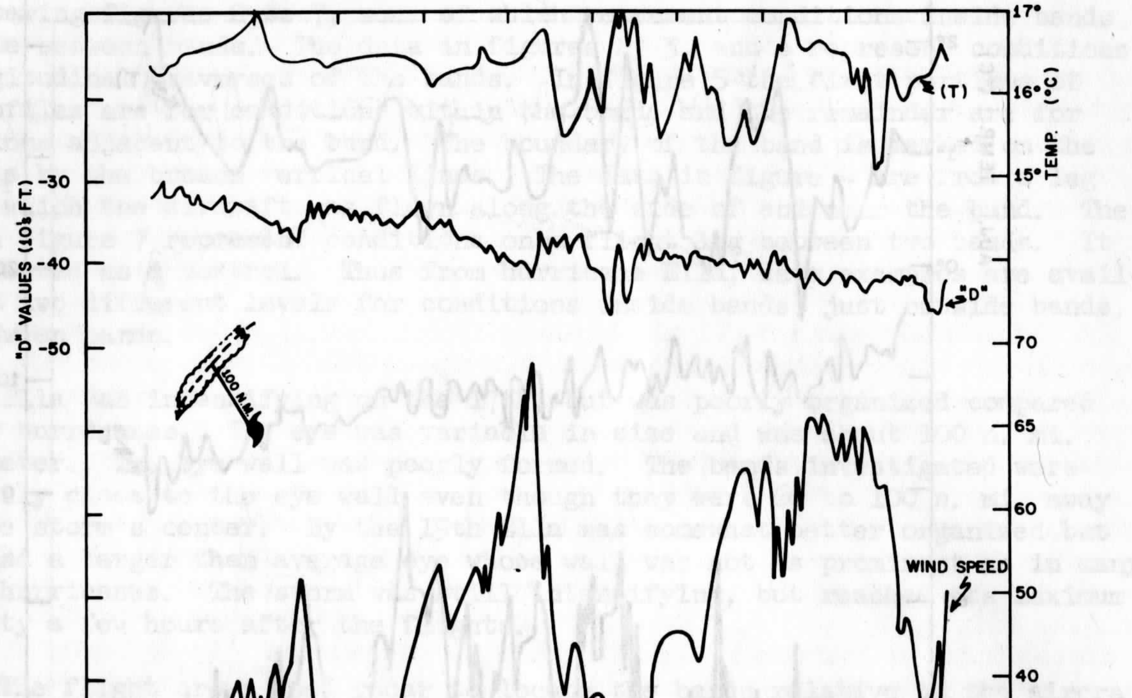

Figure 3. - Temperatures, D-values, and winds recorded on longitudinal traverse of rainband about 100 n. mi. northwest of center of hurricane Ella, October 17, 1962. Wind speeds are in knots. Flight elevation, 3250 ft.

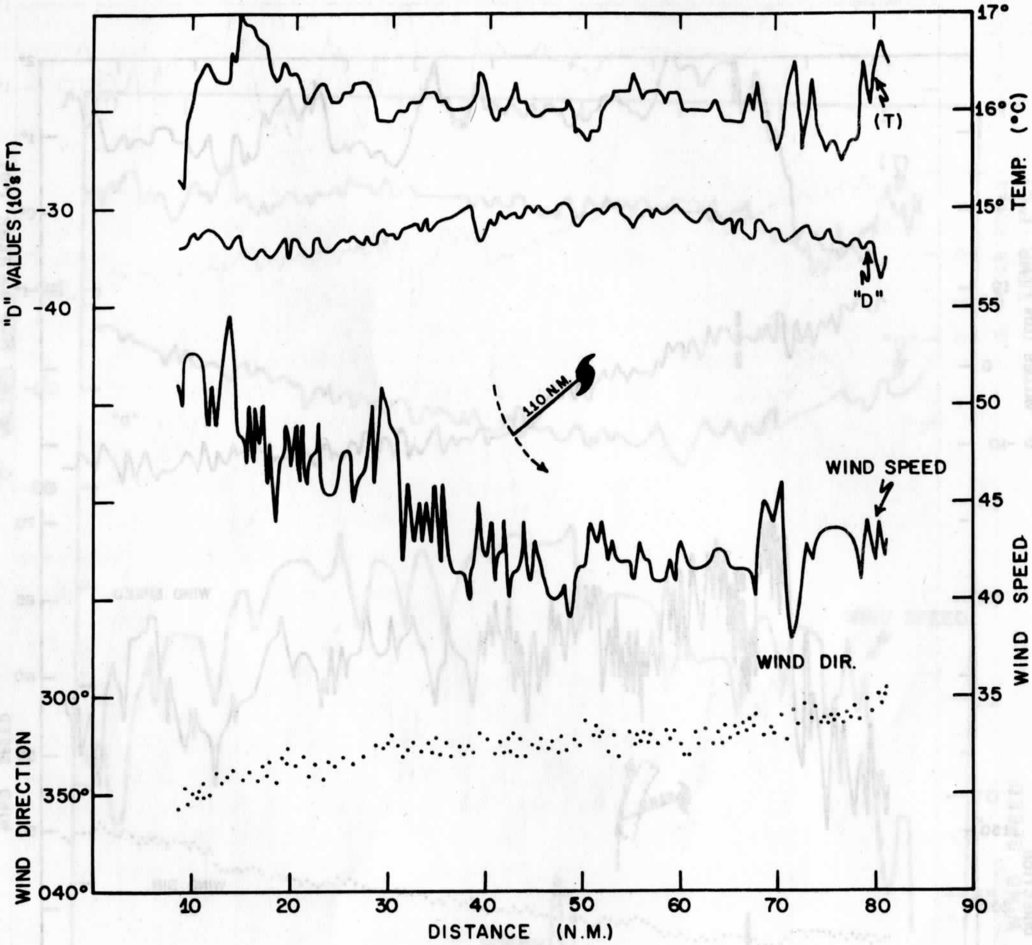

Figure 4. - Temperatures, D-values, wind speeds, and wind directions recorded on flight along but just outside of a rainband about 110 n. mi. southwest of center of hurricane Ella, October 17, 1962. Wind speeds are in knots. Flight elevation, 3250 ft.

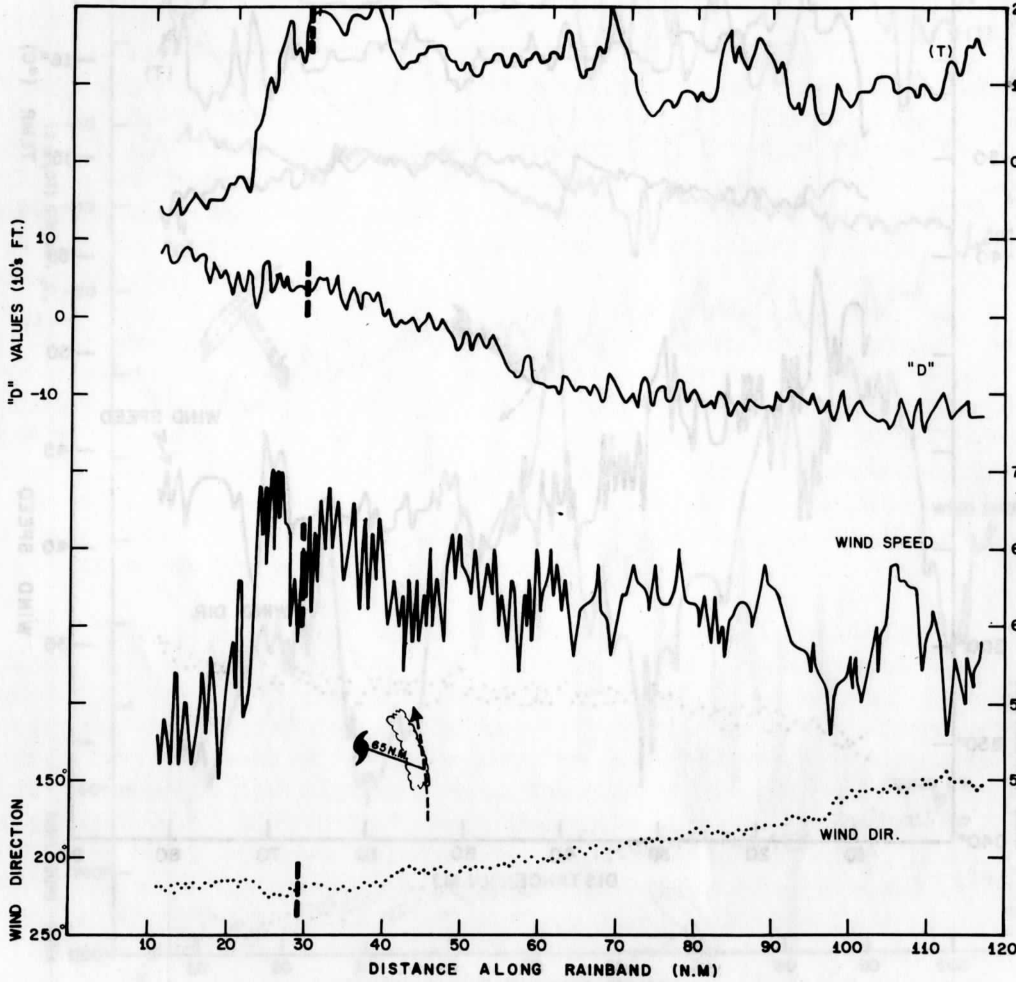

Figure 5. - Temperatures, D-values, and winds recorded on flight along a rainband, partly inside and partly just outside the band, about 65 n. mi. east of center of hurricane Ella, October 19, 1962. Broken vertical lines on profiles mark boundary of band. Wind speeds are in knots. Flight elevation, 13,800 ft.

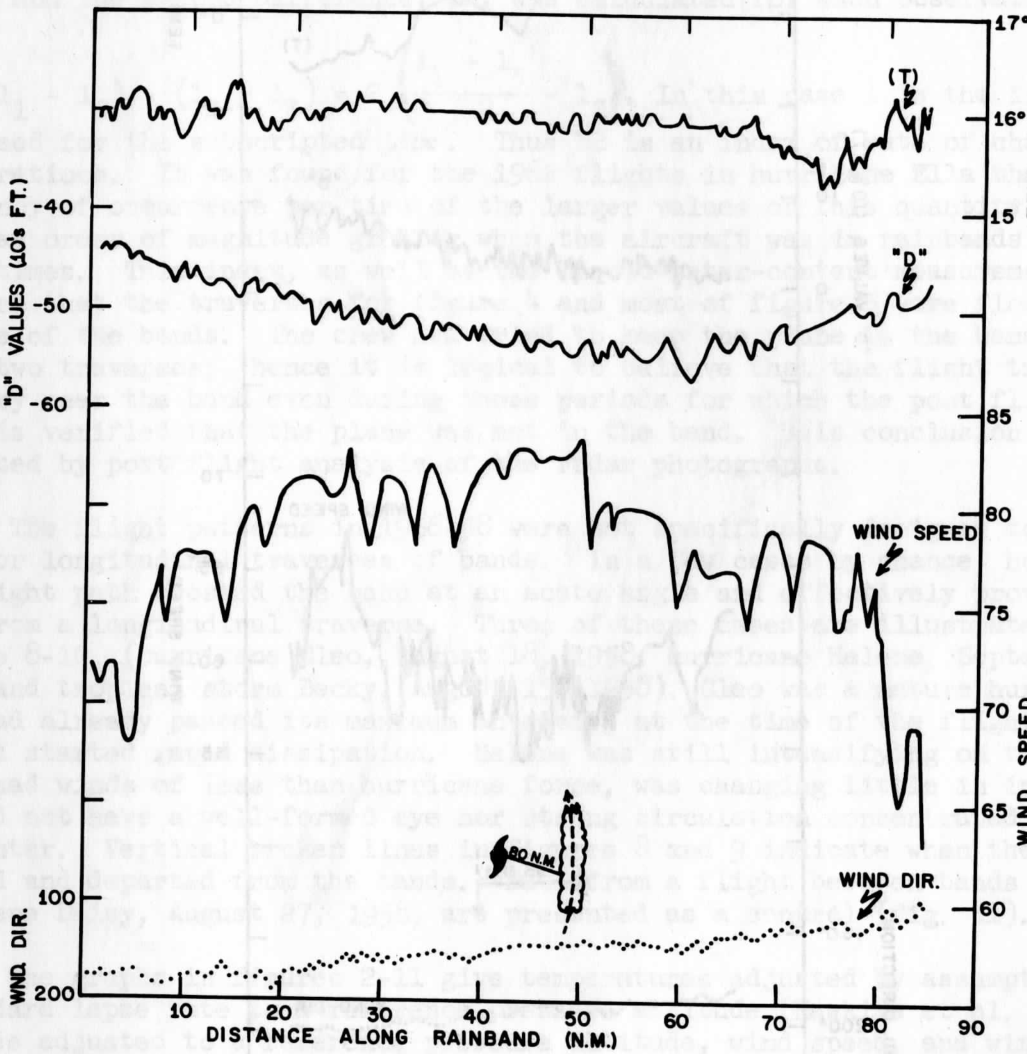

Figure 6. - Temperatures, D-values, and winds recorded on longitudinal traverse of rainband about 80 n. mi. east of center of hurricane Ella, October 19, 1962. Wind speeds are in knots. Flight elevation, 3250 ft.

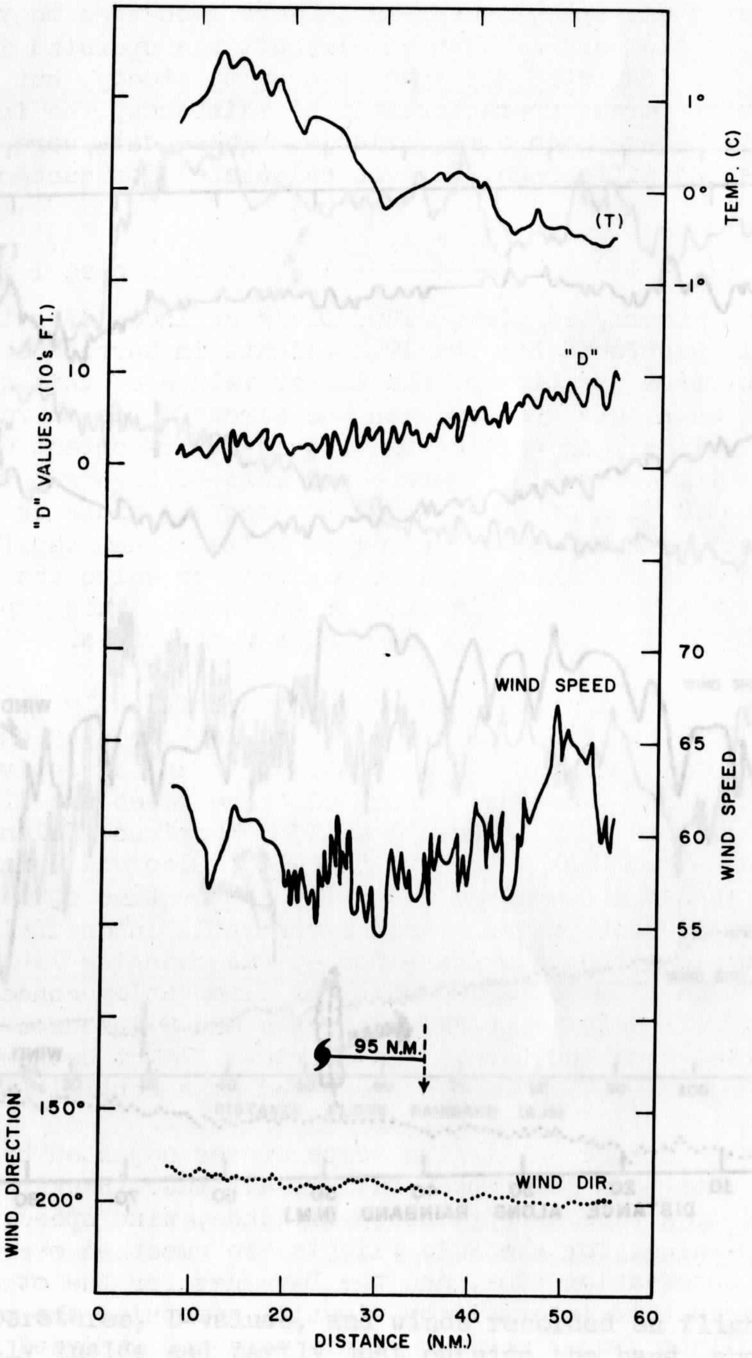

Figure 7. - Temperatures, D-values, and wind recorded on flight between rainbands about 95 n. mi. east of center of hurricane Ella, October 19, 1962. Wind speeds are in knots. Flight elevation, 13,800 ft.

The indicated air speed measurements were also used to verify when the aircraft was in the bands. When an aircraft was operated in relatively undisturbed air, the indicated air speed was quite steady, but once the plane entered the turbulent areas characteristic of rainbands, the indicated air speed measurements became much more variable. These data were recorded each second and the second difference, D2, was calculated for each observation, where,

$D2 = (l_1 - l_2) - (l_2 - l_3) = 2\left(\frac{l_1 + l_3}{2} - l_2\right)$. In this case l is the indicated air speed for the subscripted time. Thus D2 is an index of rate of change of accelerations. It was found for the 1962 flights in hurricane Ella that frequency of occurrence per time of the larger values of this quantity was at least an order of magnitude greater when the aircraft was in rainbands than at other times. This index, as well as the liquid-water-content measurements, verified that the traverses for figure 4 and most of figure 5 were flown outside of the bands. The crew had tried to keep the plane in the band for these two traverses; hence it is logical to believe that the flight track was very near the band even during those periods for which the post flight analysis verified that the plane was not in the band. This conclusion is supported by post flight analysis of the radar photographs.

The flight patterns in 1956-58 were not specifically designed to provide for longitudinal traverses of bands. In a few cases by chance, however, the flight path crossed the band at an acute angle and effectively provided data from a longitudinal traverse. Three of these cases are illustrated in figures 8-10 (hurricane Cleo, August 18, 1958; hurricane Helene, September 24, 1958; and tropical storm Becky, August 15, 1958). Cleo was a mature hurricane that had already passed its maximum intensity at the time of the flight, but had not started rapid dissipation. Helene was still intensifying on the 24th. Becky had winds of less than hurricane force, was changing little in intensity, and did not have a well-formed eye nor strong circulation concentrated about the center. Vertical broken lines in figures 8 and 9 indicate when the plane entered and departed from the bands. Data from a flight between bands in hurricane Daisy, August 27, 1958, are presented as a control (fig. 11).

The graphs in figures 2-11 give temperatures adjusted by assumption of a standard lapse rate to a reference pressure altitude (Hawkins et al. [13]), D-values adjusted to a reference pressure altitude, wind speed, and wind direction. The D-values for the Ella flights are smoothed over 3-sec. intervals centered on observation time, and the D-values for the other flights are smoothed over longer time intervals by visually smoothing the plotted data. Data used to calculate these latter D-values were not recorded as precisely, or as often, as in the case of Ella, and are included in the graphs only to give an indication of the trends in D-value on the flight tracks. They are represented by broken lines in figures 8-11, and are not used in any of the summaries presented later in the paper. The winds and temperatures were not smoothed except to the extent that the aircraft instrumentation integrated values because of instrumental lags. The abscissas are distance in nautical miles along the flight track. Reference pressure altitudes for various flight legs are given in table 1. Unless stated otherwise, all altitudes used in this paper are in feet of pressure altitude, ICAO Standard Atmosphere. The approximate location of each flight leg relative to the center of the storm and the direction of the flight are indicated on each illustration.

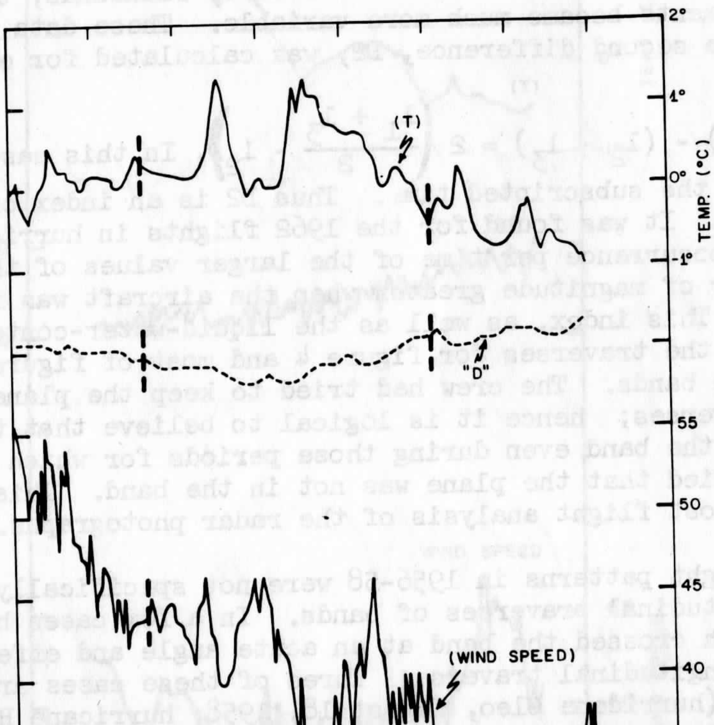

Figure 8. - Temperatures, D-values, and winds recorded on longitudinal traverse of rainband about 50 n. mi. north-northwest of center of hurricane Cleo, August 18, 1958. Broken vertical lines on profiles indicate boundaries of band. Wind speeds are in knots. Flight elevation, 15,600 ft.

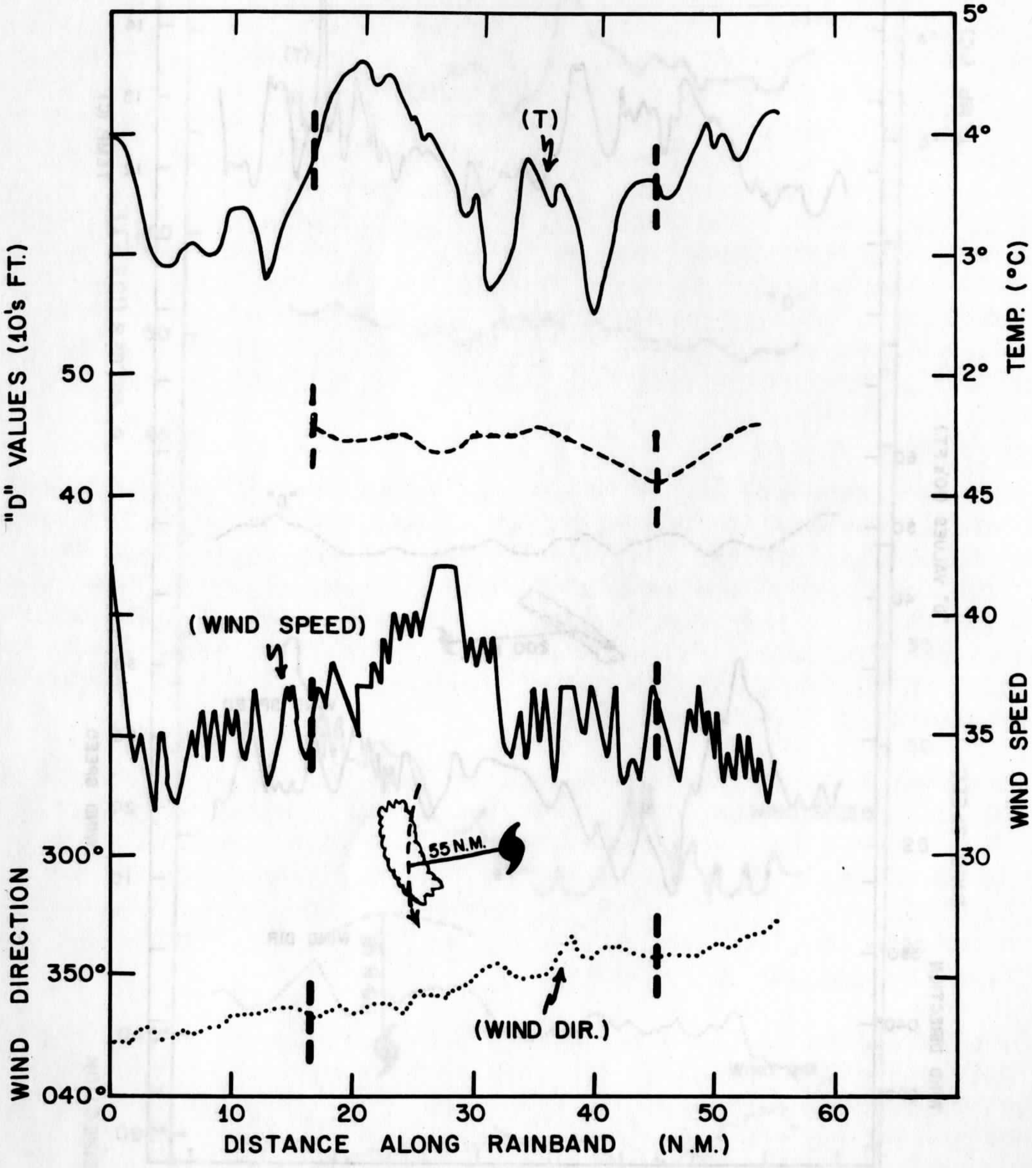

Figure 9. - Temperatures, D-values, and winds recorded on longitudinal traverse of rainband about 55 n. mi. west of center of hurricane Helene, September 24, 1958. Broken vertical lines on profiles indicate boundaries of band. Wind speeds are in knots. Flight elevation, 13,000 ft.

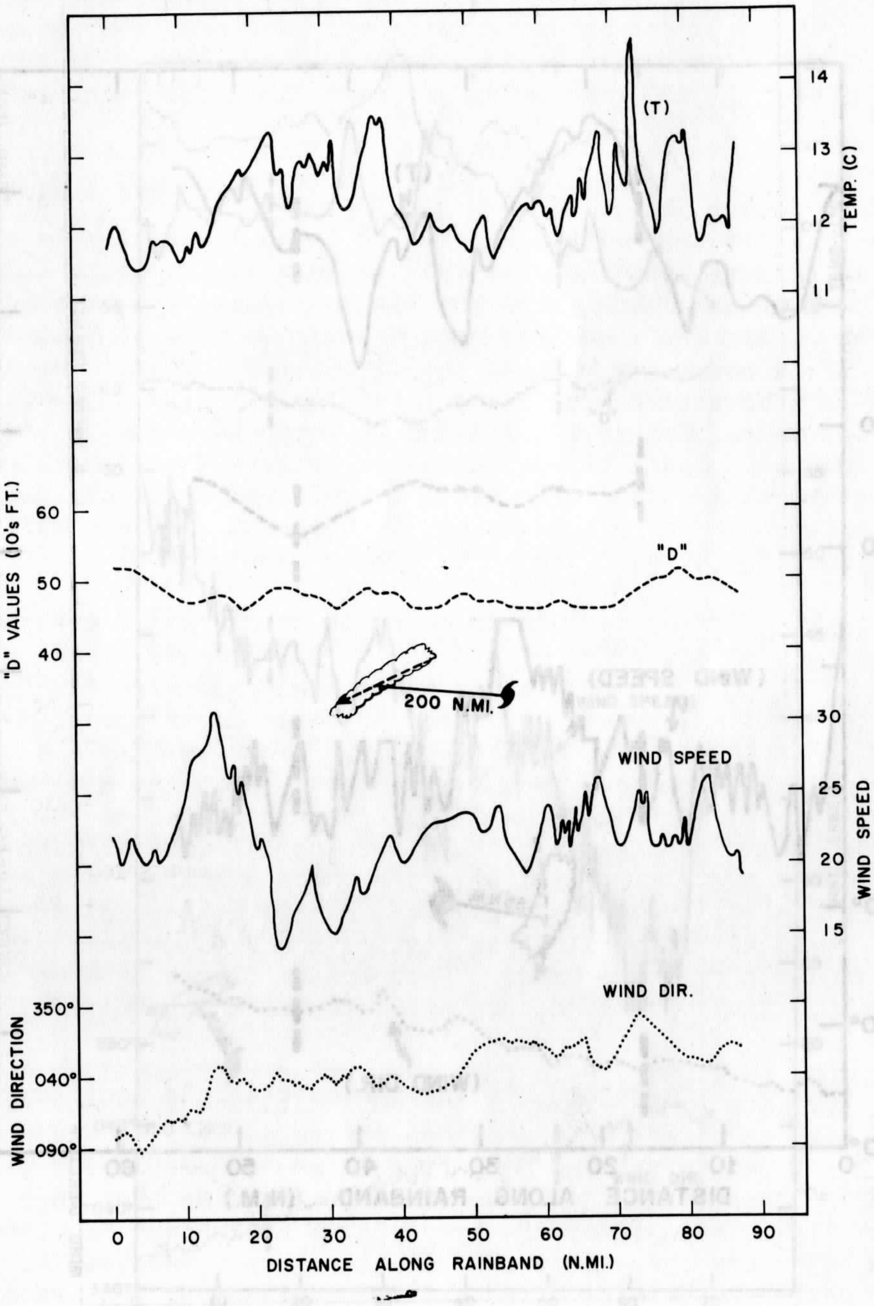

Figure 10. - Temperatures, D-values, and winds recorded on longitudinal traverse of rainband about 200 n. mi. west of center of tropical storm Becky, August 15, 1958. Wind speeds are in knots. Flight elevation, 6400 ft.

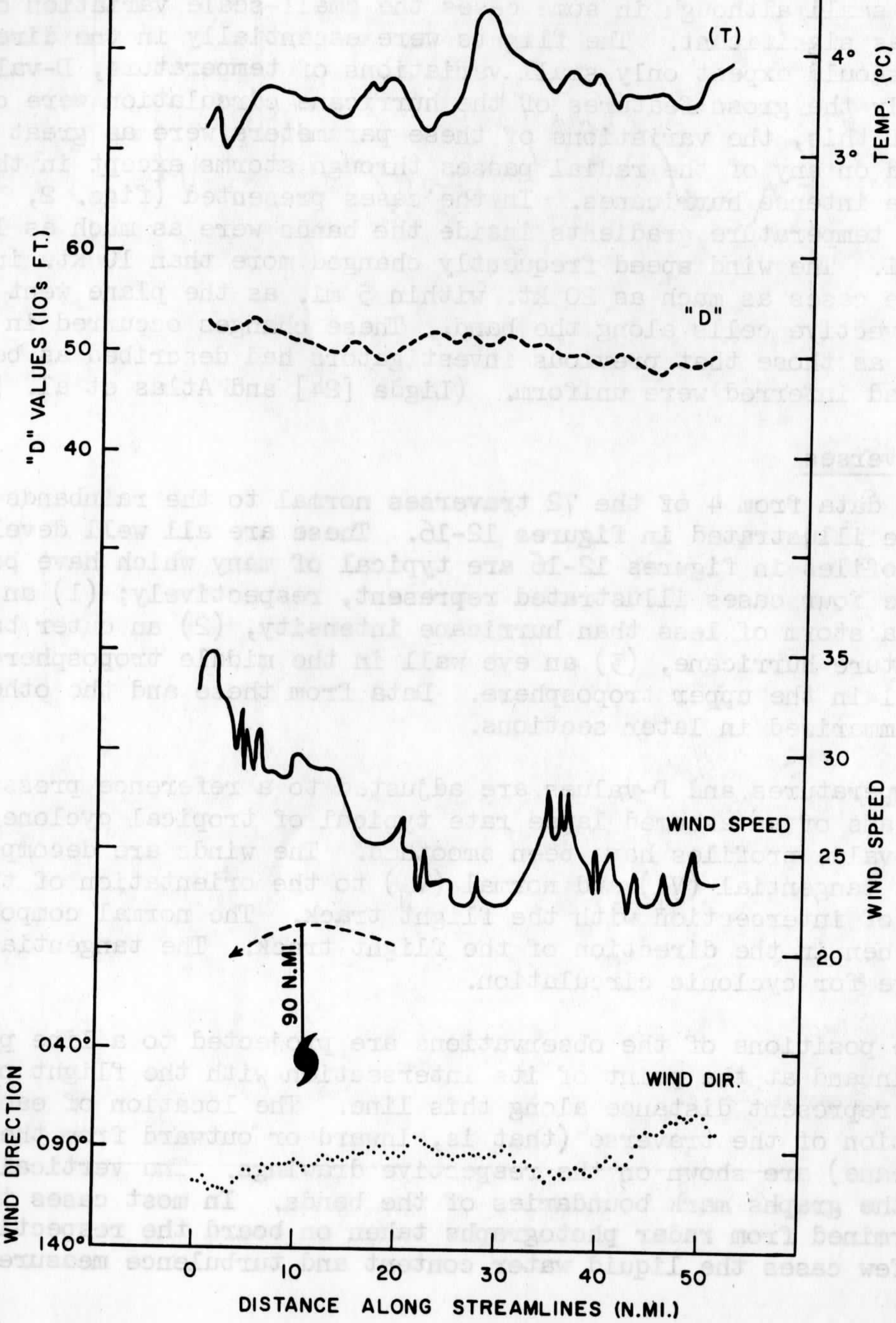

Figure 11. - Temperatures, D-values, and wind components along an approximate streamline about 90 n. mi. north of center of hurricane Daisy, August 27, 1958. Wind speeds are in knots. Flight elevation, 13,000 ft.

The longitudinal traverses are approximately along streamlines and isobars of the over-all circulation of the hurricane. From the illustrations it can be seen that the total variation in D-value for each flight leg was rather small although in some cases the small-scale variation of this quantity was significant. The flights were essentially in the direction in which one should expect only small variations of temperature, D-value, and wind if only the gross features of the hurricane circulation were considered. In spite of this, the variations of these parameters were as great as were encountered on any of the radial passes through storms except in the eye wall of the more intense hurricanes. In the cases presented (figs. 2, 3, 5, 6, 8, 9, 10), temperature gradients inside the bands were as much as 1.8°C. per 2 n. mi. The wind speed frequently changed more than 10 kt. in 5 mi. and in some cases as much as 20 kt. within 5 mi. as the plane went in and out of convective cells along the band. These changes occurred in inner bands such as those that previous investigators had described as being diffuse and had inferred were uniform. (Ligda [24] and Atlas et al. [4]).

Normal traverses

The data from 4 of the 72 traverses normal to the rainbands that were studied are illustrated in figures 12-16. These are all well developed bands, but the profiles in figures 12-16 are typical of many which have been prepared. The four cases illustrated represent, respectively; (1) an outer band from a storm of less than hurricane intensity, (2) an outer band of an intense mature hurricane, (3) an eye wall in the middle troposphere, and (4) an eye wall in the upper troposphere. Data from these and the other bands will be summarized in later sections.

Temperatures and D-values are adjusted to a reference pressure altitude by means of an assumed lapse rate typical of tropical cyclone air masses and the D-value profiles have been smoothed. The winds are decomposed into components tangential (V_T) and normal (V_N) to the orientation of the band at the point of intersection with the flight track. The normal component is positive when in the direction of the flight track. The tangential component is positive for cyclonic circulation.

The positions of the observations are projected to a line perpendicular to the rainband at the point of its intersection with the flight path. The abscissas represent distance along this line. The location of each band and the direction of the traverse (that is, inward or outward from the center of the hurricane) are shown on the respective drawings. The vertical broken lines on the graphs mark boundaries of the bands. In most cases the boundaries were determined from radar photographs taken on board the respective airplanes, but in a few cases the liquid water content and turbulence measurements were also used.

If horizontal divergence is expressed as,

$$\nabla \cdot V_H = \frac{\delta V_N}{\delta N} + \frac{\delta V_T}{\delta D} \qquad (1)$$

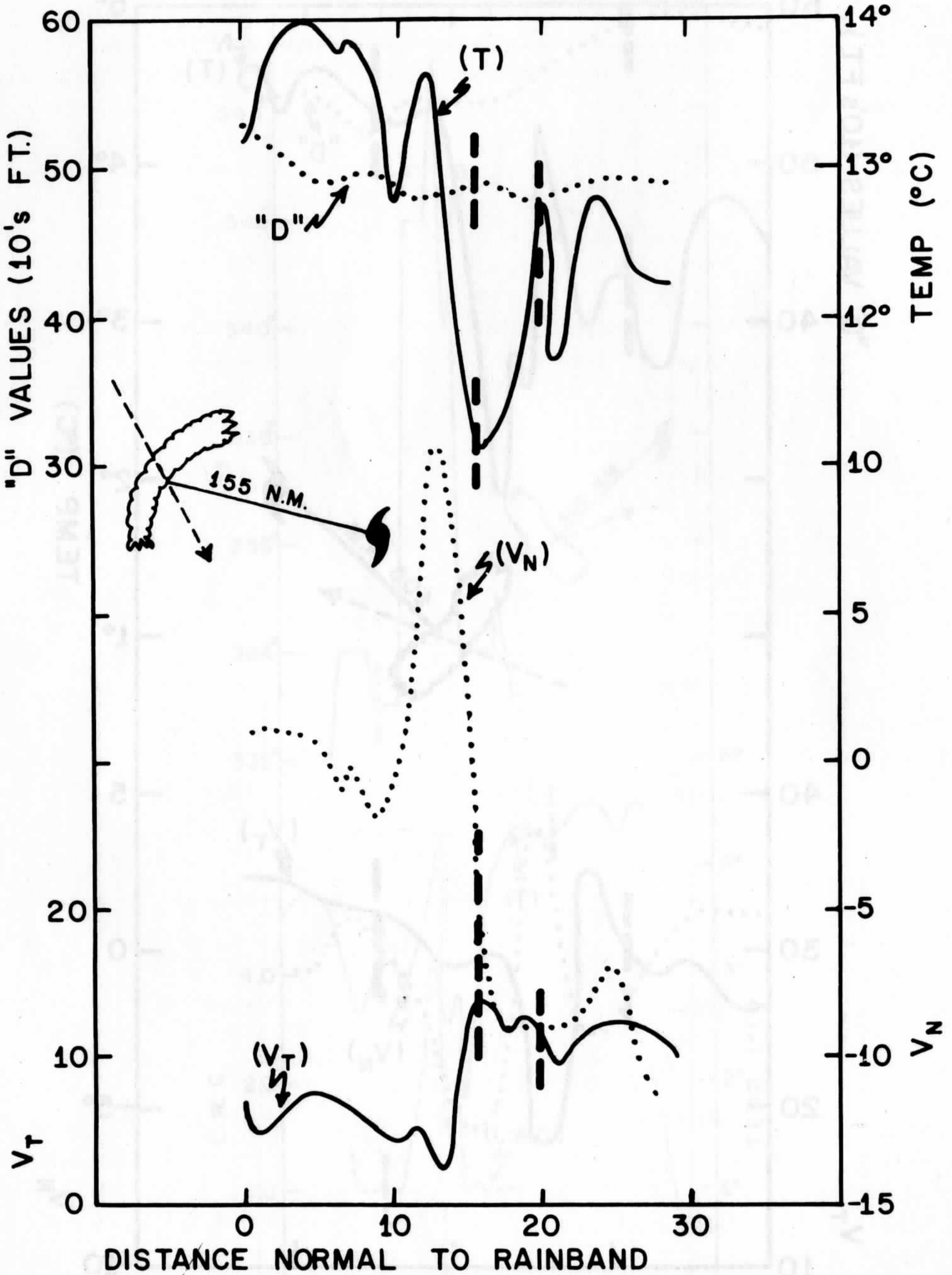

Figure 12. - Temperatures, D-values, and wind components (in knots) along a track normal to rainband about 155 n. mi. west-northwest of center of tropical storm Becky, September 15, 1958. Broken vertical lines on profiles mark band boundaries. Flight elevation, 6400 ft.

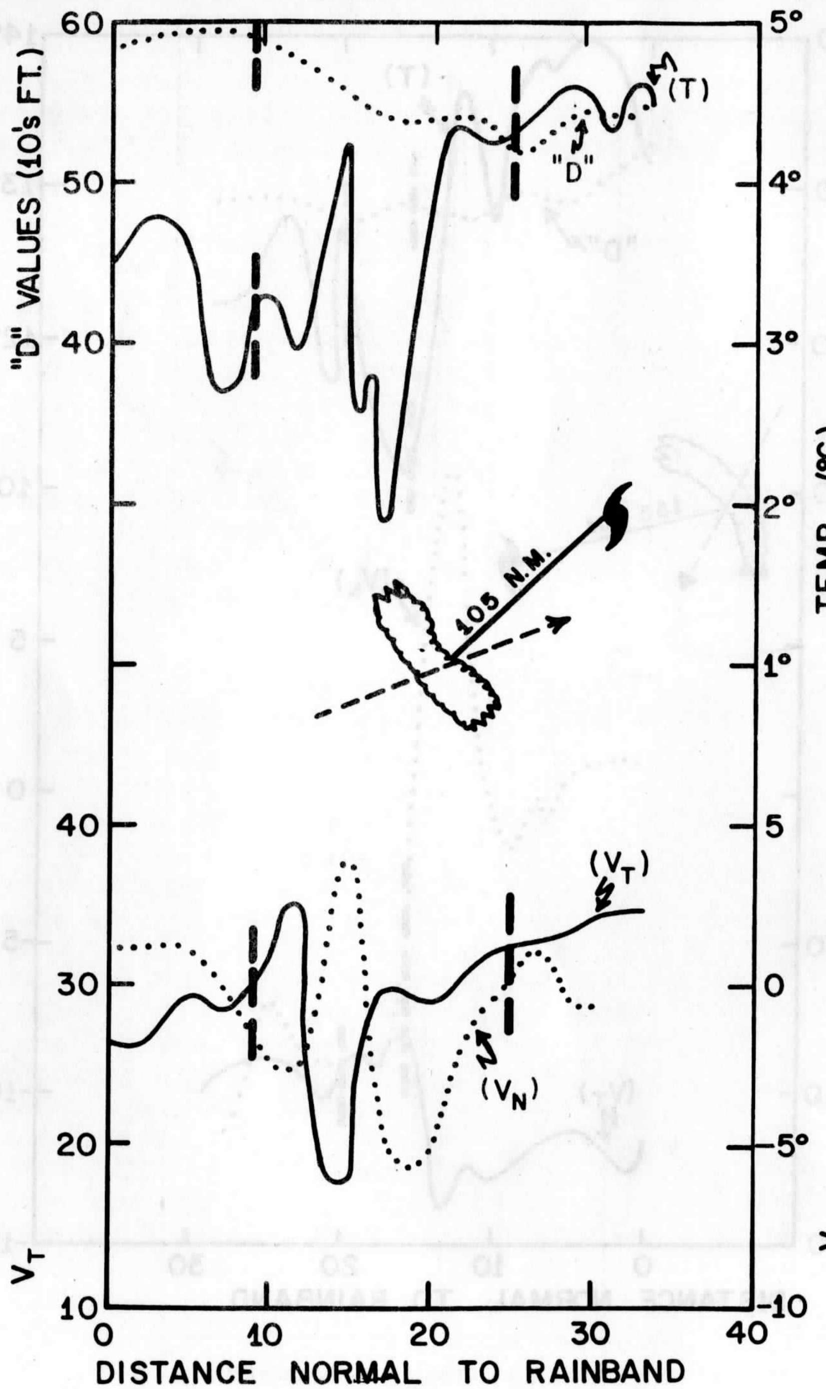

Figure 13. - Temperatures, D-values, and wind components (in knots) along a track normal to rainband about 105 n. mi. southwest of center of hurricane Daisy, August 27, 1958. Broken vertical lines on profiles mark band boundaries. Flight elevation, 13,000 ft.

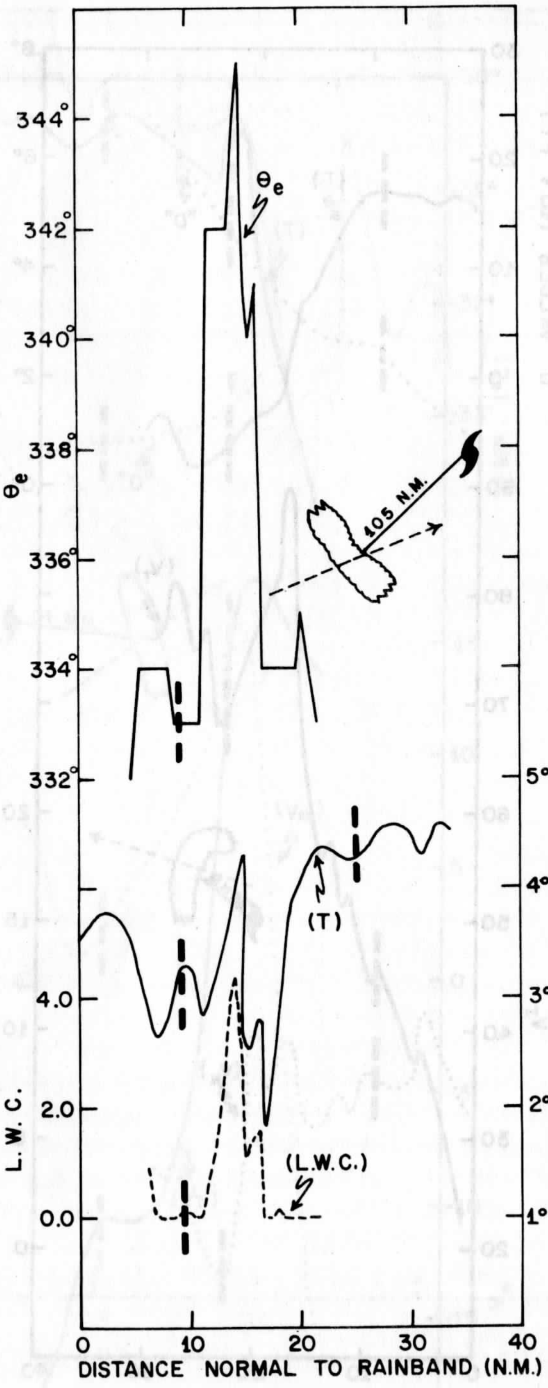

Figure 14. - Same as figure 13 except data are equivalent potential temperatures, liquid water content, (gm. m.$^{-3}$), and temperatures.

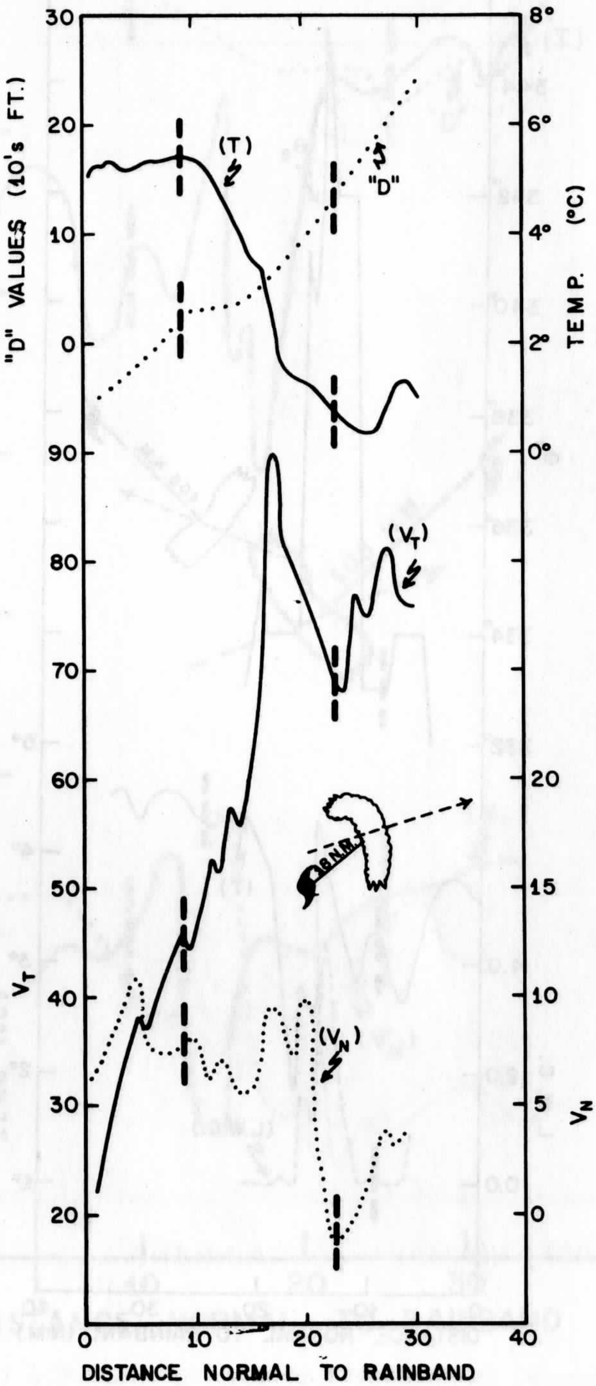

Figure 15. - Temperatures, D-values, and wind components (in knots) along a track normal to eye wall in northeast quadrant of hurricane Cleo, August 18, 1958. Broken vertical lines mark wall boundaries. Flight elevation, 15,600 ft.

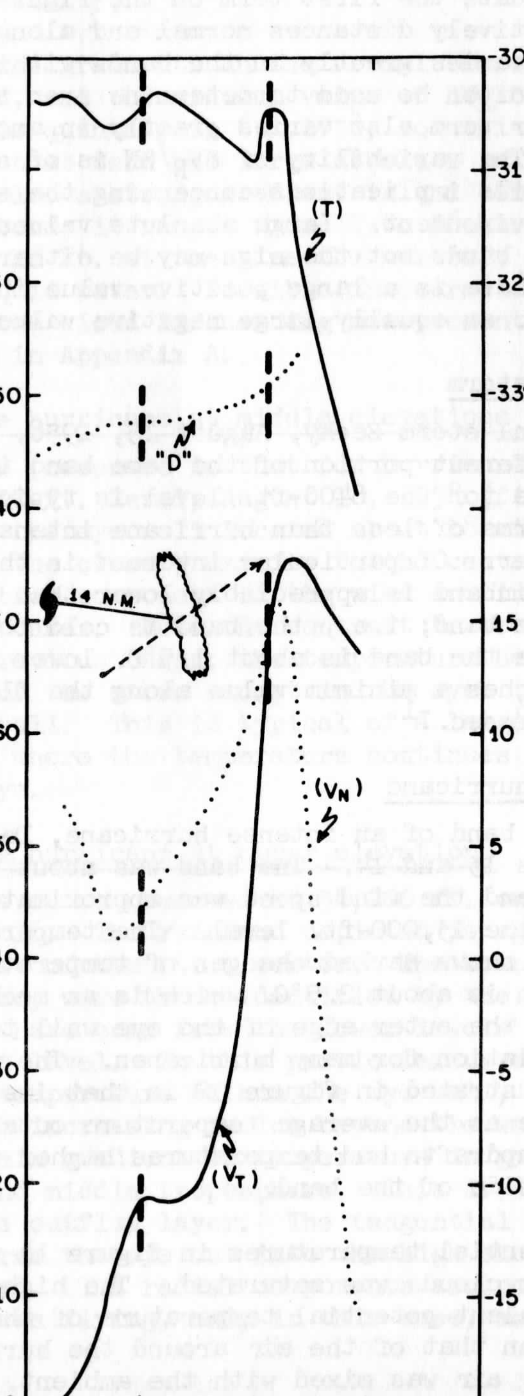

Figure 16. - Temperatures, D-values, and wind components (in knots) along a track normal to eastern eye wall of hurricane Helene, September 26, 1958. Broken vertical lines across profiles mark wall boundaries. Flight elevation, 34,200 ft.

then the normal components of the wind are plotted so that the slope of the graph may be used to evaluate the first term on the right (figs. 12, 13, 15, 16). (N and D are respectively distances normal and along the band.) The value of this first term varies greatly in the bands within short distances. Unfortunately, it cannot often be used to determine even the sign of the divergence because the other term also varies greatly in amount as will be discussed in Section 9. The variability of $\delta V_N/\delta N$ is of special interest, nevertheless, because of its implications concerning the exchange of air between the band and its environment. Large absolute values of this term are typically associated with bands but the sign may be either positive or negative, and in many bands there is a large positive value in one portion of band and within 1 or 2 mi. an equally large negative value.

Outer band of a tropical storm

A band from tropical storm Becky, August 15, 1958, is presented in figure 12. This is a different portion of the same band illustrated in figure 10. The temperature trace for the 6400-ft. level is typical of several that have been studied for storms of less than hurricane intensity and for bands far removed from the center. Of particular interest is the fact that the temperature inside the rainband is appreciably lower than the average temperature on either side of the band; i.e., the band is cold core. In this case the air temperature inside the band is about 1.5°C. lower than in the ambient air. The term $\delta V_N/\delta N$ reaches a minimum value along the flight track (at 14 to 16 mi.) of -2.6×10^{-3} sec.$^{-1}$

Outer band of an intense hurricane

Data from an outer band of an intense hurricane, Daisy of August 27, 1958, are given in figures 13 and 14. The band was about 105 n. mi. southwest of the storm center and the wind speed was approximately 30 kt. The temperature data are for the 13,000-ft. level. The temperature trace (reproduced in both figures) shows marked changes of temperature within the band. In this case the variation is about 2.5°C. which is as much as the total variation in temperature from the outer edge of the eye wall to the outer edge of the strong cyclonic circulation for many hurricanes. The difference between this band and the one illustrated in figure 12 is that its average band temperature is about the same as the average temperature outside the band, and some of the warm buoyant updrafts had temperatures higher than in the ambient air on the high pressure side of the band.

The equivalent potential temperatures in figure 14 were calculated on the assumption that air in clouds was saturated. The highest value is about 20°K. less than the equivalent potential temperature of the surface air but more than 10°K. higher than that of the air around the hurricane at the same level. Thus the ascending air was mixed with the ambient. (For further discussion, see Section 11.)

The peak in the temperature trace at 14.8 mi. and the secondary peak at 16.3 mi. were both associated with very large concentrations of liquid water (fig. 14). The liquid-water-content values are those prepared by Ackerman [1]. In this case, as well as in the preceding case, the measured temperature increased rather than decreased as the aircraft departed from the rainband and entered the relatively dry ambient air, which strongly suggests that temperature variations recorded by the sensing element are not caused by the wet-bulb effect (Section 3).

There are large gradients in the normal component of the wind in the vicinity of the band, and the minimum value of $\delta V_N/\delta N$ is -10^{-3} sec.$^{-1}$ The maximum value of this quantity is 6×10^{-4}, so this band is an example of the group for which that term has large absolute values of each sign. In this band there is also a strong gradient in the component of the wind tangential to the rainband; it ranges from 17 to 36 kt. within the band. This component decreased 16 kt. at the time the aircraft encountered the heavy concentration of liquid water. Possible inaccuracies of the wind as a result of liquid water in the cloud influencing measurements made by the Doppler radar are discussed in Appendix A.

Eye wall of a mature hurricane at middle elevations

The next case presented is that for hurricane Cleo with the data observed for the 15,600-ft. level, August 18, 1958 (fig. 15). These data are for that portion of the eye wall located about 18 mi. northeast of the storm center. Because of the close proximity to the center of the storm, the variation in the tangential component of the wind and in the temperature is greater than in the earlier cases. Note the contrast between this case, however, and either of the two previous cases; the temperature here is much higher than in all other portions of the storm except in the eye. The main temperature gradient was in the eye wall. This is typical of a large group of storms. There are those, however, where the temperature continues to increase with decreasing radius inside the eye.

Eye wall of a mature hurricane at upper elevations

Data for Helene, as observed at 34,200 ft. on September 26, 1958, are presented in figure 16. The rainband depicted is again that of the eye wall; this time to the east of the storm center. The boundaries of the eye wall, as in the other cases, were those identified by the radar pictures, and the major return should have come from the lower levels of the atmosphere rather than from the flight level. In this particular case there is relatively little fluctuation in temperature within the eye wall, but the temperature decreases rapidly with increasing radius beyond the wall. In most hurricanes the radius of the main gradient of temperature is greater at higher elevations than in the lower and middle troposphere. This is due to the ring of warm air expanding in the outflow layer. The tangential component of the wind increases rapidly from the eye out into the high energy portions of the storm as should be expected. The radial components are positive in the direction in which the plane was flying, and, in this case, are blowing away from the eye.

The term $\delta V_N/\delta N$ has large positive values over the eye wall, but is negative over the eye and over the area immediately beyond the eye wall.

5. TEMPERATURE VARIATIONS

The profiles presented in Section 4 contain samples of temperature measurements made in both longitudinal and normal traverses of rainbands of tropical cyclones. While it has long been known that temperature varies considerably along the radius of a hurricane (Riehl [36], and earlier surface observations made during passages of rainbands implied that there would be considerable variation in temperature on the normal traverses of the bands (Wexler [51]), the variation found inside the bands on the longitudinal traverses had not been suggested by previous investigations. In this section summaries will be presented which illustrate the variation of temperature within and across the bands, and the variation of the mean band temperature anomaly with elevation, radial distance from the storm center, and with the intensity of the storm. These variations and their effect on the energetics of the hurricane will be discussed.

Variations of temperature in a rainband strongly support the hypothesis that the hurricane in general, and the rainband in particular, are predominantly convective phenomena (LaSeur [21]). Gradients of temperature on a pressure surface, both along and normal to the contours, are far greater in the rainbands of a hurricane than in the undisturbed tropical atmosphere. In fact the temperature frequently changes more within 5 mi. in a band than it does in 1000 mi. in the undisturbed tropical atmosphere.

Temperature range in longitudinal traverses

Table 1 summarizes data from the longitudinal traverses which are grouped according to whether or not the aircraft was in a band. Within groups the arrangement is by decreasing altitude. Traverses 109 and 112 were along but just outside of bands, while 110 and 111 were between bands. The approximate mean altitude of each flight is given in column 3, and the approximate distance of the flight leg from the center of the storm is in column 4.

To get a measure of the temperature changes on the longitudinal traverses the difference between a minimum (maximum) and the extreme maximum (minimum) within the next 10 mi. along the flight track was used. The largest absolute value of all such changes on each longitudinal traverse was recorded in table 1, column 6, and the mean of the absolute values for each traverse was recorded in column 7. For the flights made at elevations of 10,000 to 18,000 ft. the mean of these values was 1.5°C. (column 7, traverses 101-105). For traverses between bands at the same elevations, the average temperature change in the bands at 3250 ft. was only 0.7°C. (column 7, traverses 107 and 108). This smaller value for the lower elevations is to be expected if the horizontal temperature gradients are created by convective processes operating in a saturated air mass where the actual lapse rate does not differ markedly from the pseudo-adiabatic lapse rate. This is true because variations in vertical motion through a layer only 3500 ft. thick of a conditionally unstable atmosphere would not create much horizontal temperature gradient. Traverse 112, outside a band, had about the same temperature changes as the others at the same elevation. This may be due partly to the lack of temperature changes at the lower levels and partly to the track being so close to the band that the temperature changes were influenced by convective circulations in and near the band. Traverse 109 at 13,800 ft. was also along but just outside a band, and had temperature changes slightly greater than those in traverses 110 and 111 which were between bands at about the same flight level. Traverse 106 was for the 6400-ft. level. This was a particularly well-marked band and the average temperature change was 1.3°C. even though the flight was at a relatively low level. These temperature differences are plotted against altitude in figure 17. Those for the flights between bands in

Table 1. - Summary of wind and temperature variations on longitudinal traverses

Trav-erse No.	Flight No.	h (10's ft.)	r (n. mi.)	In Band	Temp. Changes Within 10 Mi.		Speed Changes Within 10 Mi.		Fig-ure
					Max.	Avg.	Max.	Avg.	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
101	80818B	1560	50	Yes	1.4	1.3	18	13	8
102	21017A	1380	75	Yes	3.0	1.9	53	18	..
103	21017A	1380	95	Yes	2.4	1.4	23	12	2
104	21019A	1380	65	Yes	2.2	1.6	20	10	5
105	80924B	1300	55	Yes	1.9	1.5	8	6	9
106	80815A	640	200	Yes	2.8	1.3	17	6	10
107	21017B	325	100	Yes	1.8	1.1	29	12	3
108	21019B	325	80	Yes	0.9	0.4	15	6	6
109	21019A	1380	65	No	1.4	0.8	11	8	5
110	21019A	1380	95	No	1.0	0.6	11	7	7
111	80827B	1300	90	No	0.7	0.4	7	5	11
112	21017B	325	110	No	1.8	0.7	11	7	4

the middle troposphere are all obviously much less than those for the band traverses at corresponding levels.

The strong gradients in temperature encountered inside the bands on the longitudinal traverses are rather conclusive evidence that the bands are not uniform longitudinally but are composed of individual convective elements and the interstitial spaces. The wind components along and normal to the bands also varied markedly. This was illustrated in Section 4 and will be discussed in Section 6. With such variation the mixing that would eventually result would soon eliminate the temperature gradients unless they were continually being recreated. The only mechanism for doing this which could possibly operate fast enough is the one already mentioned, that is, dif-

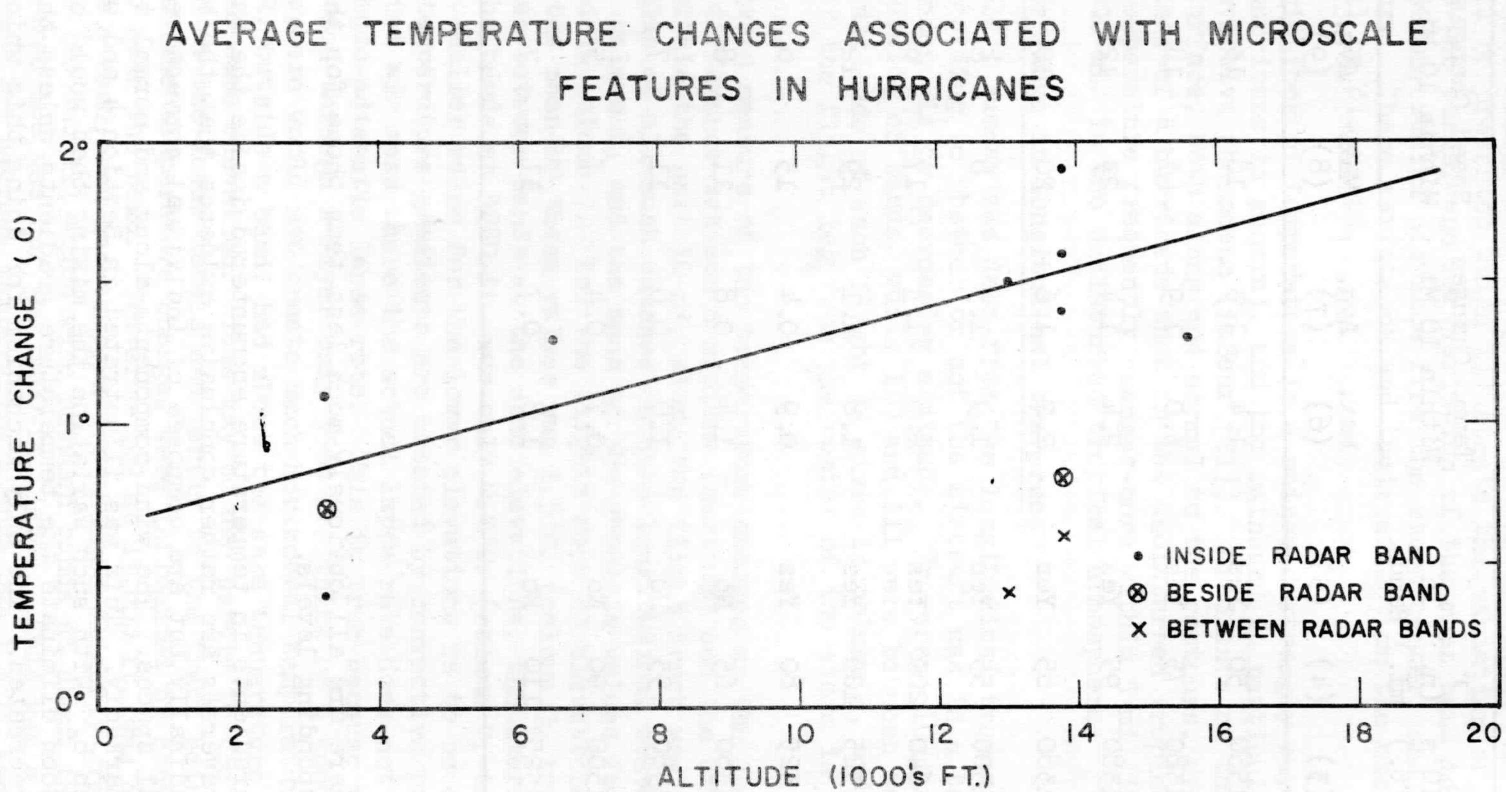

Figure 17. - Variation with altitude of average of changes in temperature between successive minimum (maximum) and greatest maximum (minimum) occurring within next 10 mi. on flight track.

ferential vertical motion through a conditionally unstable atmosphere. Radiation would not be effective and the air entering a hurricane is ordinarily so homogenous that advection could rarely produce gradients of the magnitude commonly observed. The fact that the temperature gradients on the longitudinal traverses are greater at middle elevations than at the lower elevations also supports this conclusion. This is true because horizontal gradients created by differential vertical motion through a conditionally unstable atmosphere would vary directly with the (1) difference between actual and pseudo-adiabatic lapse rates, and between the gradients of each, (2) gradient of the vertical motion, and (3) depth through which the vertical currents have operated.

Percentage of areas with anomalous temperatures

One of the questions posed in Section 1 was whether there were warm buoyant columns through which air ascended from the lower inflow layer to the upper outflow layer without mixing with the ambient air. Such columns have been hypothesized to explain the variation of the equivalent potential temperature with height (Riehl and Malkus [37]). This subject will be discussed in greater detail in Section 11, but the temperature data can be used to determine what percentage of the area of the rainbands (or of the storm) have temperatures appreciably higher than the ambient air at the same level. Checks can then be made to see if reasonable vertical velocities operating through areas of this size could transport the quantity of air known to flow through the vertical circulation of a typical hurricane. The percentages of the bands having temperatures above or below normal will also be useful in interpreting the representativeness of some of the temperatures measured on the normal traverses. This will be discussed in later paragraphs.

The computations of the percentage of the longitudinal traverses in which the temperature was considerably above (or below) normal were made after arbitrarily assuming that temperatures were significantly departed from normal if they differed from the mean temperature of the surrounding air in the band by 0.375°C. which is 1/4 of the average change within 10 n. mi. in temperature along the bands at middle elevations (table 1, col. 7, traverses 101-105). The departure was measured from a smoothed curve drawn to give a best fit (by eye) to the data and to eliminate effect of any general trend. The percentage of each of the longitudinal traverses in which the temperature was more than 0.375°C. higher or lower than this best fit temperature, was computed. For the traverses of the bands in the 13,000-16,000-ft. layer the mean of these values was 22 and 23 percent, respectively. For the bands traversed at 3250 ft. and for the flights between bands the means of these percentages were 8 and 5, respectively. Even in the active bands at about the 14,000-ft. level, less than 1/4 of the traverse was through relatively high temperatures. Thus in a single crossing normal to a narrow band one would have only about 1 chance in 4 or 5 of encountering relatively high (low) temperatures.

Temperature variations in normal traverses of bands

Table 2 contains information about the temperature and wind variations for traverses normal to the bands. Traverses in this table are grouped in the following classes: (1) outer bands in the lower troposphere (more than

Table 2. - Temperature and wind variations in normal traverses of radar bands

Traverse No.	Flight No.	r (n mi)	h (10's ft)	Band Percentage		$\overline{T}_B - \overline{T}_A$	Departures from Normal			V_N	ΔV_N	$\frac{\delta V_N}{\delta N}$ In Band Per Second		
				Warm	Cold		$\overline{T}_B$	T_{Max}	T_{Min}			Max $\times 10^4$	Min $\times 10^4$	Avg $\times 10^4$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Outer Bands in Lower Troposphere														
1	80902B	105	1560	0	100	-0.7	+0.8	+0.9	+0.6	25.0	14	4.2	-6.0	1.0
2	80902B	75	1560	14	43	-1.3	+1.2	3.0	-0.2	M	9	3.4	-7.1	1.1
3	80902A	85	820	0	67	-0.6	0.0	0.7	-0.6	-1.0	5	1.1	0.0	1.1
4	80827B	43	1300	29	0	0.2	+0.2	0.9	-0.3	18.0	11	17.6	-19.9	3.4
5	80827B	50	1300	39	0	0.2	+1.1	+1.5	+0.6	+3.0	16	19.9	-9.3	3.4
6	80827B	44	1300	40	0	+0.3	+1.1	+1.4	+0.8	7.0	4	...	-2.1	-1.7
7	80827B	42	1300	0	100	-0.6	+0.4	0.4	0.4	8.0	7	10.5	0.0	10.5
8	80827B	60	1300	0	100	-1.0	+0.4	+1.5	+0.1	-9.0	9	0.0	-3.8	-3.8
9	80827B	65	1300	0	0	-0.3	+1.2	1.4	1.0	-4.0	5	0.0	0.0	0.0
10	80827B	100	1300	36	27	0.0	+0.4	1.3	-1.2	-1.0	9	9.9	-12.2	-0.5
11	80827B	105	1300	0	53	-0.6	+0.4	1.3	-1.2	-2.0	10	6.5	-12.2	0.3
12	80825B	62	1560	20	0	0.0	+1.2	1.5	+0.8	10.0	4	0.0	-2.8	-2.8
13	80825B	41	1560	50	0	+0.3	+0.9	1.2	+0.5	14.0	4	0.0	-7.9	4.4
14	80818B	60	1560	0	0	0.0	+1.7	2.2	1.3	14.0	9	15.9	-26.5	1.6
15	80818B	43	1560	0	23	0.0	+2.7	3.2	2.3	27.0	9	9.3	...	3.6
16	80818B	47	1560	0	0	-0.1	+1.1	1.2	1.1	-8.0	7	...	-2.1	-2.1
17	80818B	55	1560	0	0	-0.1	+0.9	+1.1	+0.7	-5.0	6	3.8	-3.4	0.4
18	80818B	65	1560	0	28	-0.3	+1.3	+1.8	+0.8	-8.0	3	3.2	-2.3	0.4
19	80818B	80	1560	0	0	-0.1	+2.3	2.5	2.1	7.0	3	0.0	-4.3	-0.8
20	80818A	60	640	0	0	0.0	0.1	0.2	0.0	-27.0	8	3.4	-2.8	-0.4
21	80818A	80	640	0	100	-0.6	-1.1	-0.9	-1.3	-28.0	17	6.5	...	6.5
22	80818A	85	640	60	0	+0.3	-0.4	0.1	-1.7	-34.0	3	4.0	-2.8	-0.9
23	80818A	80	640	0	100	-1.1	-1.0	-0.6	-1.4	-10.0	9	2.3	0.0	1.1
24	80818A	65	640	0	0	0.0	-0.1	+0.3	-0.6	-17.0	5	2.4	-4.8	0.5
25	80818A	80	640	0	0	-0.1	-0.5	-0.4	-0.7	-35.0	6	3.4	-3.8	-1.8
26	80815B	105	1560	0	0	-0.1	-0.5	-0.3	-0.6	-6.0	6	1.7	-4.3	-0.5
27	80815B	315	1560	13	29	-0.3	-1.7	-0.8	-2.4	5.0	4	2.2	-4.3	-0.1
28	80815A	205	640	0	79	-0.6	-3.0	-2.7	-3.3	6.0	13	2.7	-10.5	-2.0
29	80815A	155	640	0	100	-1.1	-3.3	-2.4	-3.8	-7.0	20	0.0	-13.2	-4.3
30	80815A	315	640	0	81	-1.3	-2.2	-1.0	-3.3	0.0	19	19.9	-12.2	2.4
31	70923A	105	160	0	100	-1.0	-3.0	-2.8	-3.2	3.0	4	1.4	0.0	1.4
	Average			10	36	-0.3				11.6	8	5.0	-5.8	0.7

Table 2. - Continued

Traverse No.	Flight No.	r (n mi)	h (10's ft)	Band Percentage		$\overline{T}_B - \overline{T}_A$	Departures from Normal			$\overline{V}_N$	ΔV_N	$\frac{\delta V_N}{\delta N}$ In Band Per Second		
				Warm	Cold		$\overline{T}_B$	T_{Max}	T_{Min}			Max $\times 10^4$	Min $\times 10^4$	Ave $\times 10^4$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Intermediate Bands In Lower Troposphere														
32	80827B	19	1300	32	0	+0.4	+0.9	1.7	-0.1	-50.0	25	11.3	-39.8	-11.3
33	80827B	16	1300	13	7	+0.4	+1.5	+2.2	+0.9	10.0	16	9.9	-22.7	1.1
34	80827B	32	1300	40	0	+0.3	+0.1	+0.4	-0.1	8.0	12	5.6	-11.3	-1.8
35	80827B	20	1300	0	67	-0.4	-0.4	+0.2	-0.8	-9.0	16	3.1	-15.9	-11.3
36	80827B	15	1300	0	0	-0.2	1.1	2.4	0.0	22.0	22	19.9	-19.9	-0.4
37	80827B	27	1300	0	0	-0.1	+0.2	0.3	0.1	4.0	11	5.6	-3.0	-2.8
38	80827B	20	1300	0	0	0.0	0.4	0.8	0.0	-4.0	9	...	-9.3	-9.3
39	80827B	25	1300	0	0	0.0	+0.1	0.1	0.1	6.0	6	4.8	...	4.8
40	80825B	12	1560	46	0	+0.5	+1.5	+1.9	1.2	+16.0	32	...	-19.9	-15.9
41	80825B	13	1560	0	71	-0.4	+0.3	0.8	0.1	-7.0	24	3.1	-2.6	2.0
42	80825B	36	1560	0	100	-0.6	-0.2	-0.1	-0.3	-14.0	8	...	-4.8	-4.8
43	80825B	37	1560	0	100	-0.6	-0.3	-0.3	-0.3	11.0	18	...	-13.2	-13.2
44	80818B	40	1560	0	0	-0.1	1.9	2.1	1.8	11.0	9	3.4	...	3.4
45	80818A	28	640	0	0	0.0	-0.1	+0.3	-0.8	-6.0	8	4.0	-5.2	-2.8
	Average			9	23	-0.1				13.0	16	5.0	-12.0	-4.4
Eye Walls In Lower Troposphere														
46	80827B	8	1300			3.0	4.3	6.9	1.8	-24.0	22	39.8	-26.5	11.3
47	80827B	8	1300			2.9	3.2	5.3	1.7	-11.0	27	...	-19.9	-14.4
48	80827B	6	1300			3.1	+5.3	7.7	2.9	1.0	32	31.8	-7.5	9.3
49	80827B	8	1300			2.4	2.9	4.0	1.4	+2.0	28	15.9	-19.9	9.9
50	80818B	14	1560			2.2	+4.0	+5.4	+2.3	0.0	11	26.5	-13.2	-4.0
51	80818B	12	1560			2.8	+4.6	+6.8	+1.9	-5.0	17	22.7	-31.8	-1.6
52	80818B	24	1560			0.3	3.1	4.7	2.3	+3.0	14	6.0	-22.7	-0.1
53	80818B	18	1560			2.6	+4.8	7.1	2.5	+7.0	12	8.8	-14.4	-1.6
54	80818B	20	1560			0.9	+2.9	+4.0	+1.4	+8.0	10	9.9	-9.9	-0.2
55	80818A	18	640			1.6	+1.5	3.3	+0.1	+2.0	10	2.7	-5.6	1.7
	Average					+2.0				6.2	23	16.0	-16.2	1.3

Table 2. - Continued

Traverse No.	Flight No.	r (n mi)	h (10's ft)	Band Percentage Warm	Band Percentage Cold	$\overline{T}_B - \overline{T}_A$	Departures from Normal $\overline{T}_B$	Departures from Normal T_{Max}	Departures from Normal T_{Min}	$\overline{V}_N$	ΔV_N	$\frac{\delta V_N}{\delta N}$ in Band Per Second Max $\times 10^4$	Min $\times 10^4$	Avg $\times 10^4$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
					Intermediate and Outer Bands in Upper Troposphere									
56	80818C	55	3500			...	...	...	...	+12.0	5	2.1	-1.9	0.1
57	80818C	30	3500			...	...	...	...	-11.0	16	2.4	-6.3	-2.7
58	80818C	32	3500			0.0	9.2	9.7	+8.7	-16.0	14	...	-9.9	-5.6
59	80818C	36	3500			+0.2	8.4	8.4	8.3	-14.0	8	3.6	...	2.6
60	80815C	55	3398			...	...	...	...	-12.0	4	2.1	-6.5	0.4
61	80815C	70	3398			-0.4	3.4	3.5	+3.4	6.0	6	1.7	...	1.4
		Average				0.1				12.0	9	2.0	4.4	-0.6
					Eye Walls in Upper Troposphere									
62	80818C	22	3500			1.0	+10.6	+10.9	+10.1	+8.0	18	5.1	-5.1	2.5
63	80818C	19	3500			1.7	+11.2	+11.6	10.8	21.0	5	2.5	-4.3	-0.1
64	80818C	22	3500			1.3	10.4	10.5	10.3	-5.0	9	3.8	-5.1	-1.5
65	80818C	20	3500			0.3	11.4	11.5	11.3	0.0	31	7.1	...	4.3
66	80818C	18	3500			M	M	M	M	-3.0	11	13.2	-6.5	1.8
67	80827C	8	3420			4.0	+10.5	11.3	9.8	-6.0	34	17.6	...	15.9
68	80827C	8	3420			4.5	11.0	12.3	10.1	10.0	27	19.9	...	14.4
69	80926C	15	3420			...	11.8	13.1	9.4	-3.0	33	5.6	...	3.8
70	80926C	14	3420			2.0	+13.0	13.2	12.5	8.0	17	7.9	...	3.3
		Average				2.1				7.1	20.6	9.2	-2.3	4.9

Note: The approximate distance of band from center of storm, r, and approximate height of band, h, are listed respectively in columns 3 and 4. Warm and cold in columns 5 and 6 refer to that percentage of each band that was .375C different than mean temperature of ambient air. The values in column 7 are the differences between the mean temperature in the band, T_B , and the mean temperature of the ambient air, T_A . Column 11 contains the mean in each band of the normal component of the wind, and column 12 lists the variation of this component for each band.

40 n. mi. from center and crossed below 16,000 ft.), (2) intermediate bands in the lower troposphere, (3) eye walls in the lower troposphere, (4) intermediate and outer bands in the upper troposphere (about 35,000 ft.), and (5) eye walls in the upper troposphere.

Inspection of the data in table 2 reveals that the temperature on the traverses normal to the bands may change either about the same amount as in the longitudinal traverses or relatively little. This noticeable variability in the maximum temperature change observed on the normal traverses may be due to variations in the intensity, character, and maturity of the bands, and it may also be due to sampling since the chances are better than even that a normal traverse will encounter neither a warm nor a cold shaft of air in a band only 3 to 4 mi. wide.

Variation of temperature anomalies with radius, elevation, and storm intensity

The bands become relatively warmer compared to the ambient air with decreasing radius. The relation is very weak, however, except for the bands very close to the eye wall, and it is easy to find examples of outer bands whose mean temperature is lower than that of ambient air. Data to illustrate these conclusions are recorded in table 2, column 7, where the mean temperature inside the band ($\overline{T}_B$) is compared with the mean ambient temperature ($\overline{T}_A$) for about 5 mi. on either side of the band (or in case of the eye wall, with the mean of the ambient temperature for 5 to 10 mi. on the high pressure side of the band). For the eye walls $\overline{T}_B - \overline{T}_A$ was + 2.0°C. on the average. Thus air in the eye walls was appreciably warmer than the air outside the walls but the difference was to some extent determined by the definition of the term "ambient". The temperature changes rather rapidly in the vicinity of the eye wall, and in nearly all cases varied inversely with the radius. The difference ($T_B - T_A$), therefore, can be varied within limits by redefining the ambient area.

It is of interest to consider the difference in temperature between the eye and the eye wall in the middle troposphere. The temperature in nearly all cases varied inversely with the radius in the eye wall. In many storms most of the change in temperature across the entire storm area was concentrated in the eye wall. In these cases the temperature on the low pressure side of the wall was essentially the same as (in some cases actually higher than) the temperature at the same level in the eye. In other cases the temperature continued to increase with decreasing radius as the aircraft passed into the eye where the mean temperature might be more than 3°C. higher than the temperature at the inner edge of the wall. In nearly all cases the mean temperature in the eye was higher, level for level, than the mean temperature in the eye wall because of the temperature gradient through the wall. The above statements all apply to the lower and middle elevations of the troposphere.

The data for the upper levels (flights mostly made near the 35,000-ft. level) show that the temperature in the outer bands was essentially the same in the mean as the ambient temperatures. Temperatures in the eye walls averaged 2.1°C. higher than the air near the wall on the high pressure side.

In some cases the mean temperature in the wall was about the same as that in the eye. This can be easily explained. The location of the band was that given by the radar in the aircraft which receives most of its return from the lower elevations; hence the boundary of the rainbands used is essentially the location of the rainband at lower levels. At upper levels, however, the outflow has already started and the ring of warm air associated with the eye and the eye wall is concentrated at greater radii than at lower elevations. Therefore, in many cases the concentrated temperature gradient at these upper levels occurs on the high pressure side of the eye wall's location for the lower levels.

The temperatures in the intermediate bands and in the eye wall of storms of hurricane intensity are higher than the mean temperatures of the Tropics. This is an obvious conclusion from data in table 2, where anomalies of the mean, maximum, and minimum temperatures, respectively, are recorded for each traverse normal to the band, in columns 8, 9, and 10. These anomalies are summarized in table 3. In each case temperatures are expressed as departures from the mean temperatures for the West Indies area for August and September (Jordan [15]). The mean temperature anomalies range from 11.2°C. above normal in the eye wall of hurricanes at the upper levels to 2.9°C. below normal in the outer bands of storms of less than hurricane intensity at lower levels (below 7000 ft.). There is a marked tendency for the temperature anomalies to vary directly with height and with the maximum intensity of the storm of which the band is a part. The temperature anomalies also vary inversely with radius in the bands within about 50 n. mi. of the eye wall.

The measured temperatures were usually above normal for bands in mature hurricanes at levels greater than 10,000 ft. In the upper troposphere, even the minimum temperatures in bands were above normal for the traverses examined. Of the 32 bands in mature hurricanes which were traversed between 7000 and 20,000 ft., 31 had positive anomalies for the mean temperatures. The anomaly of the other one was only 0.4°C. below normal and some of the temperatures measured in that band were higher than the mean tropical temperature for the elevation (Jordan [15]).

Maximum temperature variations

The greatest temperature variation inside bands was measured in the eye walls at the 11,000 to 15,000-ft. levels. In hurricane Daisy, August 27, 1958, the temperature varied 5.2°C. during one normal traverse of the eye wall at 13,000 ft. In 7 cases out of 10 the temperature changed more than 3°C. along a constant pressure surface during normal traverses of the eye wall at these elevations. In the outer bands the greatest temperature variation measured during a traverse normal to the band was 3.2°C. in traverse 2, a band 75 mi. from the center of tropical storm Ella, September 2, 1958.

Significance of temperature variations

The summaries presented so far show that temperature anomalies of air in the bands vary directly with the intensity of the storm, directly with elevation and, for the bands within 50 n. mi. of the eye wall, inversely with radius. These facts support conclusions already expressed. Namely, the

Table 3. - Average departures of rainband temperatures from mean tropical temperatures (August and September).

Flight Elevation (ft)	Intensity	Mean Temperature of Traverses			Maximum Temperature			Minimum Temperature		
		Band Radius (n mi)								
		Eye Wall	r < 70	r ≥ 70	Eye Wall	r < 70	r ≥ 70	Eye Wall	r < 70	r ≥ 70
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
h ≥ 30,000	HURCN.	11.2 (8)	8.8 (2)	. .	11.8 (8)	9.0 (2)	. .	10.5 (8)	8.5 (2)	. .
	STORM	. .	3.4 (1)	. .	. .	3.5 (1)	. .	. .	3.4 (1)	. .
7,000 < h < 20,000	HURCN.	3.9 (9)	0.9 (20)	1.0 (3)	5.8 (9)	1.3 (20)	1.7 (3)	2.0 (9)	0.5 (20)	-0.1 (3)
	STORM	. .	0.6 (6)	0.0 (5)	. .	0.8 (6)	0.7 (5)	. .	0.3 (6)	-0.6 (5)
h ≤ 7,000	HURCN.	1.5 (2)	0.0 (3)	-0.6 (4)	2.8 (2)	0.3 (3)	-0.4 (4)	0.4 (2)	-0.5 (3)	-1.3 (4)
	STORM	. .	. .	-2.9 (4)	. .	. .	-2.2 (4)	. .	. .	-3.4 (4)

Note: Number of cases in Parentheses.

hurricane and its rainbands are convective phenomena existing in a conditionlly unstable atmosphere in which the horizontal temperature gradients are largely a function of the vertical circulation through the storm, and the temperature lapse-rate and moisture content of the air mass. They also support the hypotheses of previous investigators that the main portion of the net vertical circulation is concentrated near the eye wall region of a hurricane (LaSeur and Hawkins [22], Riehl [36], and Riehl and Malkus [37]). This is evident from the fact that the principal positive anomalies at all levels are restricted primarily to the eye wall or its vicinity. Undilute ascent in the outer and intermediate bands would have given greater positive anomalies than those indicated in table 3. This suggests that much of the air ascending in the bands is mixed with ambient air, which is confirmed by data in table 1, column 7, where the differences between the mean temperature in the band and the ambient air are recorded. On the average these differences were very small for bands beyond the eye wall. This was true even for the upper troposphere. On the other hand, the mean temperatures in the bands as well as the temperatures of the air near the bands were higher than mean tropical temperatures on the average, thus indicating that the release of latent heat in the ascending columns gave a net increase to the air temperatures in the various layers. This was confirmed by the tabulation of the equivalent potential temperatures in the bands which will be discussed in Section 11. Thus the vertical component of the circulation in the bands contributed to the general warming of the atmosphere around the center of the hurricane and contributed to the establishment of the baroclinic field in the high energy portion of the hurricane circulation which has been hypothesized as a requirement for hurricane development (Yanai [52]) and is a necessary requirement for hurricane maintenance. The temperature data indicate that the greatest contribution to this baroclinic development occurred in and near the eye walls, but the other bands did make some contribution. The outer bands contributed in another sense also. It will be shown in Section 9, that even in the eye wall there is considerable exchange and mixing between the ascending currents and their environment. The general warming and introduction of air of higher equivalent potential temperature into the middle tropospheric layers of the hurricane brought about by the bands produced a buffer between the ascending air in the eye wall and the relatively cold air outside the hurricane and prevented the effectiveness of the vertical circulation near the eye from being greatly diminished by mixing with air of much less equivalent potential temperature.

6. WIND VARIATIONS

The wind speed and the wind direction also vary considerably inside the bands. The amount of variation is summarized in tables 1 and 2, and illustrated in figures 2, 3, 5, 6, 8-10, 12, 13, 15, and 16. It can be seen that the gradients in wind speed on the longitudinal traverses of bands were mostly those associated with the micro-structure of the bands. The change in wind speed along each traverse was recorded from each minimum (maximum) to the maximum (minimum) reached within the next 10 n. mi. of flight (figs. 2 to 11). The data in columns 8 and 9 of table 1 are the maximum and mean, respectively, of such values for each traverse. The variation in wind speed and direction is greater in the mean at the middle levels of the troposphere (12 kt.) than at the lower levels (9 kt.) and is about twice as great within the bands in the middle troposphere (12 kt.) than outside the bands at the same levels (7 kt.). The difference, however, is not as pronounced or as consistent as the similar variation in the temperature data. The gradients in wind speed measured on the longitudinal traverses were frequently greater than those normally found in smoothed profiles of wind speed versus radius outside the eye and eye wall areas. The variations in wind speed along the bands suggest that deformation and shearing of the masses of air take place at a rapid rate and that values of horizontal divergence may be quite variable along the bands.

Normal components

The wind measurements made during the traverses normal to bands were decomposed into components normal and tangential to the orientation of the band at the intersection of the band and the flight track. (See Section 4.) The mean value of these normal wind components for each band in the normal traverse group was tabulated in table 2, column 11. The sign of these values is determined by the direction of flight (positive forward). The averages of the absolute values were computed for each group of traverses and are: 12 kt. for outer bands, 13 kt. for intermediate bands, and 6 kt. for eye walls in the lower troposphere; and 12 kt. for intermediate and outer bands and 7 kt. for eye walls in the upper troposphere. There is a wide range in the mean values for individual bands. Even though the normal wind component does not equal zero in the band, one cannot immediately say that the air is blowing across the band because the band may be moving with the normal component of the wind. Since there is such wide variation in the size of the normal components in the same hurricane, even within a single traverse of a band, however, it is almost certain that rapid exchange of air takes place between the bands and their environment at all levels investigated. This would not be the case if the air entered the band at low levels and ascended to high levels before being evacuated.

The normal components over the eye walls in the upper troposphere nearly all indicated flow away from the band, and in 5 of the 9 cases studied, indicated flow toward the eye from the inside of the wall and toward greater radii from the outside of the wall.

Variation of tangential components

The variation of the tangential component of the wind (V_T) during the traverses normal to the band was just as marked as the variation of the normal components (figs. 12, 13, 15, and 16). Since the normal traverses were approximately along radii of the hurricane, it is difficult to separate the variation due to the band from the strong inverse relationship between the wind speed and the storm radius. The profiles of the tangential components were examined, however, to determine if there was any preferred location relative to the band for the maximum wind measured during the traverse. For bands close enough to the center to be in the area where the wind speed changes rapidly with radius, the wind speed was nearly always higher on the low pressure side of the band than on the high pressure side. This is true because the microscale changes are so much smaller than the gross changes associated with the storm's circulation. If, however, a smoothed profile is drawn for V_T one can frequently identify the wind maximum associated with the rainband by noting the place of greatest positive departure of the observed wind profile from the smoothed one. The normal traverses were examined with this in mind. It was found that in about 20 percent of the cases the wind maximum was on the high pressure side of the band and in the remaining cases it was on the low pressure side.

Summary and significance

The winds were found to be much more variable in the bands than between the bands. Regarding the hurricane circulation as a whole the wind speed varies inversely with the radius outside the eye. Except in the vicinity of the eye and eye wall the mean variation with the reciprocal of the radius is, however, frequently not as great as many of the variations found in the bands on both the normal and longitudinal traverses. The variations occur on a scale that make them appear to be ordered by convective scale systems. Thus the wind data, just as the temperature data, strongly suggest that the bands are composed of convective elements and interstitial spaces. The variation of the total wind and its components further suggests that there is rapid exchange of air between the bands and their environment. The former action could explain why the bands have such a uniform appearance in many radar photographs, for if the large water drops were dispersed evenly along the band before falling to the surface, their reflectivity would cause the radar echoes to be uniform.

The idea that there is rapid exchange of air between band elements and the band's environment will be discussed in Sections 9 and 11. It is important for verifying the hypotheses related to methods of transporting air from the lower inflow layer to the upper outflow layer.

7. PRESSURE VARIATIONS (D-VALUES)

The pressure variation in the bands is represented by profiles of D-values. Data were available for most of the band traverses (figs. 2, 3, 5, 6, 8-10, 12, 13, 15, and 16). There was considerable variation of D-values in the bands, but in a somewhat different manner than for the temperatures and winds. In the profiles of figures 2-7 the data were smoothed over 3 sec. to eliminate high frequency variations. There remained a quasi-periodic variation of about 2 mi. wavelength which was not nearly so prominent in the temperature and wind speed profiles. There were also the longer wavelength disturbances that were noticeable in the profiles of the other parameters. Changes of D-value of 40 to 50 ft. within 2 to 3 mi. were common in the longitudinal traverses and changes as great as 200 ft. within 5 mi. were measured.

The D-value profiles for the traverses normal to the bands were examined for location of the minimum relative to the axis of the bands, using the same technique as for the wind speed profiles. That is, a smoothed profile was drawn and the departures from this smoothed line were attributed to the band's effect. Simpson and Starrett [46] found that in 6 of 12 cases examined there was a dip in the D-value profile on the high pressure side of the band. Examples of this type of structure are in evidence in the bands of hurricane Carrie (Staff, National Hurricane Research Project [48]) and can be examined in figure 18. Several examples of this type were found in the data used for this study. Of 30 cases examined, 15 had inconclusive indications, 7 had minima on the inside of the band, and 8 on the high pressure side of the band. In some cases the minimum was of sufficient magnitude to reverse locally the pressure gradient associated with the storm, that is, in places the D-value varied inversely with the radius for about 2 n. mi. Since many of the variations observed on the longitudinal traverses were also greater than the storm's gradient in D-value, there is strong evidence that there are probably convective-scale gradients in D-value which are opposite in direction to that of the hurricane in general. This is most likely to occur in the relatively weak pressure gradients outside the area of great pressure change near the center of the storm.

The changes in pressure associated with passage of rainbands had been noted in surface data by previous investigators. Ligda reproduced a microbarograph trace and wrote that it "gives clear-cut evidence of 'kinked-back' isobars" ([24] p. 33). Wexler [51] also presented pressure traces which were recorded while rainbands were passing weather stations and which show relatively sudden changes that temporarily reversed the pressure gradient associated with the storm. Examination of these and other cases reported by earlier investigators influenced Tepper [49] to hypothesize that rain-

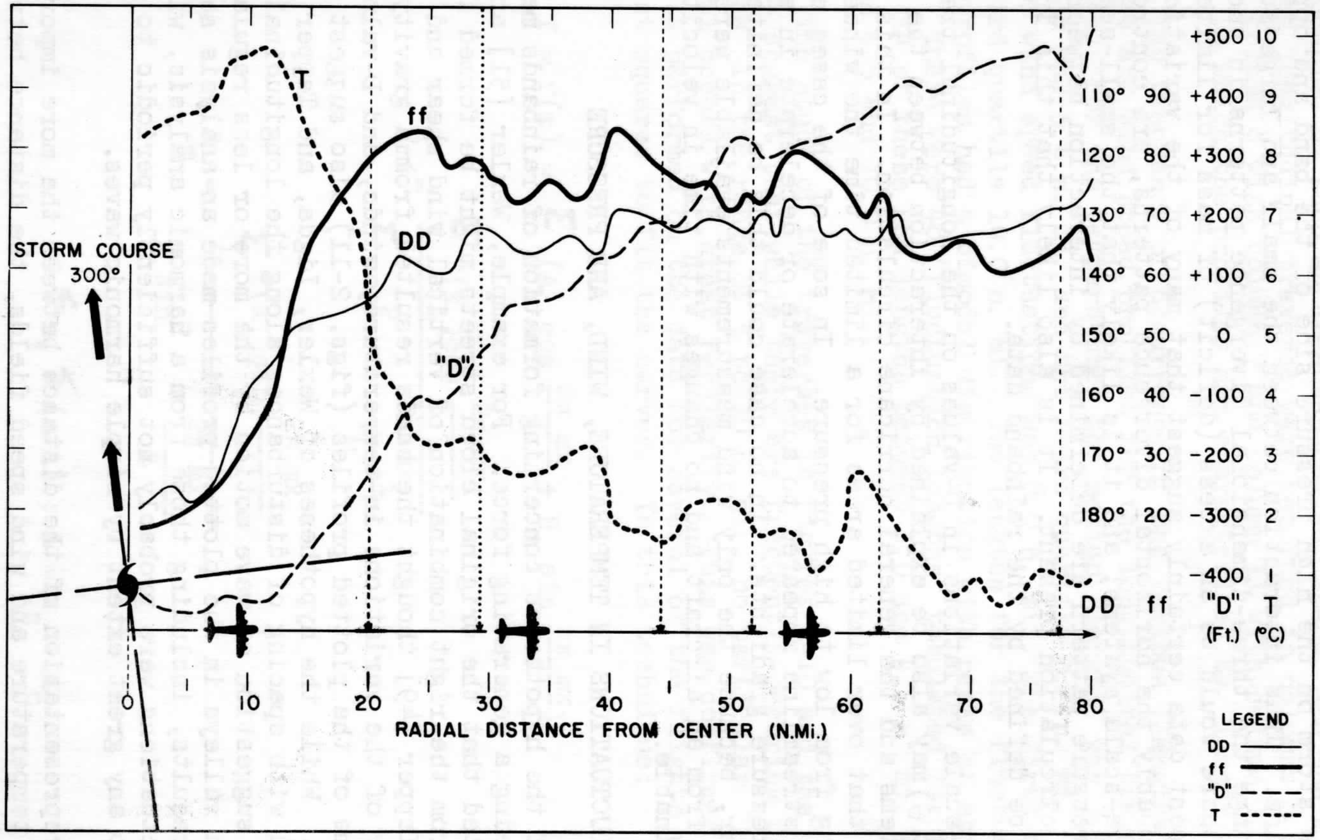

Figure 18. - Profiles of wind, temperature, and D-values from the center of hurricane Carrie north-northeastward, September 15, 1957. (From [48]). Dotted vertical lines mark band locations. The wind speeds, "ff", are in knots.

bands were similar to squall lines and that the pressure-jump hypothesis might be applicable.

Simpson and Starrett [46] offered the explanation that the pressure minimum on the high pressure side of the band was caused by the outflow from a convective element in the upper troposphere reinforcing the mean outflow circulation of the storm on the high pressure side of the band and opposing it on the other side. Thus interaction between the small and large-scale systems would arrange the three-dimensional divergence patterns in such a way that locally there would be an excess (deficit) of mass for limited periods. The present data certainly suggest that many of the variations in the winds, and probably the horizontal divergence patterns, are controlled by these convective-scale systems; and it is likely that the small-scale features of the pressure pattern are determined by interaction between the various scales of circulation present. It is also likely that this interaction is too complex to be defined by the rainband data.

The small-scale variations in D-values on the longitudinal traverses (figs 2, 3, 5, and 6) may also be explained by interaction between the convective-scale systems and the general hurricane circulation. In this case the data indicate that over limited areas for a limited time the winds may actually be blowing from low to high pressure. In some of the cases examined the winds along a streamline appeared to accelerate or decelerate in accordance with these pressure gradients. In no case could this be definitely determined, however, because the only wind measurements available were the spot measurements from an aircraft and no changes with time in velocity of a parcel are obtainable.

8. FLUCTUATIONS IN TEMPERATURE, WIND, AND PRESSURE

Several of the hypotheses concerning formation of rainbands mentioned waves as being a generating force. For example, Wexler [51] and Ligda [24] suggested that the original cloud streets might be formed from waves resulting from the right combination of vertical wind shear and thermal instability; and Tepper [49] thought the bands resulted from a gravity wave propagation. Many of the variations in temperature, winds, and D-values represented in some of the plotted profiles (figs. 2-11) also suggest waves of varying length. While the hypotheses of Wexler, Ligda, and Tepper had not been concerned with spacing of disturbances along the longitudinal axis of the bands, the suggestion of wave motion by the more or less regular recurrence of peaks and valleys in the plotted profiles made an analysis seem worthwhile. The results, including those from a harmonic analysis, will show that the fluctuations were probably not sufficiently periodic to have been influenced to any great extent by simple harmonic waves.

To get a representation of the distance between the more important variations in the temperature and wind speed fields, the distance between positions of each two successive minima on the profiles for the longitudinal traverses were tabulated when the following conditions were met: (1) distance was greater than 3 n. mi., and (2) the difference between the intervening maximum temperature (wind speed) and the average of the 2 adjacent minimum temperatures (wind speeds) was at least 1°C. (5 kt.). This difference was called the range, and the distance between the locations of two such minima was called the length of the fluctuation. The means of the "lengths" and "ranges" for each longitudinal traverse were tabulated in table 4, columns 6, 7, 9, and 10. In most of the traverses there were some areas where none of the fluctuations met the second condition. The distance along the band occupied by such an area was called "space" and the means of the "spaces" for each longitudinal traverse were recorded in columns 8 and 11. A comparison of column 8 with column 7 and column 11 with column 10 will indicate the degree to which the profiles are characterized by "larger fluctuations."

The frequency of occurrence of the various "lengths" in both the temperature and wind speed profiles for the longitudinal traverses of bands was computed. For the temperatures the median "length" was 7.0 n. mi., the first quartile was 5.4 n. mi. and the third quartile 8.3 n. mi. The median "length" for the wind speed fluctuations was 8.0 n. mi., the first quartile 4.4, and the third quartile 10.0 n. mi. The lengths for the fluctuations in the wind speed profiles had a bimodal distribution with peaks at about 3.5 and 8.5 n. mi. There were 48 "fluctuation lengths" tabulated for the wind speed cases; 14 of these had lengths between 3.0 and 4.5 n. mi. and 21 had lengths between 6.5 and 10.0 n. mi.

The study of the traverses in figures 2-10 and the data tabulated in table 4 suggest that while there are frequently-occuring fluctuations with "lengths" in the range of 3 to 10 n. mi., no particular "length" in this interval occurs with great regularity. This was confirmed by a harmonic analysis performed on the data for several of the flights using the method of least squares to fit the curves. In this technique:

$$Y = f(x) = \sum_m \left(A_m \cos \frac{2\pi\, mx}{L} + B_m \sin \frac{2\pi\, mx}{L}\right) \qquad (2)$$

$$A_m = \frac{\sum_i f(x_i) \cos \frac{2\pi\, mx_i}{L}}{\sum_i \cos^2 \frac{2\pi\, mx_i}{L}} \qquad (3)$$

$$B_m = \frac{\sum_i f(x_i) \sin \frac{2\pi\, mx_i}{L}}{\sum_i \sin^2 \frac{2\pi\, mx_i}{L}} \qquad (4)$$

$$0 \leq x_i \leq (n-1) \; ; \; L = x_n - x_o$$

For most of the cases L was about 50 n. mi. and the input data contained 4 points per n. mi. Coefficients A_m and B_m were computed for all wave numbers (m) from 1 to 50. The amplitude and wavelength for the 7 waves with greatest amplitude for each parameter were tabulated in table 5. The amplitudes marked with an asterisk were significant at the 5 percent level (Brooks and

Table 4. - Mean length and range of "larger fluctuations" in temperature and wind profiles

Traverse No.	Flight No.	h (10's ft)	r (n mi)	In Band	Mean Data for Fluctuations: Temperature Range (deg C)	Temperature Length (n mi)	Temperature Space (n mi)	Wind Speed Range (kt)	Wind Speed Length (n mi)	Wind Speed Space (n mi)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
101	80818B	1560	50	Yes	1.3	9.8	35.0	8.6	7.1	8.7
102	21017A	1380	75	Yes	1.6	5.7	8.7	15.1	5.6	5.7
103	21017A	1380	95	Yes	1.5	6.4	10.0	10.5	6.6	6.6
104	21019A	1380	65	Yes	1.4	7.0	28.3	9.4	5.2	5.6
105	80924B	1300	55	Yes	1.6	13.5	13.8	7.0	13.0	49.0
106	80815A	640	200	Yes	1.6	8.8	14.0	7.9	11.7	21.8
107	21017B	325	100	Yes	1.5	9.7	29.0	12.0	12.3	12.7
108	21019B	325	80	Yes	...	...	...	6.7	13.4	15.6
109	21019A	1380	65	No	1.2	14.0	38.5	7.9	9.9	10.0
110	21019A	1380	95	No	1.3	22.5	47.5	6.9	8.3	10.5
111	80827B	1300	90	No	1.0	12.0	52.0	5.0	17.0	47.0
112	21017B	325	110	No	1.4	12.0	65.0	6.6	3.9	18.0

Table 5. - Amplitude of most important waves (wave length in nautical miles in parentheses)

Flight No.	Altitude (10's of ft.)	Rank 1	2	3	4	5	6	7
		Temperature (°C)						
80818B	1,560	.34(54.3)*	.21(27.1)*	.20(18.1)*	.20(10.8)*	.15(9.0)	.12(13.6)	.09(5.4)
80924B	1,300	.49(24.8)*	.34(49.5)*	.24(12.4)*	.19(8.3)*	.16(16.5)	.11(7.1)	.11(9.9)
21017A(1)	1,380	.68(16.9)*	.63(50.8)*	.47(25.4)*	.40(10.1)*	.20(5.1)	.16(4.2)	.15(2.7)
21017A(2)	1,380	.31(14.3)*	.22(8.2)*	.21(19.1)*	.20(11.4)*	.18(3.4)*	.17(28.6)*	.17(57.3)*
21017B	325	.35(18.3)*	.26(9.1)*	.21(10.9)*	.13(27.4)	.13(6.1)	.11(13.7)	.10(54.8)
21019A	1,380	.27(25.8)*	.25(17.2)*	.13(5.2)*	.11(8.6)*	.10(7.4)	.09(6.4)	.08(5.1)
		D-Value (ft.)						
21017A(1)		18.8(24.4)*	15.6(48.8)*	9.8(2.2)	7.6(6.1)	7.6(16.3)	6.7(1.8)	5.9(1.6)
21017A(2)		13.1(36.5)*	8.8(3.0)	7.3(2.1)	6.4(3.3)	6.4(4.6)	6.4(2.0)	5.3(1.5)
21017B		11.2(23.8)*	10.8(47.5)*	7.5(15.8)	6.6(9.5)	6.6(11.9)	6.6(7.9)	5.8(2.4)
21019A		12.3(47.3)*	9.1(23.6)*	6.7(2.0)	4.8(2.6)	4.8(4.7)	4.4(11.8)	4.4(2.1)
		Wind Speed (kt.)						
80818B		7.0(44.3)*	4.9(22.1)*	3.6(14.8)*	1.9(2.0)	1.8(2.6)	1.8(1.6)	1.8(6.3)
80924B		2.2(55.3)*	1.2(27.6)*	1.0(9.2)*	0.9(3.5)*	0.7(13.8)	0.6(18.4)	0.4(3.7)
21017A(1)		12.7(48.8)*	9.2(16.3)*	6.5(24.4)*	4.8(9.8)	3.3(8.1)	3.2(7.0)	2.4(12.2)
21017A(2)		3.8(58.0)*	1.9(9.7)*	1.6(8.3)*	1.1(7.3)	1.1(19.3)	0.9(1.5)	0.9(3.2)
21017B		6.3(54.8)*	4.0(18.3)*	3.4(27.4)*	2.7(13.7)*	1.8(9.1)	0.9(6.8)	0.9(5.5)
21019A		2.1(44.3)*	1.4(14.8)*	1.2(22.1)*	0.8(5.5)	0.6(4.9)	0.6(8.8)	0.4(6.3)

*Significant at 5 per cent level.

Carruthers [6]). The amplitudes listed in table 5 should be doubled before being compared with the ranges listed in table 4. Data in this table show that the most prominent waves (listed in decreasing order of amplitude) have lengths of about 53, 10, 17, and 26 n. mi. in the temperature profiles; 45, 2, and 25 n. mi. in the D-value profiles; and 51, 9, 15, and 25 n. mi. in the wind speed profiles.

The harmonic analysis did not identify in the temperature or wind profiles any prominent waves with lengths corresponding to the characteristic "fluctuation lengths" identified in the data used in preparing table 4. This strongly suggests that while the disturbances causing the fluctuations usually have characteristic dimensions of 3 to 10 n. mi. along the longitudinal axis of the bands, none of these dimensions recurs periodically. Hence, there is a relatively small amount of periodicity in the fluctuations and the spacing between successive minima (maxima) along the longitudinal axis of a band is probably controlled primarily by influences other than inertia or gravity waves of the simple harmonic type.

9. MASS EXCHANGE WITHIN BANDS AND BETWEEN BANDS AND ENVIRONMENT

Evidence is available in the wind, temperature, and moisture fields that rapid exchange of air must take place between cells in the same band and between the bands and ambient areas. This is true for all the bands including the eye wall. The fact that this exchange takes place on a scale that introduces considerable air from outside the hurricane circulation into the high energy portions of the hurricane at middle elevations is important to the energetics of the storm and to the temperature distribution through the storm. It is also important information for verifying some of the hypotheses concerning the mass circulation through the storm. These concepts will be discussed more fully in later sections. In this section the evidence of mixing and of air exchange in the larger scales of motion will be presented. Deductions concerning the vertical component of the circulation through the bands will also be made from this evidence.

Evidence of mass exchange

There was great variability of wind speed along the longitudinal traverses of the rainbands even though those traverses were flown approximately along streamlines (see table 1). Measurements of movement of radar echoes (Ackerman [1]) indicated that the echoes in some of the rainbands included in the present study did not move with the winds. It is certain that all of the echoes did not move with all the winds, because of the great variability of the latter. Likewise, for the normal components of the winds on the normal traverses, the bands could not have been moving with all of the winds in and near a band because of the great variability of the former. The difference between the maximum and minimum normal component observed during each traverse normal to a band, including the areas 5 mi. on either side of the band, is recorded in table 2, column 12. The mean of these differences is 8 kt. for the outer bands, 16 kt. for the intermediate bands, 23 kt. for the eye walls in the lower troposphere, and 21 kt. for the eye walls in the upper troposphere. If these numbers were halved we would have at least a lower limit of the rate at which some of the air particles were moving relative to the band. For the bands within 40 n. mi. of the center and including the eye walls, this would mean there were air particles moving relative to the band in a perpendicular direction at a rate of at least 8 kt. for the average band. Thus the variability of the wind and the movement of air parcels relative to the echoes in the rainbands offers conclusive evidence that there was exchange of air between the ascending currents in the bands and the interstitial areas and between the rainbands and their environment. As will be discussed in a later section, this has great significance for the temperature structure of the bands.

The exchange of air and the resulting mixing in the bands are also emphasized by results of a study of the variability of the value of terms in the divergence equation for areas near and in the bands. In equation (1), divergence was expressed as:

$$\mathrm{DIV}\,\mathbf{V}_H = \frac{\delta V_N}{\delta N} + \frac{\delta V_T}{\delta D} \qquad (1)$$

The values of each of these terms varied greatly in the bands within relatively short distances. The value of the first term on the right can be determined from the normal components of the winds (Section 6). The maximum, minimum, and mean values of the quantity $\delta V_N/\delta N$ for each normal traverse of a band were recorded, respectively, in columns 13, 14, and 15 of table 2. Positive and negative values of this term frequently exceeded in absolute value 10^{-3} sec.$^{-1}$ and, in some cases, such values were in the same band within about 3 mi. of each other.

The second term on the right of equation (1) cannot be evaluated as directly as the first, because the tangential components of the wind for the longitudinal traverses were not computed. The wind was blowing approximately along the band, however, which permits using the actual wind speed in lieu of the tangential wind speeds with only a small error (less than 10 percent error when the flight track heading was within 25° of the orientation of the streamline). Such computations were made and it was found that for the cases illustrated in figures 2-11, the second term on the right of equation (1) frequently gave larger absolute values than those in table 2 for the first term, $\delta V_N/\delta N$. This is not only sufficient evidence that either one of the terms alone can not be used to determine the sign of the divergence at the middle elevations, but it is also strongly suggestive that microscale wind patterns associated with the bands were largely controlled by the convective elements embedded within the band. The great variability of the size of this term spatially along the band is again indicative of the strong shearing and deformation that must have been taking place. Of course these wind patterns should have eventually been dissipated by the mixing process.

If there were little exchange of air between the bands and the ambient areas, one would expect the air to converge toward the bands in the lower levels and to diverge from the bands at the upper levels. Thus one would expect the first term on the right in equation (1) to be negative at the lower levels, relatively small in the middle troposphere, and positive at the upper levels if there were little mixing. Actually, there was no systematic pattern to the sign or size of this term in the outer bands. This indicates, as has already been suggested, that the bands were not uniform entities, but were composed on many convective cells which were arranged along a spiral and gave the appearance of a band. There was a tendency for this term to have negative values in the mean in bands in the lower and middle troposphere within 40 n. mi. of the center, and to have positive values in the eye wall at the upper levels. The latter relationship was the only one, however, that was very pronounced. It occurred in 7 of the 9 cases examined. In the other 2 cases the absolute values were relatively small. Furthermore this term was negative in the upper troposphere over several of the hurricane eyes and thus strongly suggests that confluence was present in those areas at the 35,000-ft. level. In the case of these measurements at the upper levels over the eye wall it is believed that the sign of the first term on the right in equation (1) and the sign of DIV $\mathbf{V}_H$ were the same, but no direct measurements were obtained which could be used to substantiate fully this hypothesis.

Mixing in the eye wall

It can be asked whether air in the eye wall rises directly from the inflow layer in the lower troposphere to the outflow layer in the upper troposphere, or whether there is rapid exchange of air between the buoyant updrafts and other portions of the eye wall and between the wall and its environment. These questions are pertinent, because the vertical motions are so great in portions of the wall cloud that it might be argued that air ascends from the surface to the upper troposphere without being mixed with the ambient atmosphere. The strongest ascending current (averaged over 10 sec.) found in a number of eye wall traverses including some of the cases used in this investigation was +25 kt. in hurricane Daisy on August 27, 1958, according to the computations by Gray [11]. In this particular traverse only 11 percent of the wall had positive vertical motion in excess of 20 kt. and only 42 percent greater than 6 kt. Assuming that the air ascended all the way from the base of the clouds to about 45,000 ft. (near the top of the storm) at the rate of 25 kt., the same air parcel would have been carried half the way around the eye in the 17 min. it would have taken for the ascent. For this same traverse the difference between the maximum and minimum normal components of the wind was 22 kt. Thus some air parcels would pass more than half way through the wall during the period of rapid ascent (assuming that some parcels were moving relative to the wall at 1/2 of the difference between the maximum and minimum normal components). If the same type of computations are made for hurricane Cleo, the same conclusions may be drawn. Since the above example considers only the maximum vertical velocity, it is obvious that most of the air in the wall circumnavigates the center one or more times before ascending to the principal outflow layer in the upper troposphere. During this period there would be time for parcels moving with the speed of V_N measured for the bands to pass through the wall more than one time. Thus there is extensive exchange of air between the eye wall and at least its immediate environment.

Summary and interpretation

The variation of the wind and divergence fields relative to the rainbands indicates that a relatively small portion of the air which starts ascending from the low level inflow layer in one of the rainbands reaches the upper outflow layer without being mixed with the surrounding air. Only in the eye wall is there a suggestion that a considerable proportion (probably less than half) of the air ascends undiluted by ambient air to the upper troposphere. The data strongly suggest that in the outer and intermediate bands much of the air which starts upward in one buoyant current may depart from that current and be in one or more other currents before finally reaching the upper troposphere. The effect of the mixing is to introduce air at middle elevations from the surrounding atmosphere into the storm circulation. As has been discussed by Simpson and Riehl [47] this acts as a constraint on hurricane development and maintenance. This introduction of the relatively colder, drier air of the mid-tropospheric mean tropical atmosphere into the middle layers of the hurricane also helps to cause the minimum in the equivalent potential temperature commonly observed in those layers in hurricanes. This will be discussed further in Section 11.

10. DISTRIBUTION OF RAINBANDS IN THE HURRICANE

It is important to know what percentage of the area of the hurricane is covered with rainbands, whether the rainbands are distributed symmetrically about the storm center, and whether the amount of echoes varies materially with time or between storms. All of these questions should be answered to provide information needed by researchers who are developing dynamical, numerical models of hurricanes and by those studying the energetics of hurricanes. In addition the answer to the first question is needed to determine whether the rainbands contribute materially to the generation of kinetic energy in the hurricane and to verify some of the hypotheses concerning the net vertical component of the circulation through the hurricane. These problems will be discussed in more detail in Sections 12 and 11, respectively.

Radar composites showing the radar picture of the rainbands for a complete hurricane have been prepared by the Staff, National Hurricane Research Project for a number of storms. From these it is convenient to get an estimate of the percentage of the storm area covered by echoes, i.e., by rainbands of sufficient intensity to be picked up by the radars on board the aircraft. These composites also show the distribution of the major rainbands in the storms. The radar were all of the 3-cm. type and thus were greatly affected by attenuation. It was not practical therefore to get an instantaneous radar picture of the entire storm. The research aircraft usually penetrated all quadrants of a storm within a period of 2 or 3 hours. By selecting pictures taken throughout such a period and compositing them, it was possible to get a representative picture of the entire storm even though it might not resemble the storm in all details at any one time. A circular grid divided into four quadrants symmetrical with respect to the direction of motion of the storm and with annular rings 20 mi. wide was superimposed over the composites, and the percentage of the area of each segment of the grid occupied by radar echoes was tabulated for each of four hurricane days. The results are displayed in figure 19. In each case the figures in the center refer to only that portion of the respective sectors between the inner edge of the eye wall and the 20-n. mi. radius.

It is of interest to note what a relatively small portion of the storm is covered with echoes. Of the area between the eye boundary and the 80-n. mi. radius for the four hurricane days, only about 20 percent was covered with echoes. It was shown in Section 4 that probably less than 1/4 of the radar bands were composed of currents of significant positive temperature anomaly; therefore, only about 5 percent of the storm was occupied by the so-called warm buoyant towers as determined by temperature measurements made at about the 13,000-ft. level. Malkus, Ronne and Chaffee [26] estimated for hurricane Daisy about 1 percent of the rain area (radius less than 200 n. mi.) was covered with photographically well-defined cumulonimbi with tops above 37,000 ft. on the day of formation, August 25, 1958. This number had increased to 2.5 percent on the day of deepening, August 26, 1958, and to 4 percent on the day of greatest intensity, August 27, 1958. On this last day about 200 such cloud towers were estimated to be in existence from the sample that could be identified from the time lapse cloud movies taken by the aircraft flying at about 34,000 ft. The percentages of area covered by warm pools at 13,000 ft. and by well-defined cumulonimbi with tops above 37,000 ft. are in quite good agreement considering the approximations that had to be made in getting the two different estimates and considering that many of the warm pools at 13,000 ft. probably did not extend to the 37,000-ft. level.

The rainbands are not only usually arranged asymmetrically with respect to the hurricane center, but the asymmetry varies with time and with the storm. That is, the percentage of each quadrant of the storm area covered by radar echoes varies from storm to storm and from day to day (sometimes, hour to hour). This has long been recognized by radar observers of hurricanes but is contrary to some of the hypotheses that have appeared in the literature (Wexler [51]). That the quadrants with the maximum coverage by echoes may vary from storm to storm is illustrated in figure 19. If the inner 20 mi. are excluded, coverage was greater in the left front quadrant for Carrie, right rear for Daisy on the 25th, right quadrants for Daisy on the 27th, and it was nearly uniform for Cleo. If one can assume that the proportion of latent heat released was distributed through the quadrants similarly to the echoes, there is information here of use to those attempting to develop numerical models of hurricanes.

The data used in preparing figure 19 suggest that the amount of the area covered with echo-producing clouds varies directly with the intensity of the storm (Daisy on the 27th was the most intense storm) and inversely with the distance from the center. These tentative conclusions are supported by results compiled for a much larger sample of storms by Ackerman [1] from analysis of percentage of flight time spent in convective clouds.

11. EQUIVALENT POTENTIAL TEMPERATURE IN RAINBANDS AS AN INDICATOR OF THE VERTICAL COMPONENT OF THE HURRICANE CIRCULATION

Knowledge of the distribution of equivalent potential temperature through a hurricane, and in particular, through the rainbands, can be used to help answer questions about the vertical component of the circulation through a hurricane. Several hypotheses concerning this circulation were listed in Section 1 and are in need of additional verification. The equivalent potential temperatures can also furnish further information concerning the accuracy of the temperature measurements which have been referred to in the other sections.

PERCENTAGE OF AREAS COVERED WITH RADAR ECHOES

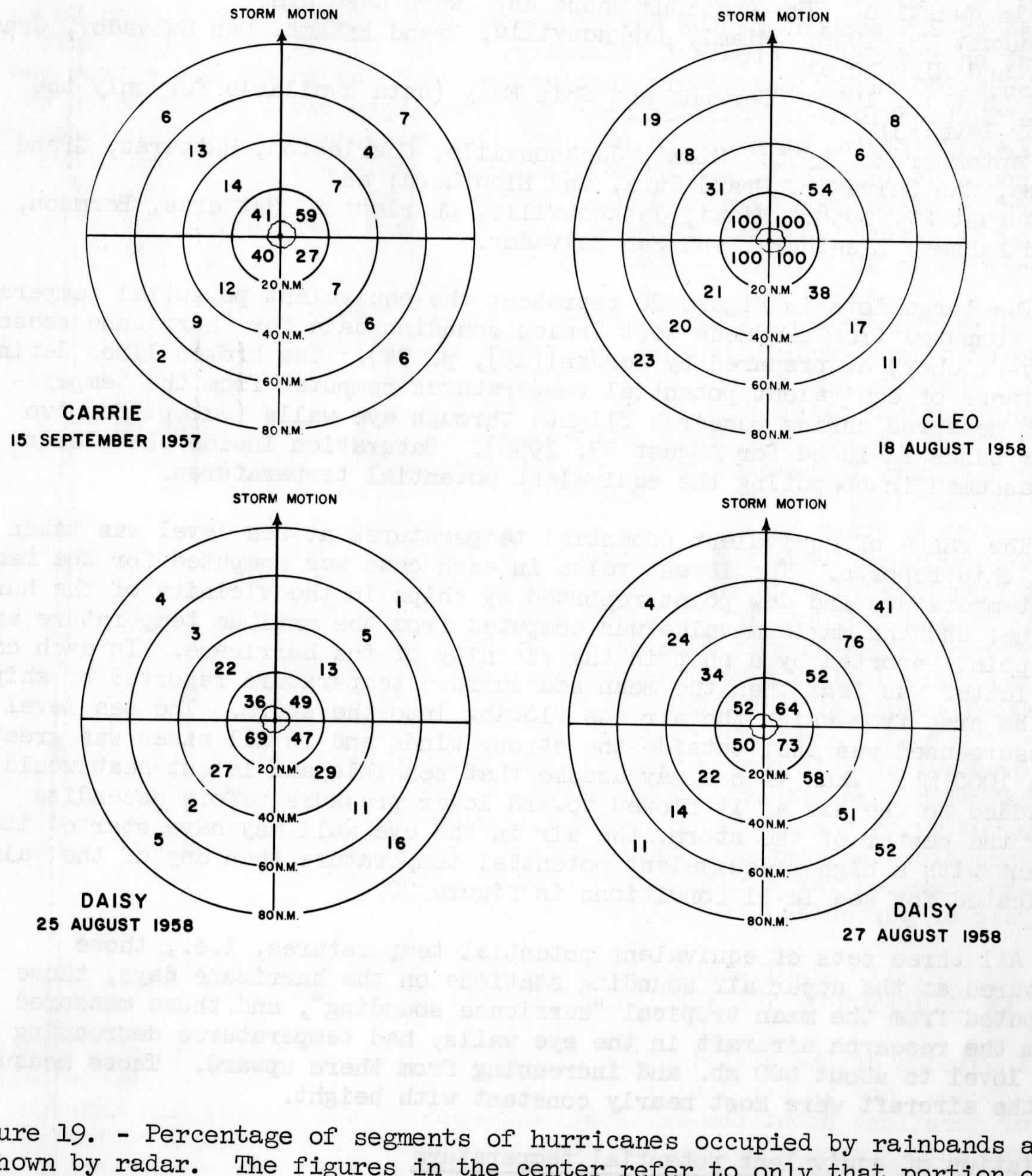

Figure 19. - Percentage of segments of hurricanes occupied by rainbands as shown by radar. The figures in the center refer to only that portion of the area between the inner edge of the eye wall and the 20 n. mi. radius.

The data

The equivalent potential temperatures in the eye walls for several flights at different levels for four different hurricane days are graphed in figure 20. The solid lines at the standard pressure levels represent the range in equivalent temperatures computed for the temperature and dew point reported at 1200 GMT from the upper air sounding stations nearest the storm on the days in question. The stations whose data were used are:

August 25, 1958: Miami, Jacksonville, Grand Bahama, San Salvador, Grand Turk, and Eleuthera;

August 18, 1958: Bermuda and Ship Easy (data available for only the higher levels);

September 26, 1958: Miami, Jacksonville, Charleston, Hatteras, Grand Bahama, San Salvador, Grand Turk, and Eleuthera; and

August 27, 1958: Miami, Jacksonville, Charleston, Hatteras, Bermuda, Grand Bahama, Eleuthera, and San Salvador.

The large dots in figure 20 represent the equivalent potential temperature computed from the mean West Indies sounding data for "hurricane season" (July-October) as prepared by Jordan([15], p. 94). The broken lines define the range of equivalent potential temperatures computed from the temperatures measured during research flights through eye walls (except for two outer bands included for August 27, 1958). Saturation inside the clouds was assumed in computing the equivalent potential temperatures.

The range of equivalent potential temperatures at sea level was taken from ship reports. The lowest value in each case was computed for the mean air temperature and dew point reported by ships in the vicinity of the hurricane, and the maximum value was computed from the maximum temperature and dew point reported by a ship in the vicinity of the hurricane. In each case the latter was less than the mean sea surface temperature reported by ships in the area from which the air was flowing into the storm. The sea level pressure used was that outside the strong winds and in all cases was greater than 1000 mb. Thus if one may assume that sensible and latent heat would be added to the air as it flowed toward lower pressure before ascending near the center of the storm, the air in the eye wall may have started its ascent with a higher equivalent potential temperature than any of the values indicated for sea level conditions in figure 20.

All three sets of equivalent potential temperatures, i.e., those measured at the upper air sounding stations on the hurricane days, those computed from the mean tropical "hurricane sounding", and those measured from the research aircraft in the eye walls, had temperatures decreasing from sea level to about 600 mb. and increasing from there upward. Those measured by the aircraft were most nearly constant with height.

Variation of equivalent potential temperature with height in the eye wall

It has been hypothesized that much of the air reaching the upper outflow layer first flows inward at low levels to the vicinity of the eye wall where it ascends to the upper layers of the troposphere (Riehl [36], Riehl and Malkus [37], and LaSeur and Hawkins [22]). The equivalent potential tempera-

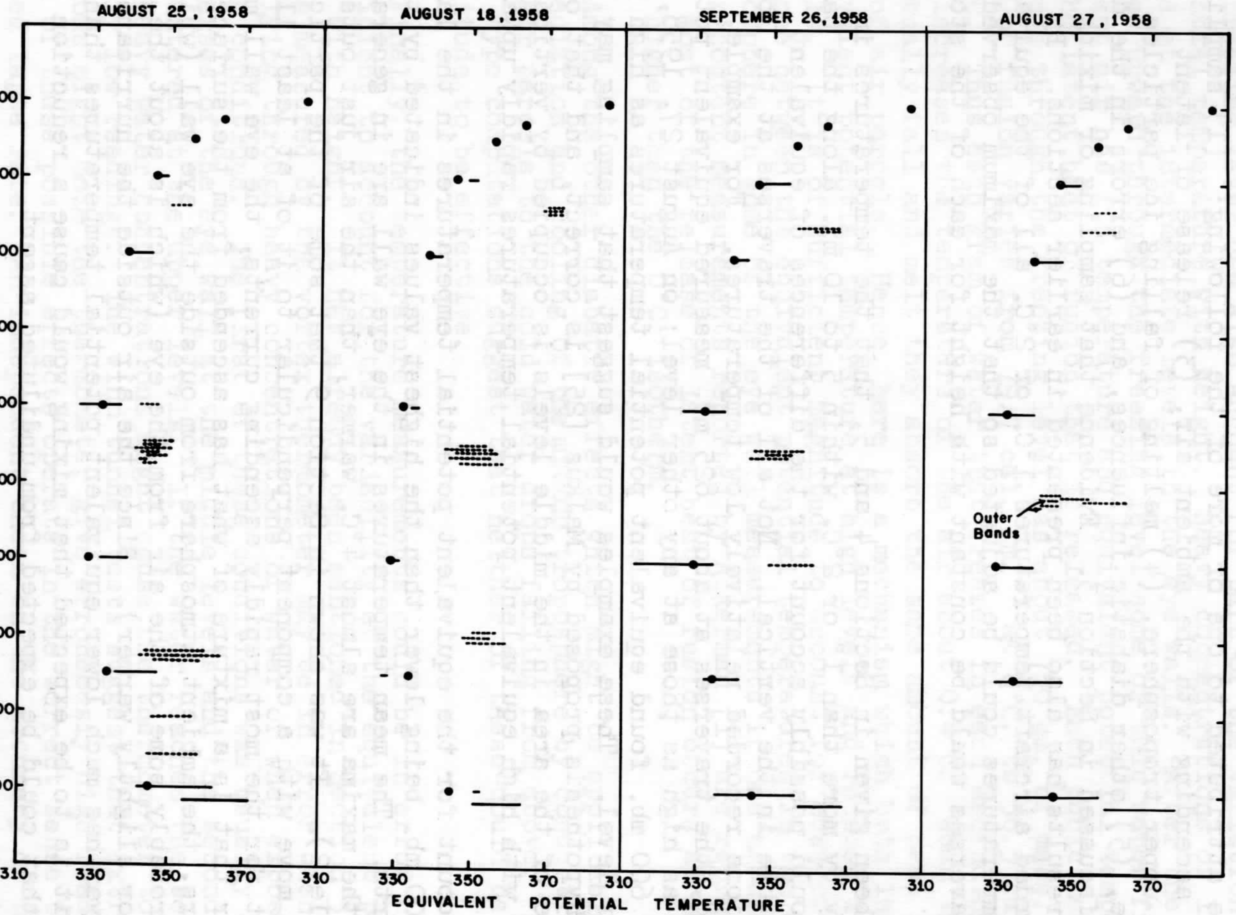

Figure 20. - Equivalent potential temperatures.

ture in the eye wall should, therefore, be constant with height if during ascent the air is not mixed with that of different thermal and moisture characteristics, and if the temperature changes are determined solely by adiabatic (including pseudo-adiabatic) processes. Since, therefore, the equivalent potential temperatures portrayed in figure 20 are not constant with height in the eye wall, the reasons for the variation need to be examined to see what effect the variability may have on the various hypotheses. The variability can be attributed to one or more of the following: (1) sampling, (2) mixing of the ascending with the ambient air, (3) release of latent heat of fusion in upper troposphere, (4) melting of falling ice particles in middle troposphere, (5) other diabatic influences, and (6) errors in the data. The errors were discussed in Section 3. Evidence that sampling or mixing might affect the results has also been presented in earlier sections. By changing the recorded aircraft temperatures 1°C. or 2°C. all of the equivalent potential temperatures could be adjusted so that the maximum observed on the various traverses would be constant with height for each of the storm days.

Evidence has been given in Sections 4 and 5, that the temperatures in the bands can vary by more than 1° or 2°C. within 5 to 10 mi. along the band. Hence, sampling could possibly account for the differences of equivalent potential temperature in the vertical. Not all of the traverses at the lower and middle elevations recorded relatively low temperatures. For example, on August 25, 1958, the traverses at about 825 mb. measured equivalent potential temperatures as high as those at any other level; on August 27, 1958, one traverse near 600 mb. found equivalent potential temperatures as high as those at any other level. These examples would suggest that sampling may be a factor if a hypothesis proposed by Malkus [25] is correct, and that only a small percentage of the area in the middle levels is occupied by vertical jets carrying air with high equivalent potential temperatures rapidly upward.

Mixing can account for the equivalent potential temperatures in the layer between 950 and 500 mb. being lower than the highest values indicated by the surface ship reports. The mean temperatures in the eye wall are in general 2°C. warmer, and the maxima are almost 4°C. warmer, than the air just outside the eye wall (table 2). It was shown in Section 9 that some of the particles near the eye wall move with a component perpendicular to it of at least 11 kt. Hence, except for the most rapidly ascending currents, the eye wall must be composed of air that is a mixture of what has ascended from the surface within recent hours, the ambient atmosphere from outside the eye wall (which is colder), and probably some of the air from the eye (which is about the same temperature or slightly warmer). Since the air outside the hurricane in this middle layer has much lower equivalent potential temperatures than the surface air, it is to be expected that mixing would cause a reduction from the maximum that could be expected from undiluted ascent.

Mixing may also cause the air at the high levels to be warmer than the air which ascends from the middle levels. The equivalent potential temperatures calculated from the mean tropical sounding are much higher in the 125 to 100-mb. layer than are those measured in the eye wall at about 250 mb. by the research aircraft. If air descends from about the 100-mb. level in the eye or in subsidence areas between bands and then gets mixed with the air that has ascended in the wall, the slight difference in equivalent potential temperature in the eye wall between the middle and upper levels of the troposphere could also be accounted for.

The release of latent heat of fusion in the upper troposphere and the heat required for melting the falling ice particles in the layers just below the freezing level can also account for part of the variation of equivalent potential temperature with height. Heavy concentrations of liquid water are found at the intermediate levels in the eye walls. After the ascending air passes upward through the freezing level some of this water freezes and the ambient air has its temperature and equivalent potential temperature increased by the latent heat of fusion that is released. Each cubic meter of air that ascends through the freezing level has about 750 gm. of mass. The latent heat of fusion varies from 79.7 cal. gm.$^{-1}$ at 0°C. to 56.3 cal. gm.$^{-1}$ at -40°C. Thus each gram of water that freezes in each ascending 750 gm. of air increases the temperature of the air about 0.4°C. When the ice particles eventually fall and melt they absorb the same amount of heat from a different set of air parcels. Hence, here is a mechanism which both increases the equivalent potential temperature at high levels and reduces it at the middle levels. It is of sufficient magnitude to account for most of the total difference between the equivalent potential temperatures in the middle and upper troposphere in some of the eye wall measurements if one assumes that liquid-water-content measurements reported by Ackerman [1] are representative, and that most of the release of latent heat of fusion occurs at levels considerably higher than the 0°C. isotherm.

Among the other diabatic effects which might be applicable to this problem is radiation and cooling of the middle troposphere by conduction of heat from the air parcels to the cold water drops falling from above. Order-of-magnitude type computations suggest that neither of these could be of sufficient magnitude to be effective.

Finally, the temperature measurements could be in error by an amount sufficient to account for the variability of the equivalent potential temperature with height. It has already been mentioned in Section 3 that the temperatures measured by the vortex thermometer may be in error when the aircraft is flying through heavy concentrations of water or when exposed to heavy icing conditions. The first of these conditions was usually encountered on traverses of the eye wall at the middle levels and the second may have been encountered at the upper levels. If the water reaches the sensing element, the heavy water concentrations might cause the thermometer to record erroneously low readings. The wind tunnel tests suggest that extreme icing conditions might make the thermometer give erroneously high readings. Thus both of these possible effects operate in the correct sense to give the recorded lapse rate. An independent check on the accuracy of the temperatures can be obtained by the pressure measurements. The approximate pressure at sea level at the inner edge of the eye wall is known for each of the hurricane days listed in figure 20. If one assumes that the height of the 100-mb. surface over each of the hurricanes was the same as in the mean tropical atmosphere (Jordan [15]), then the mean equivalent potential temperature for the air between the surface and this level is essentially a function of the sea level pressure, and would have the following approximate values for the inner edge of the eye wall on the hurricane days listed in figure 20: August 25, 1958, 350°K.; August 18, 1958, 360°K.; September 26, 1958, 369°K.; and August 27, 1958, 367°K. Comparison of these values with the graphs in figure 20 gives reason to believe that the recorded temperatures in the middle levels may be too low on September 26, 1958, and the recorded temperatures in the upper levels may be too high on the other days. In general, the evidence is that the errors in temperature measurements are relatively small.

Although the precise explanation for the variability with height in the eye wall of the equivalent potential temperature can not be identified with the data available, it would seem that most of it could be explained by a combination of the following: (1) sampling causing the data at particular levels to be nonrepresentative, (2) mixing of the ascending air with ambient air of different thermal properties, (3) release of latent heat of fusion in the upper troposphere, and (4) melting of falling ice particles in the middle troposphere. If these are the principal causes and if the effect of errors in the data is comparatively minor, then the rainband data give strong support for the hypothesis that much of the air reaching the upper troposphere relatively unmodified by mixing ascends through the eye wall. There would be less requirement for all of the air to ascend in warm buoyant towers undiluted with ambient air of different properties, although there is certainly evidence that this occurs to a significant extent.

<u>Equivalent potential temperature in the outer bands and the vertical component of the hurricane circulation</u>

The equivalent potential temperatures were computed with the assumption of saturation for the maximum and minimum temperatures observed in the lower and middle elevations for several of the outer bands in order to get further information about the mass circulation through hurricanes. Results of the computations are given in table 6. Columns 5 and 6 list the maximum and minimum, respectively, for each band, and column 7 lists the equivalent potential temperatures interpolated from the West Indies sounding data for "hurricane season" prepared by Jordan ([15] p. 94). In all cases even the minimum is higher than the value from the mean sounding, and in all cases the maximum is less than the likely equivalent potential temperature of the air at sea level or in the upper troposphere in the respective storms. All of the temperatures can be explained, however, by assumption that the air in the bands that has ascended from below is mixed with air of mean tropical characteristics. This implies there is relatively little undilute ascent of air through the outer bands from the lower inflow layer to the upper outflow layer. Since the equivalent potential temperatures in the bands in the middle troposphere are lower than those in the upper outflow layer, there is evidence that much of the air which ascends in the outer bands also descends within the storm area rather than being evacuated through the outflow layer in the upper troposphere. This mixed air would, however, form a buffer between the air outside the hurricane and the air in the inner rainbands and permit the latter to have a higher equivalent potential temperature even after being mixed with the air closest to them.

Table 6. - Equivalent potential temperatures in outer bands.

Traverse No. (1)	Flight No. (2)	h (10's ft) (3)	r (n mi) (4)	θ_e in Band Maximum (5)	θ_e in Band Minimum (6)	θ_e West Indies (7)
2	80902B	1560	75	349	338	331
3	80902A	820	85	348	344	330
11	80827B	1300	105	345	341	330
14	80818B	1560	60	347	344	331
23	80818A	640	80	345	342	333
29	80815A	640	155	340	335	333
30	80815A	640	315	346	337	333

12. PRODUCTION OF KINETIC ENERGY

The importance of several questions concerning the role of the rainbands in the energetics of the hurricane was discussed in Section 1. Some of the hypotheses that have been advanced concerning the intensification and development of hurricanes imply that most of the important energy transformations, of necessity, take place in or near the eye wall. For verification of some of the model studies of hurricanes now underway, it is important to know if this is true. The fact that much latent heat of condensation is released in the rainbands other than the eye walls, as evidenced by the heavy rainfall frequently observed in the bands, gives reason to believe that the other rainbands are also important in the energy system of the tropical cyclones. In fact, the data collected for this study were sufficient to show that the rainbands do play an important role in the transformation of potential energy into kinetic energy even though the data were insufficient for making a complete kinetic energy budget. Computations made by other investigators for some of the same hurricanes from which data were collected for the rainband investigation were used to supplement the rainband data. From this combination it was possible to make reasonable deductions as to the importance of the rainbands to the energy processes in tropical cyclones and to give an indication of whether the eye wall is much more important in this respect than the other bands.

It can be shown (Margules [27], and Palmén [32]) that kinetic energy is generated from potential energy when vertical motion and temperature anomalies are positively correlated. Data from the rainbands were used to determine the degree of correlation between these two quantities in the eye walls and in the other bands. It was also shown that the kinetic energy generated by this mechanism is an important part of the total for the storm.

The equations

The rate of change of horizontal kinetic energy (Palmén [32]) is a fixed volume v of the atmosphere that is bounded from the outside atmosphere by a cylinder that extends from sea level to the top of the atmosphere can be expressed:

$$\frac{\partial}{\partial t}\int_v \rho K dv = -\frac{1}{g}\int_o^{p_o}\int_L K V_n \, dL \, dp$$

$$-\frac{1}{g}\int_o^{p_o}\int_A \mathbf{V}_H \cdot \nabla \phi \, dA \, dp$$

$$-\int_o^{\infty}\int_A \rho \mathbf{V}_H \cdot \mathbf{F} \, dA \, dz \qquad (5)$$

where ρ is the density of the air, g is the acceleration of gravity, K the kinetic energy of horizontal motion per unit mass, $\mathbf{V}_H$ the horizontal wind vector, ϕ the geopotential of the arbitrary isobaric surface, V_n wind component normal to cylinder wall and positive outward, T absolute temperature, R gas constant, and $\mathbf{F}$ the horizontal frictional force per unit mass. The area of intersection between the cylinder and a constant isobaric surface is denoted by A and the length of its circumference by L. Both A and L are independent of height and pressure. The first term on the right represents the outflow of kinetic energy through the vertical boundary of the cylinder, the second term denotes the work done by the horizontal pressure forces inside v, and the last term represents the dissipating influence of friction.

The rate of change to kinetic energy within the portion of a hurricane included in the volume v is represented by the second term on the right. This term can be equated to K_g and expanded in the following manner (Riehl [35], and Lateef [23] presented similar developments):

$$K_g = -\frac{1}{g}\int_o^{p_o}\int_A \nabla \cdot \phi \mathbf{V}_H dA \, dp + \frac{1}{g}\int_o^{p_o}\int_A \phi \nabla \cdot \mathbf{V}_H dA \, dp \qquad (6)$$

$$K_g = -\frac{1}{g}\int_0^{p_o}\int_L \phi V_n \, dL\, dp + \frac{1}{g}\int_0^{p_o}\int_A \bar{\phi}\, \overline{\nabla \cdot V_H}\, dA\, dp$$

$$+ \frac{1}{g}\int_0^{p_o}\int_A \overline{\phi' \nabla \cdot V'_H}\, dA\, dp \qquad (7)$$

where the bar and the prime indicate, respectively, the mean over the area and departure from this mean. Then,

$$K_g = -\frac{L}{g}\int_0^{p_o} \widetilde{\phi V_n}\, dp + \frac{1}{g}\int_0^{p_o}\int_L \bar{\phi} V_n \, dL\, dp + \frac{A}{g}\int_0^{p_o}$$

$$\overline{\phi' \nabla \cdot V'_H}\, dp \qquad (8)$$

$$K_g = -\frac{L}{g}\int_0^{p_o} \tilde{\phi}\, \tilde{V}_n\, dp - \frac{L}{g}\int_0^{p_o} \widetilde{\phi'' V''_n}\, dp + \frac{L}{g}\int_0^{p_o} \bar{\phi}\, \tilde{V}_n\, dp$$

$$-\frac{A}{g}\int_0^{p_o} \overline{\phi' \frac{\partial \omega'}{\partial p}}\, dp \qquad (9)$$

Here the symbol $\sim$ and the double prime denote an average along the pressure surface around the circumference of the cylinder and the departure from this average; and $\omega = dp/dt$. This expression can be further expanded to

$$K_g = -\frac{L}{g}\int_0^{p_o} \tilde{V}_n (\tilde{\phi} - \bar{\phi})\, dp - \frac{L}{g}\int_0^{p_o} \widetilde{\phi'' V''_n}\, dp$$

$$-\frac{AR}{g}\int_0^{p_o} \frac{\overline{T'\omega'}}{p}\, dp \qquad (10)$$

The first term on the right represents the effect of the mass circulation acting on the mean geopotential difference between the boundary and the interior of the cylinder. It can be evaluated, at least to an order of magnitude, by substituting data obtained on the same flights used to get the rainband data. It is of the order of 10^{14} kj. day^{-1} for the cylinder centered on the hurricane and having a radius great enough to include all the eye wall and only enough of the high energy area surrounding it to insure that there is net inflow in the lower layers. The quantity, $(\tilde{\phi} - \bar{\phi})$, is always positive in a hurricane for the inflow layer where V_n is negative. Since the hurricane is a warm core storm, this quantity decreases with height and, therefore, is either much smaller, or possibly of the opposite sign, in the outflow layer where V_n is positive. Except for storms deepening at a very abnormal rate

$$\hat{\tilde{V}}_{n_1} \Delta p_1 \approx -\hat{\tilde{V}}_{n_0} \Delta p_0 \tag{11}$$

Here the subscripts 1 and 0 refer, respectively, to the inflow and outflow layers, Δp denotes pressure interval of the subscripted layer, and the circumflex indicates a mean with height. Thus the first term on the right of equation (10) will always contribute to accumulation of kinetic energy in a cylinder containing the high energy portions of a hurricane. Data were sufficient for an order-of-magnitude type calculation of this term which was made (Appendix B) and the results were tabulated in table 9, along with those obtained by other investigators.

The second term on the right in equation (10) cannot be evaluated with data available. Measurements from a few hurricane flights were used to get an estimate of its size. The values varied greatly from flight to flight; and sometimes the quantity was positive and sometimes negative. The limited data available indicated that the absolute value of the term would be no greater than that of the first term, and the variability of results for individual levels of different storms suggested that the total integrated value for a storm might be much smaller. For different data and a larger area, Riehl [35] concluded that this term was neglible compared to the first term.

The third term on the right in equation (10) says that kinetic energy is generated when departures from area means of T and ω are negatively correlated. The data collected during the longitudinal traverses of hurricane Ella and some of the other storms are suitable for determining the sign of this correlation and for getting an estimate of its size.

The variability both in time and space of the temperatures and wind velocities in the bands and the limited resources available for collecting data made it desirable to use statistical techniques for evaluation of $\overline{T'\omega'}$. (Additional discussion of the reasons for this procedure was given in Section 1). The correlation coefficient for T and ω,

$$r_{T,\omega} = \frac{\sum T'\omega'}{\sqrt{\sum (T')^2}\sqrt{\sum (\omega')^2}} = \frac{\sum T'\omega'}{N \sigma_T \sigma_\omega} \qquad \overline{T'\omega'} = r_{T,\omega}\, \sigma_T\, \sigma_\omega \tag{12}$$

where σ is the standard deviation of the subscripted parameter. The standard deviation of the temperatures was available, and the standard deviation of the vertical velocities for many of the same bands used in this investigation was computed from data which had been prepared by Gray [11]. This latter quantity was converted to the standard deviation of ω by the following approximation:

$$\omega = - \rho g w \qquad (13)$$

Thus the only information needed to give an estimate of the last term in equation (10) was the correlation coefficient for T and ω, $r_{T,\omega}$.

Correlations of temperature and vertical motion

Direct measurements of the vertical motion were not available to make a simple computation of the correlation coefficient of T and ω. It was found, however, that the aircraft itself could be used as a sensor to get a measure of at least the sign of the vertical motion. While this could not be relied on for any particular measurement, it was believed to be sufficiently reliable to use statistically where deductions would be made from a large number of cases. The technique used is explained in succeeding paragraphs.

During the 1962 season the pilots kept the power setting on the aircraft engines constant for long periods, and also attempted to maintain a constant pressure altitude. These flight characteristics were used as a means of determining the sign of the vertical motion. A study of the flight data revealed that anytime the aircraft departed from the assigned altitude there was immediately a tendency to return to that altitude. This results in departures from the altitude being highly correlated with vertical motion of the air. Since the air pressure at the aircraft flight level and the temperature were recorded automatically on magnetic tape every second, it was convenient to compute the correlation coefficients between these two quantities and also the correlation of the flight level pressure with temperature adjusted for changes in altitude (Section 4).

The lapse rate in hurricanes is close to the moist adiabatic; hence, in a vertical column of air the temperature nearly always decreases with height or with decreasing pressure. If there were no horizontal temperature gradients, a reconnaissance aircraft should therefore measure increasingly lower temperatures when ascending along an inclined track to a lower pressure and should measure gradually higher temperatures when descending to higher pressure, and temperature and pressure should have high positive correlation. If the ascending currents were warmer than the descending currents, one might find that low pressures would be correlated with high temperatures and vice versa as long as the pressure changes were principally caused by altitude changes resulting from the airplane being carried upward (to lower pressure) by warm ascending currents or downward (to higher pressure) by cold descending air. That is, if ascending (descending) currents were relatively warm (cold), a negative correlation between temperature and pressure might be expected for the flights along the rainbands in hurricane Ella, October 1962. This is what happened. The correlations are tabulated in table 7.

Table 7. - Correlation coefficients for the bands

Traverse No. (1)	Flight No. (2)	h (10's ft) (3)	r (n mi) (4)	Correlation Coefficients T, P (5)	T_A, P (6)	P, Pch. (7)
101	80818B	1560	50	-.56	-.68	...
102	21017A	1380	75	-.40	-.48	.62
103	21017A	1380	95	-.36	-.64	.73
104	21019A	1380	65	-.77	-.78	.86
105	80924B	1300	55	+.20	-.41	...
106	80815A	640	200	.15	-.43	...
107	21017B	325	100	+.05	-.12	.80
108	21019B	325	80	+.45	+.15	.77

The correlation coefficients for temperature and pressure are in column 5, and for adjusted temperature (adjusted to the reference pressure by use of an assumed lapse rate) and pressure in column 6.

For some of the flights, column 7 contains the correlation coefficients for pressure and pitch. The size of the positive correlation of this parameter gives a measure of the tendency for the aircraft to return to the reference pressure altitude. All of the values in columns 5 and 6 for traverses 101-104 are significant at the 5 percent level even when the degrees of freedom are equated to 25 percent of the number of observations to reduce the effect of autocorrelation. The adjusted temperature and pressure correlation for traverse 106 is also significant at the 5 percent level. The correlation coefficients could be large enough to indicate a considerable effect on the rate of generation of kinetic energy without being statistically significant. The fact that they are large enough to be statistically significant, however, gives support to the belief that the relationship found between temperature and pressure in these few bands must be representative of other portions of the same bands and of other bands not sampled. The fact that temperature and pressure are negatively correlated (column 5) is considered especially significant for the reasons given earlier. As was discussed in Section 4, the temperature gradients at the lower levels (traverses 107 and 108) were small and not so dependent on convective processes as at the higher levels. It is not surprising therefore that the coefficients for these levels lack significance. The flights made in the earlier years did not show the same tendency to return promptly to assigned altitude as did the flights in 1962. Traverses 101, 105, and 106 were made in 1958, while the others were made in 1962. In the earlier data the over-all change in altitude (pressure) along a traverse frequently overshadows the smaller pressure changes caused by passage through convective currents. This makes the usual correlation coefficient ineffective. For the three earlier traverses the tetrachoric correlation (Brooks and Carruthers [6]) was used in order to isolate the effects of pressure changes from convective currents sweeping the aircraft off its assigned pressure altitude. The correlation coefficient for traverse 105 was the only one at the higher altitudes with a value so small that it was not significant at the 5 percent level. It is not known whether this should be attributed to the crudeness of the tetrachoric analysis technique, to the collected data being nonrepresentative of the band as a whole, or to this particular band being one in which not much kinetic energy was being produced. The profiles in figure 9 and data for traverse 105 in table 1 show that the temperature and wind did not vary as much in this band as in the others at the same approximate altitude, so the latter explanation may be correct.

For some of the individual outer bands, the correlation technique suggests that the band may have been consuming kinetic energy rather than producing it. The correlation coefficients were positive and large enough to indicate considerable kinetic energy dissipation. Although the absolute magnitude of the correlation coefficients were about as great as those presented in table 7, the degrees of freedom were much less and the coefficients were not significant at the 5 percent level. Although this does not affect the rate of kinetic energy generation calculation from the bands sampled, it does indicate a greater possibility that the coefficients may not be as representative of other outer bands as the coefficients in table 7 are believed to be for the inner and medium range bands. In general, the correlations that were computed suggest strongly that most of the bands near the eye walls were producing kinetic energy although not as rapidly per unit area as the eye walls.

<u>Computing the kinetic energy production</u>

The correlation coefficient between adjusted temperature and pressure need not be identical to the correlation coefficient between T_A and ω (r_{T_A}, ω), but considering the process for obtaining the former, it is reasonable to assume that the two correlations should have the same sign and about the same magnitude. This is believed to be true because it is thought that the computed correlations between T_A and p were large because the air parcels moving across pressure surfaces at a rate ω were causing the aircraft to change altitude in such a way as to record the proper changes in pressure. An order of magnitude calculation of the third term on the right in equation (10) can be made if one assumes that the two correlations are equivalent.

Values for the various quantities in equation (12) were most reliable and complete for the layer between 11,000 and 15,000 ft. For purposes of the computations, it was assumed that $\overline{T'\omega'}$ was constant between 700 mb. and 300 mb., had half that value between 800 and 700 mb., one-fourth that value between 300 and 200 mb., and that the total in the other layers was insignificant. These are admittedly approximations but are based on indirect evidence from numerous data samples and are believed to be of the correct order of magnitude. The values of the parameters used are listed in table 8.

Table 8. - Values used in making kinetic energy computations

	$r_{T_{A}',\omega}$	σ_T	σ_ω	$\overline{T'\omega'}$
Bands	-.63	0.7	.017	-.0075
Eye Wall	-.63	1.7	.025	-.0268

It was assumed that the values in table 8 would apply to the area of the storm covered with radar echoes and that a storm with rainbands similar to those of hurricane Daisy, August 27, 1958, (fig. 19) could be used in making the computations. The kinetic energy production in units of 10^{14} kj. day^{-1} indicated from the third term on the right in equation (10) under the assumed conditions amounted to 0.15, 0.97, and 1.68, respectively, for the rings of 0 to 20, 20 to 40, and 40 to 60 n. mi. radii. The production from the mass flow term was 4.8 x 10^{14} kj. day.$^{-1}$ The amount of 7.6 x 10^{14} kj. day^{-1} generated inside the 60 n. mi. radius by influences represented by the two terms for total generation is the same order of magnitude as that found by the other investigators whose results are also reproduced in table 9. Except in the inner ring the production from the vertical eddy term was the same order of magnitude as other investigators had found for the total production for similar rings. While the values computed from the rainband data are certainly open to question as to their absolute accuracy, they highly suggest that the rate of generation of kinetic energy in the rainbands brought about by positive correlation of departures from the means of temperature and vertical motion is an important part of the total production. There is also reason to believe that much of the generation accounted for by the mass flow term also takes place in the rainbands. This is especially true for the inner cylinder where most of the ascending motion occurs in the eye wall.

One question we wanted to answer was: what is the importance of the eye wall relative to the other bands for the generation of kinetic energy. While the data were not sufficient to furnish a definite answer, they strongly suggest that both the eye wall and the other bands are important. If one may assume the data in table 8 to be representative, the total production of kinetic energy by the eddy term is much greater in the other bands than in the eye wall. This is due solely, however, to the greater area covered by the bands. The generation of kinetic energy due to the vertical eddy term is about 4 times as great per unit volume in the eye wall as in the other bands. If the mass flow term is considered, the same general statements hold, but here the production per unit volume is weighted even more heavily in favor of the region containing the eye wall. Other investigators (Riehl and Malkus [37], and Miller [31]) have found, for some of the same storms used in the rainband study, that kinetic energy was advected into the inner ring at about the same rate as it was generated there. If this is true and if kinetic energy per unit volume is generated much more rapidly in the eye wall than in the other bands, then it is easy to account for the observed inverse relation-

Table 9. - Generation of kinetic energy (10^{14} kj. day^{-1})

Radial interval (n mi)	0-20	20-40	40-60	0-60	0-120
$-\frac{L}{g}\int_{0}^{P_o} \widetilde{v_n}\,(\widetilde{\phi}-\bar{\phi})\,dP$ (mass flow through cylinder)	2.38			4.8	
$-\frac{RA}{g}\int_{0}^{P_o} \frac{\overline{T'\omega'}}{P}\,dP$ (vertical eddy term)	0.15	1.0	1.7	2.8	
Sum of preceding terms	2.53			7.6	
Total in Helene (Miller, [31])	0.90	3.6	2.4	6.9	
Total in Daisy 26 August 1958 (Riehl and Malkus, [37])	1.00	2.0	1.5	4.5	
Total in mean hurricane (Palmén and Jordan, [33])				4.1	

Note: Terms are defined in equations 5-10.

ship between wind speed and radius normally found in hurricanes in the area outside the eye.

Only that part of the storm area covered by the radar echoes has been considered in calculations for the vertical eddy term. What would be the effect of the remaining area? The measurements of the various parameters made thus far suggest that in these areas the contributions from the eddy term would be rather small and the sign uncertain.

We may conclude (assuming the rate of kinetic energy generation computations are at least of the right order of magnitude) that kinetic energy is generated in bands (and maybe between bands) throughout the storm.

13. SUMMARY AND CONCLUSIONS

The data from several tropical cyclones since 1957 have been analyzed and used to define the three-dimensional structure of hurricane rainbands. This was considered necessary in order to provide information for verifying the many hypotheses which have been advanced concerning the bands, and to furnish a basis for developing improved hypotheses which may explain development and maintenance of the bands. The information furnished by the data supports the conclusions listed in later paragraphs concerning the mechanism by which the mass flowing through the hurricane ascends from the low-level inflow layer to the upper tropospheric outflow layer, and the deductions about the energetics of the storm.

Structure

Variability is a prime characteristic of rainbands. In the outer bands of the storm shown in figure 1, it is obvious that there are many independent cells arranged in a quasi-spiral to form a band. That the inner bands are about as cellular in character as are the outer bands, even though they appear in the picture to be more or less homogenous, is confirmed by the detailed measurements of the temperature, wind, and water distributions made in similar bands. This was also brought out by the fact that temperature and wind variations were just as great on the longitudinal traverses as on the normal traverses of the various bands. This variation along the band had not been expected because earlier investigators had suggested that the inner bands were relatively uniform and homogenous.

The rainbands have a rather complex microstructure. Convergent and divergent areas alternate along the band and are associated with the many convective cells which are aligned approximately along a spiral. Mixing in the direction the wind is blowing - which usually is within 20° to 40° of the orientation of the band - helps to distribute products of the convective activity along the spiral and to give the band the appearance of being uniform. Results of the present investigation suggest that much of the variability associated with the bands is ordered by the convective cells themselves and their interaction with each other and with the larger-scale circulations in the hurricane.

The principal gradients of temperature, horizontal and vertical wind components, pressure, and liquid water in hurricanes occur in the rainbands (including the eye wall). While these gradients are greater across the eye wall than in the other bands, changes of the parameters in the other bands far exceed those encountered in the normal tropical atmosphere. For example, greater changes in temperature and wind may be encountered in 10 mi. on either a longitudinal or normal traverse of a band than in a traverse of more than 1000 mi. of relatively undisturbed tropical atmosphere. Turbulence is much greater in the bands than in the other areas in the storm.

Temperature changes as great as 5.2°C. were measured in bands while flying normal to eye walls, and as great as 3.2°C. while flying normal to outer bands. On longitudinal traverses of bands in the middle troposphere, the average temperature change within 10 n. mi. was about 1.5°C. and the average change in wind speed was about 10 kt. Changes greater than 20 kt. in 10

n. mi. frequently were observed. These gradients of temperature and wind speed are produced by differential vertical motion in a conditionally unstable lapse rate and are modified by intense mixing processes.

Many of the outer bands are colder in the mean than the ambient areas (at least in the lower and middle troposphere). Even in these bands, however, there were usually warm cores which had temperatures higher than the nearby atmosphere. The bands nearer the center not only had higher temperatures per arbitrary altitude than did the outer bands but were also more likely to have a mean temperature higher than that of the air just outside the band.

Wind measurements indicate that air moves relative to the bands and relative to the individual echoes forming the bands in such a manner that mixing is very great in all the bands of hurricanes. There would be even larger temperature variations except for the fact that all of the air being mixed is so nearly homogenous because of the normally small gradients found in the Tropics. Even in the eye wall where the ascent is most vigorous, much of the air is thoroughly mixed with that of its nearby environment before it ascends to the upper troposphere.

Conclusions

The anomalous temperature gradients and the lapse rates of equivalent potential temperature found in hurricane rainbands can be accounted for largely by the horizontal and vertical velocities known to exist and by the mixing that is indicated by the data reported in this research. The fact that there is a minimum in equivalent potential temperature in the middle troposphere at radii greater than that of the eye wall indicates that there is relatively little undiluted ascent from near the surface to the upper troposphere in the outer bands. The fact that the equivalent potential temperature is more nearly constant with height in the eye wall indicates that the air ascending in that region is mixed less with air of normal tropical mid-tropospheric characteristics, than is the air ascending in the outer bands. The variation of the temperature anomaly, directly with height and inversely with radius (most noticeable in the vicinity of the eye wall), can be explained in two ways. In the first place, air flowing inward at low levels acquires latent and sensible heat from the ocean surface and has a higher equivalent potential temperature before starting its ascent than does the air which starts rising in one of the outer bands. In the second place, the gradual increase in temperature anomaly with decreasing radius at the middle and upper levels of the troposphere means that the air rising in the eye wall is mixed with much warmer ambient air than is the air rising in one of the outer bands. Although convective elements in all the bands entrain ambient air, those in the inner bands have air with much higher equivalent potential temperatures to entrain than do the elements in the outer bands.

The asymmetries of the rainbands and the fact that the asymmetries vary from hour to hour and from storm to storm may be of importance to many theoretical studies of hurricanes.

The rainbands are prolific converters of other forms of energy to kinetic. The vertical eddy term accounts for a greater proportion of the generated kinetic energy per unit volume in the eye wall than elsewhere, because of the strong vertical motions and gradients in temperature anomalies found there. However, the total production of kinetic energy by the eddy term is much greater in the outer bands than in the eye wall because of the much greater volume of the outer bands. The kinetic energy generated in the bands, due to the correlation between vertical motion and temperature anomalies, is smaller but still of the same order of magnitude as the total kinetic energy generated in some hurricanes, as estimated by previous investigators. The kinetic energy generated in the bands as a result of the positive correlation between vertical motion and temperature anomalies is less than the kinetic energy generated by the mass flow operating on the pressure gradient, but much of the kinetic energy generation by the latter may also occur in the bands (including the eye wall).

Future plans

It is planned to make, at the first opportunity, longitudinal traverses of hurricane rainbands in a mature well-formed hurricane that has originated at low latitudes. Most of the data collected on longitudinal traverses were secured in hurricane Ella, 1962, in which the rainbands were not as well developed as those frequently observed in hurricanes which developed at more southerly latitudes. In future flights it is planned to try again to get data at three levels simultaneously and to fly closed patterns around sections of the band in an attempt to verify the deduction concerning vertical motion made from correlations of pressure and temperature by calculations of the vertical motion made from divergence patterns.

Because there is still some doubt as to the accuracy of the temperatures measured when the aircraft is flying in and out of clouds and of the wind measurements when the aircraft is flying over heavy concentrations of liquid water in clouds or over a moving sea surface, continued efforts will be made to get further verification of the dependability of the data already collected. It is planned to make special flights to determine the effect of the moving sea surface on the wind measurements. Continued efforts will be made to compare temperatures measured by the vortex thermometer with those measured with other types of thermometers.

ACKNOWLEDGMENTS

The writer wishes to record his appreciation for the guidance received from Professor Noel E. LaSeur of the Department of Meteorology, Florida State University, and the assistance furnished by the Staff of the National Hurricane Research Project. He is also appreciative of the contributions of the crews of the Air Weather Service of the U. S. Air Force and of the Research Flight Facility of the U. S. Weather Bureau who made the flights to collect the data used in this research.

Appendix A

Effect of Heavy Concentrations of Water on Wind Measurements

In Section 4, figures 13 and 14, a case is illustrated in which the recorded wind speed inside the area of heavy concentration of liquid water was about 16 kt. less than the mean of the wind speeds measured outside the liquid water belt. Since the decrease in wind speed occurred nearly simultaneously with entry into the liquid water, it can reasonably be asked if the Doppler radar used in the wind measureing system was getting its return from the water in the cloud rather than from the ocean surface and was furnishing the wind computer a false ground speed. No definite answer can be given to this question, but the evidence in the data suggests that this was not the case. The wind variation represented in figure 13 is reasonable. The evidence collected in the present study is very strong that wind speed and wind direction both are extremely variable in and near the rainbands regardless of whether or not the liquid water concentration is abnormally great. The rainband data strongly suggest that the winds are ordered by convective cells imbedded in the bands.

By assuming that the true wind did not vary appreciably within the band, one can compute the rate of movement of the water drops that would be required to give a spurious ground speed of the right amount to produce the measured fluctuations. Then one can determine if such a rate of movement of the water drops (presumably approximately the wind speed at the level of the drops) is reasonable for that level. The average of the measured winds near the band but outside the liquid water concentration was 300°,34 kt. The average in the water area was 282°, 18 kt. If the former was the true wind at flight level the velocity of the surface reference plane required to produce a measurement of 282°, 18 kt. would have been 317°, 18 kt. This assumes that the Doppler uses the strongest return signal and ignores the others as was discussed in Section 3. If the latter velocity represented the horizontal movement of the water drops below the level of the aircraft (13,000 ft.) there must have been a rather unusual vertical wind shear, which certainly suggests large variation in the winds on a convective scale. The velocity 317°, 18 kt. would have been reasonable for the surface spray, except that at that speed there should not have been enough spray to furnish a signal for the Doppler. If the Doppler were taking the return signal from drops near the aircraft, the measured wind would have been about zero, for presumably the water drops would have been moving approximately with the wind. This, however, is not what happened. Therefore, it can be concluded that the heavy water concentration probably did not appreciably affect the measured winds; and it is certainly true for this particular case that the winds in the band were quite variable whether or not the water in the clouds affected the wind measurements.

Appendix B

Computing the Kinetic Energy Generated by the Mass Circulation through a Hurricane

The accumulation of kinetic energy in a cylinder due to conversion from potential energy, K_g, was expressed in equation (10) of Section 12 as,

$$K_g = -\frac{L}{g}\int_0^{p_o} \tilde{V}_n (\tilde{\phi} - \bar{\phi})\, dp - \frac{L}{g}\int_0^{p_o} \widetilde{\phi'' V''_n}\, dp - \frac{RA}{g}\int_0^{p_o} \frac{\overline{T'\omega'}}{p}\, dp \qquad (10)$$

The first term on the right represents the rate of generation of kinetic energy resulting from the mass flow through the storm operating on the mean difference in the geopotential on the boundary, $\tilde{\phi}$, and in the interior of the cylinder, $\bar{\phi}$. If this term is equated to K_m, then

$$K_m = -\frac{L}{g}\int_0^{p_o} \tilde{V}_n (\tilde{\phi} - \bar{\phi})\, dp \qquad (14)$$

where L is the circumference of the cylinder, V_n is the component of the wind normal to the cylinder, and g is the acceleration of gravity. This quantity can be evaluated approximately with data collected on the same flights as some of the rainband data.

For the high energy portion of a hurricane it is usually assumed that most of the inflow is confined to the lower part of the troposphere and most of the outflow to the upper troposphere. It can be shown that when the central pressure of a hurricane is not changing extremely rapidly (not much faster than 1 mb. per hr.)

$$\hat{\tilde{V}}_{n_1} \Delta p_1 \approx -\hat{\tilde{V}}_{n_0} \Delta p_0 \qquad (11)$$

where the subscript 1 and 0 refer to the inflow and outflow layers. Using this relationship and assuming that

$$\hat{\tilde{V}}_n = 0$$

in the stratosphere and the middle troposphere, then

$$K_m \approx -\frac{L}{g}[\hat{\tilde{V}}_{n_1} \Delta p_1 (\hat{\tilde{\phi}}_1 - \hat{\bar{\phi}}_1) + \hat{\tilde{V}}_{n_0} \Delta p_0 (\hat{\tilde{\phi}}_0 - \hat{\bar{\phi}}_0)]$$

$$K_m \approx +\frac{L}{g}\hat{\tilde{V}}_{n_1} \Delta p_1 [(\hat{\tilde{\phi}}_0 - \hat{\tilde{\phi}}_1) - (\hat{\bar{\phi}}_0 - \hat{\bar{\phi}}_1)]$$

$$K_m \approx L \tilde{V}_{n_1} \Delta p_1 (\tilde{z} - \bar{z}) \qquad (15)$$

where $\hat{\sim}$ and $\hat{-}$ over parameters indicate, respectively, the mean value for the surface on the boundary of the cylinder and for the volume contained in the cylinder; and $\tilde{z}$ and $\bar{z}$ are respectively, the mean thickness around the cylinder and for the volume between the mean elevations of the inflow and outflow layer. Using the hypsometric equation, and assuming: (1) Δp = 280 mb., (2) middle of inflow layer is 840 mb., and (3) middle of outflow layer is 260 mb., one gets

$$K_m \approx \frac{345L}{g} \hat{\tilde{V}}_{n_1} \Delta p_1 \Delta \hat{T}^* \qquad (16)$$

where $\Delta \hat{T}^*$ is the difference of the mean virtual temperature along the boundary and over the interior of the cylinder between 840 and 260 mb., and all units are in the meter-ton-second system.

Temperature data along approximate radii were measured at a number of levels in hurricanes Daisy and Cleo in 1958. Temperatures from some of these flights for a number of traverses from the center out for 60 n. mi. are summarized in table 10. Using these data as a guide, it was assumed that -2.4°C. and -1.6°C., respectively, for the 20 to 60 n. mi. cylinders, would be reasonable values to use for $\Delta \hat{T}^*$ in estimating K_m.

Data were available from three independent sources for estimating V_{n_1} at the 60 n. mi. radius. Palmén and Riehl [34] used mean data from a number of hurricanes and some assumed relationships to prepare profiles of radial velocity against pressure at different radii for the "mean" hurricane. Using their values for the 60 n. mi. radius, one gets a mean inflow of 5.8 m.p.s. through a depth of about 3 km. Miller [30] used winds measured during reconnaissance and rawinsonde flights to reconstruct the three-dimensional wind field for hurricane Donna, September 9-11, 1960 (a very intense hurricane). He found that the average inflow through a depth of about 3 km. varied on the three days from 4.8 to 6.2 m.p.s. Winds at about 1600 ft. measured at a radius of approximately 70 n. mi. during a circumnavigation of hurricane Carrie, September 15, 1957, gave a mean inflow which agreed approximately with the profile prepared by Palmén and Riehl [34]. With these data as a guide it was assumed that V_{n_1} = - 5 m.p.s. at 60 n. mi. radius would be adequate for the order of magnitude type calculation proposed.

Table 10. - Mean difference in temperature between boundary and inside of ring

Hurricane	Flight	h (10's ft)	Average ΔT* Radius of ring (n mi) 20	40	60	Number of Traverses
Cleo	80818C	3500	-0.1	-1.7	-2.3	4
Daisy	80827C	3420	-2.9	-2.3	-2.3	4
Daisy	80827B	2050	-2.3	-1.5	-1.3	2
Cleo	80818B	1560	-3.2	-1.9	-2.0	6
Daisy	80827B	1300	-3.3	-1.7	-0.8	6
Cleo	80818A	640	-1.9	-1.5	-0.9	5
Daisy	80826A	640	-1.1	-1.2	-1.1	1

It was difficult to compute V_{n_1} at 20 n. mi. directly from wind measurements available; however, it can readily be determined that it should lie within a rather limited range of values. In the model being used, it is assumed that the eye wall is inside this radius, so it is clear that V_{n_1} at the boundary of the cylinder must be negative. It is equally clear that V_{n_1} = 0 at r = 0. From continuity considerations, the rate of inflow must vary with the vertical velocity inside the area, and this relationship will be used to get an estimate of V_{n_1}. For the assumed model where the inflow layer extends from the ground up to about the 700-mb. level, the mean radial component must equal in absolute magnitude about 5 times the mean vertical component of the wind at the top of the inflow layer inside the 20 n. mi. cylinder. It is known, however, that in the eye the vertical component is either very weak or negative in value. The same is probably also true for other cloud-free areas included in the cylinder. Reconnaissance crews frequently report encountering not only large updrafts but also strong downdrafts in the eye wall and its vicinity. Judging from radar photographs there is reason to believe that only about 1/2 or less of the area inside the 20 n. mi. radius circle is covered by significant updrafts and at least some of the remaining area may be covered by significant downdrafts. Therefore, the mean vertical velocity in the area will be much less than that of the drafts occasionally encountered in flights through the eye wall.

Gray [11] analyzed data collected on some of the same flights used in the rainband study to get an estimate of the vertical velocities. In particular, he analyzed the data from nine traverses of eye walls - four from hurricane Daisy on August 27, 1958, when it was at its greatest intensity, and five from hurricane Cleo on August 18, 1958 while it was still a mature, intense storm but past its peak. The vertical motions were much greater for the eye wall of Daisy, but the maximum 10-sec. averaged vertical velocity computed by Gray was 25 kt. and that for only a small portion of the wall. For the four traverses of Daisy the 10-sec. averaged vertical velocity exceeded 6 kt. only 33 percent of the time that the plane was in the wall cloud.

Are Gray's values reasonable? He had to use several approximations in making the computations, but other semi-qualitative data indicate that his maximum values are reasonable considering the size of the sample. Lieutenant Scott Hinkle (navigator) flew on a reconnaissance mission into typhoon Ophelia, January 15, 1958, from Guam, with Captain Tunis Marrow as the aircraft commander. When the plane was departing from the eye toward the east it encountered an updraft which carried the WB-50 aircraft from 10,000 ft. to 18,000 ft. in about 2 min. The data were not recorded automatically, so there is no way of making computations after the fact in the manner that Gray has done for the other data. Neither is it known to what extent the pilot was attempting to keep the airplane from ascending. It seems certain, however, that the updraft must have been of the order of at least 40 kt.

In hurricane Esther, September 17, 1961, the B-57 aircraft of the Weather Bureau's Research Flight Facility while flying at 40,000 ft. crossed the eye wall northeast of the storm center at constant power and attitude. According to Simpson, Ahrens and Decker [45] the rate-of-climb meter indicated a steady +2200 ft. $min.^{-1}$ while the aircraft was approaching the eye, and then a rapid reversal to -1800 ft. $min.^{-1}$ upon entering the eye. These convert to approximately +22 kt. and -18 kt. respectively. Other such data have been accumulated by reconnaissance crews, but in most tropical cyclone flights these extreme values are not encountered. It would seem, therefore, that Gray's values could be used at least for getting an estimate of the true vertical velocity. The average vertical component in the eye wall of hurricane Daisy, August 27, 1958, according to Gray's computations for four traverses, was 3.5 kt. About 0.65 of the area inside the circle of 20 n. mi. radius was covered with echoes and about 0.3 of the area was covered with relatively intense echoes. An estimate of $\overline{V_{n_1}}$ along the boundary of the cylinder can be obtained by assuming $\overline{w} = 0$ except in the echoes, and by assuming that the mean vertical velocity computed for the eye wall was either representative of all the echoes or was representative of only the relatively intense echoes. The two assumptions give values for V_{n_1}, respectively, of -6.6 and 3.1 m.p.s. For purposes of computing the values recorded in table 9, it was assumed that V_{n_1} = -5.0 m.p.s. at the 20 n. mi. radius.

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