AN ANALYSIS OF HURRICANE CLEO (1958) BASED ON DATA FROM RESEARCH RECONNAISSANCE AIRCRAFT

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[Manuscript received July 5, 1963; revised September 6, 1963]

ABSTRACT

The structure of hurricane Cleo (1958) is presented, based on observations of wind, temperature, pressure, humidity, clouds, and precipitation obtained from three research reconnaissance aircraft of the National Hurricane Research Project. Insofar as possible, the data are analyzed in terms of departures from the mean tropical atmosphere; and the physical processes which produce these departures are discussed. The central eye region of the hurricane emerges as the seat of the most important contributions to the structure of the entire storm, a result anticipated by Wexler from what may be termed the first research reconnaissance of a hurricane in 1944.

1. INTRODUCTION

On September 14, 1944, a little more than one year after the first aircraft flight into a hurricane, Dr. Harry Wexler (then a Major in the Army Air Corps) participated in what may be called the first research reconnaissance flight into a hurricane. In his published account of the mission [1], which describes the data collected (largely visual observations and qualitative physical impressions) and gives his interpretation of their significance in terms of hurricane structure, Wexler arrived at a conclusion which was truly prophetic. He stated in part: "One is led to the conclusion that the major portion of this hurricane cloud was caused by a strong but narrow area of ascending air near the center of the storm and that outside this area, descending air was found."

This result was partly fortuitous since the penetration was made in the left-rear quadrant of a mature hurricane which was accelerating northeastward after recurvature, the very circumstances under which this type of structure is most easily perceived from qualitative observations. Wexler was quite aware that conditions observed on one particular flight might not be representative of all sectors of all hurricanes at every stage in their life cycle, but he must be credited with the courage to present the interpretation suggested by these meager data even though it was completely at variance with the accepted models of that time.

Aircraft reconnaissance of hurricanes has progressed rapidly in the years since 1944. The pioneering efforts of Simpson, who participated as a supplementary observer aboard operational military reconnaissance planes, produced many valuable results [2]. However, the limited observational capabilities, especially of wind, plus the necessity of manual recording of data were severe handicaps in such flights. The first aircraft equipped with instruments and data-recording facilities capable of overcoming such difficulties was the research aircraft (B–29) of the Geophysics Research Directorate, Air Force Cambridge Research Center, utilized for hurricane reconnaissance during the 1955 season [3]. Since 1956, the National Hurricane Research Project (NHRP) of the U.S. Weather Bureau has employed multiple aircraft equipped with further improvements in instruments and automatic data recording systems. One of the principal results of such modern research reconnaissance has been increasing evidence that the ascent of air in the cloud-wall surrounding the central eye of the hurricane is of essential importance in the structure and maintenance of the entire storm, a remarkable verification of Wexler's deduction quoted above.

The purpose of this paper is to discuss the structure of hurricane Cleo (1958) based on data obtained by three NHRP research aircraft operating simultaneously at different levels and, insofar as possible, to provide a physical interpretation of the observed structure. The details of the equipment on board these aircraft may be found in [4]. Further details of the instrumental characteristics and the data reduction procedures may be found in [5].

2. PURPOSE AND PLAN OF FLIGHTS

On August 18, 1958, hurricane Cleo was located approximately 400 n. mi. east-northeast of Bermuda, moving north-northeast at a moderate speed after recurvature but before it had acquired any extratropical characteristics. The objective of the reconnaissance was to obtain, at three levels, simultaneous observations along a flight track which provided maximum coverage of the storm area. Operational considerations also influenced the final choices of 800 mb. (~6300 ft.), 560 mb. (~16,500 ft.), and 240 mb. (~37,000 ft.) as the levels to be reconnoitered. These will be referred to as A, B, and C flights, respectively.

The flight pattern was designed to provide, at each level, three traverses of the storm along different diameters, as well as a circumnavigation of the eye region. The location of the storm and the range of the aircraft limited the area to be reconnoitered to that within a radius of 120 n. mi. of the center, except for initial approach to and exit from the storm area. The first portion of the flight consisted of a direct penetration of the eye to provide a fix with reference to which the remainder of the flight plan would be flown. The authors served as observers on board the two lower-level flights.

Because of differences in the cruising speeds of the three aircraft at the chosen levels, and in the precision of in-flight navigation, the objective of simultaneous observations at identical relative positions at each level was not completely realized. But the departures were not sufficiently large to nullify the objectives of the mission. Figure 1 illustrates the actual track flown by each plane relative to the storm center. It can be seen that the horizontal separation of the three aircraft rarely exceeded 30 n. mi. Along the radial portions of the tracks within 60 n. mi. of the center, the horizontal separation was mostly less than 10–15 n. mi. From the times given in figure 1 it can be seen that differences between the times at which the different aircraft traversed the same region seldom exceeded 45 min. and were mostly less than 30 min. The total elapsed time for the two lower aircraft was about 10 hr., with 6 hr. spent within 120 n. mi. of the storm center. During the period of reconnaissance the hurricane moved steadily toward 018° at a speed of 15 kt.

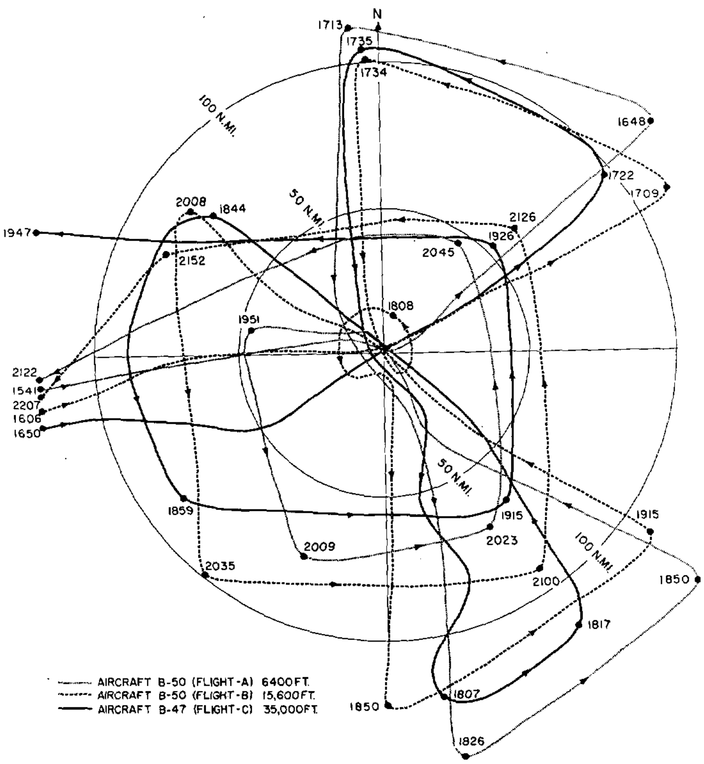

Figure 1.—The track of each aircraft relative to hurricane Cleo on August 18, 1958, with time (GMT) indicated at various points along tracks.

3. DATA PROCESSING

The first problem in processing the data recorded from each plane was to position each report correctly relative to the storm center; i.e., to remove the effects of the translation of the hurricane during the time data were collected. Although there were small differences in the eye locations for each of the flights, the velocities of the hurricane computed from the three eye fixes available from corrected navigation logs for each aircraft were in close agreement. They also agreed closely with the value obtained from the fixes reported by the Air Force hurricane reconnaissance aircraft which reconnoitered the storm at 700 mb. during the same period. The position of the eye reported at the time of the second penetration by the low-level aircraft was arbitrarily chosen as the reference to which all data were adjusted. Temporal and spatial differences among the three aircraft were at a minimum at that time. The point chosen as the center of the storm was the geometric center of the annular radar echo associated with the wall cloud enclosing the eye of the hurricane. This echo was distinctly observed on each aircraft radar at each eye penetration, with only very slight changes in size, shape, and intensity during the period. Its conservative character provided the most objective and reliable measure of storm position. Although there may be small errors in the absolute geographical position of the eye, this technique insures that the data from all levels and times have been positioned as accurately as possible relative to the storm center and each other. In fact, all further analysis of the data was performed in terms of position relative to the storm center, and not in terms of actual latitude and longitude.

Comparisons between repositioned reports which occurred in the same relative position, but at different times, revealed that the hurricane retained very nearly the same structure during the period of data collection. This steady state in a coordinate system which moves with the storm is further substantiated by data from the Air Force hurricane reconnaissance plane. Three dropsondes re-

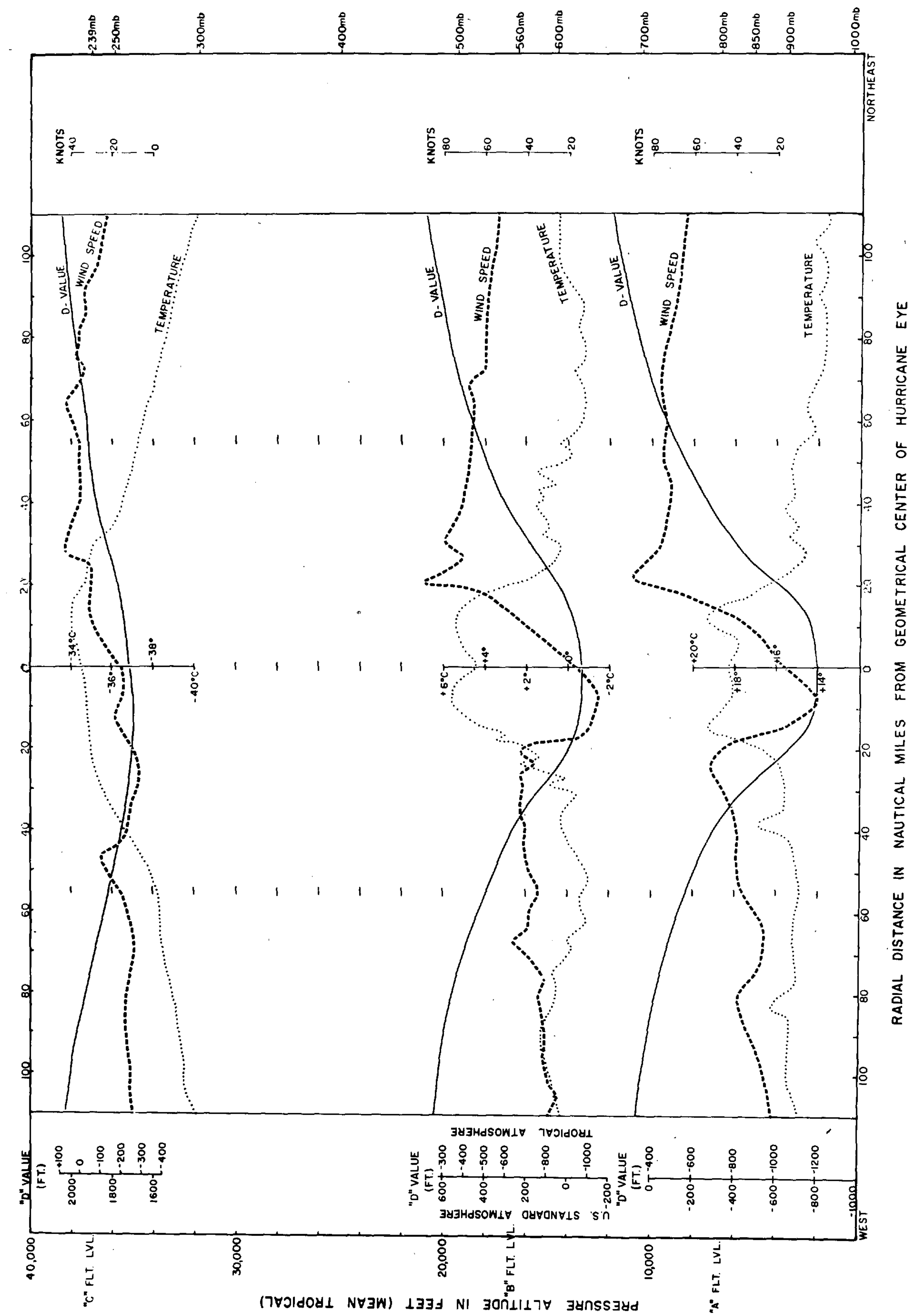

FIGURE 2.—Curves of D-value, temperature, and total wind speed along first traverse of hurricane Cleo.

leased from 700 mb. in the eye, at 1000, 1400, and 2000 GMT, reported central surface pressures of 973, 974, 971 mb., respectively. Thus, to a good approximation the storm can be considered a permanent-type system, and repositioning the reports to remove the translation of the hurricane allows the data to be considered as representative of the synoptic structure of the storm during the reconnaissance period.

Since it was intended that a major effort in the analysis of the data be devoted to a study of the vertical structure of the hurricane along the diameters traversed nearly simultaneously by the aircraft, the first plots of the repositioned data were in form of "profiles" of various parameters as a function of radial distance from the storm center. Figure 2 shows such curves of temperature, "D" value, and (total) wind speed at each of the three levels along the first traverse of the storm. This representation allows quick and convenient comparison of the various elements at different heights, as well as facilitating hydrostatic and other checks on the data. Such plots are also useful in the preparation of vertical cross-sections through the hurricane. More detailed discussion of this diagram will be deferred until later sections; however, we may note some major features. The temperature curve clearly reveals the warm eye region at the lowest and intermediate levels, becoming much broader and less well-defined at the upper level. At the two lower levels the highest temperatures occurred in the clear air immediately inside the wall cloud. This has been observed in other storms and cannot be ascribed to an effect of liquid-water on the thermometer since it occurred both on entrance into and exit from the eye. The strongest temperature and "D"-value gradients occurred in the eye wall cloud coinciding with the strongest winds. To the left (west) of the storm, wind speeds were significantly less than to the right (east) of the hurricane.

4. RADAR AND VISIBLE CLOUD DATA

Each aircraft was equipped with essentially the same radar, a 3-cm. search radar with an antenna designed such that echoes are detected throughout the layer from flight level to the earth's surface. This wavelength and antenna design are not the optimum for meteorological purposes; nevertheless much useful qualitative information can be obtained. Through comparison of radar data with visual and instrumental records some semiquantitative information can be obtained. The best photographs of the PPI scope were obtained from the upper plane which flew above the largest liquid water concentrations. Good pictures were available from the intermediate level but only poor results from the low-level aircraft which flew through more and heavier rain. Because of variations in the individual radars and in such factors as the gain setting chosen by the radar operators in each plane, the echoes do not appear exactly identical in size and shape even on photographs taken in the same area within a few minutes of each other. However, the differences are mostly as to detail of size and shape; major features such as the annular wall cloud around the eye and segments of convective bands crossed by the aircraft can be identified on photographs taken of the different PPI scopes.

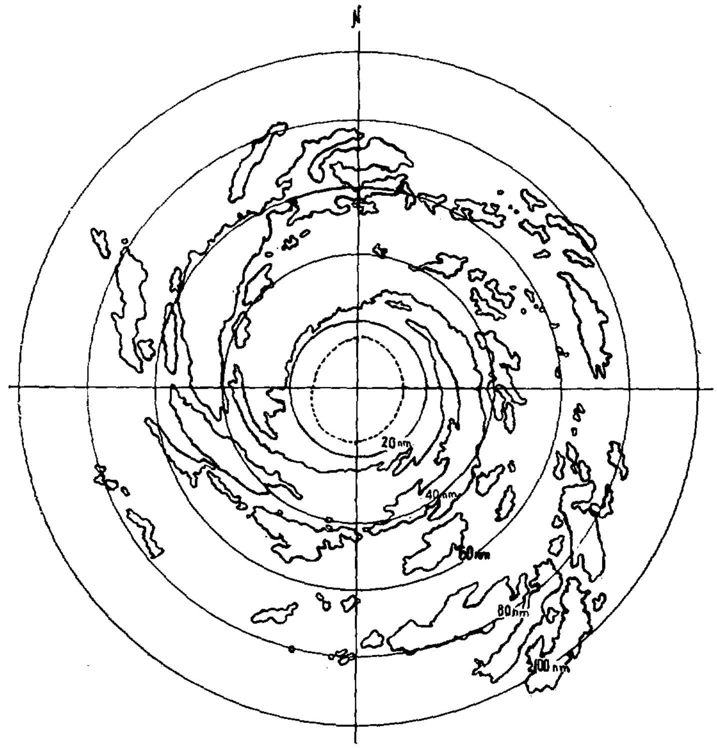

FIGURE 3.—Composite of stronger radar echoes observed from upper reconnaissance aircraft, 35,000 ft. pressure altitude.

Figure 3 is a composite of the well-defined echoes observed on several thousand radar-scope photographs taken from the highest level of reconnaissance. All echoes have been plotted in the correct position relative to the storm center. Of the area within a radius of 120 n. mi. about 25 percent contains "strong" echoes. As will become more evident from the discussion which follows, these echoes correspond to the regions of heavier precipitation and liquid water content often associated with active convection. Extensive areas of light to moderate rain associated with stratiform clouds do not appear as echoes, primarily because of the reduced gain settings at which the radar was operated.

Each aircraft was also equipped with a 16-mm. time-lapse motion picture camera which photographed the field of view ahead of the plane at intervals of about two seconds. Projection of such films at normal rates allows one to review a 10-hr. flight in about 20 min. Knowledge of the lens characteristics and other factors permits quantitative measurements of cloud height, position, etc. These films were supplemented with event recorders which could be activated by the observer to indicate qualitatively on the data records the duration and intensity of turbulence and precipitation, and the presence or absence of

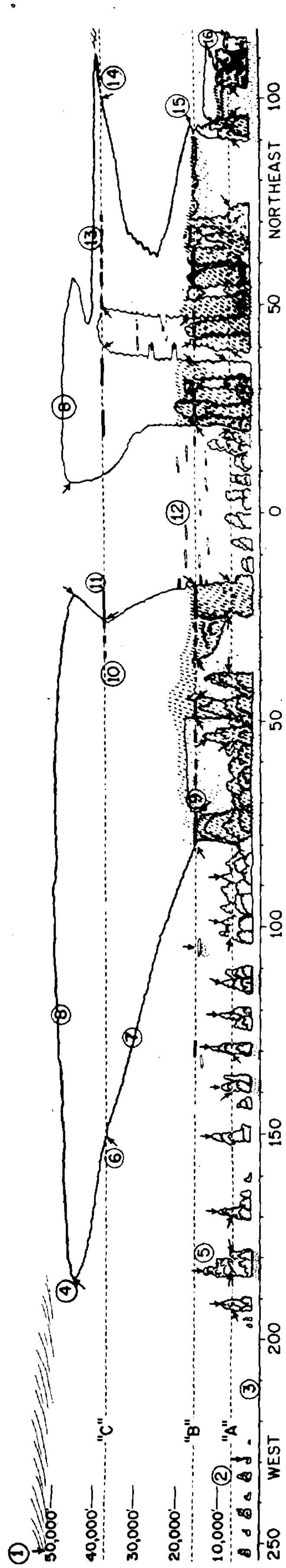

FIGURE 4.—Vertical cross-section of cloud, precipitation, and strong radar echoes observed on first traverse of hurricane Cleo. Data from radar film, time-lapse cloud film and observers' notes were used in the construction of this diagram. Small arrows indicate cloud features determined quantitatively by photogrammetric measurements; solid lines along flight track indicate strong radar echo at or below flight level. Circled numbers refer to the following comments: (1) outermost cirrus, separate from main cloud mass; (2) disorganized cumulus outside storm circulation; (3) distinctive clear zone, apparently marking west side of hurricane; (4) edge of main cirrostratus cloud shield; (5) bands of cumulus oriented along the wind, entirely below the freezing level, some of which produced showers; (6) upper aircraft enters cirrostratus which was continuous to the eye; (7) cirrostratus gradually lowers to altostratus, no precipitation from these clouds; (8) tops actually unknown, have been shown at levels determined quantitatively at inside and outside boundaries; (9) first major cloud band to penetrate upper cloud shield, rain continues to fall from upper nimbostratus; (10) upper-level radar inoperative to this point; (11) radar echo from wall cloud below aircraft is indicated after plane breaks into clear; (12) interior of eye is clear above scattered lenticular altostratus and lower broken cumulus; (13) cirrostratus very thin above upper aircraft; (14) upper plane emerges from high cloud shield, clear to east; (15) middle plane emerges from altostratus, only lower cumulus to east; (16) lower plane turns to northwest, lower clouds extend eastward beyond this point.

clouds at flight level. Figure 4 is a vertical cross-section of the distribution of clouds and precipitation along the first traverse of the hurricane, prepared from the data discussed above. Although the portrayal of clouds is somewhat schematic, the patterns include more than 100 quantitative determinations of positions, heights, and other cloud characteristics. The diagram clearly shows the correspondence between the stronger radar echoes and active convective clouds. Note that the radar in the upper plane recorded the echo from the western side of the wall cloud even though the aircraft had broken into the clear air above. The tilt of the cloud-free portion of the eye to the north and west, and the overhanging shelf of cirrostratus clouds on the east and south sides, are clearly discernible in the time-lapse cloud pictures. Below about 30,000 ft. the eye wall was nearly vertical. The eye was relatively free of clouds above 6,000–8,000 ft.; below this there were broken cumulus and stratocumulus. Through the breaks it was possible to see the surface of the sea.

To the west of the extensive clear area about 200 n. mi. from the storm center the low cumulus clouds were randomly spaced with no organization. East of the clear area the cumulus and stratocumulus were organized in the bands and lines (along the wind) characteristic of the hurricane proper. The low-level wind shifted from SW and W to NNW across the clear area.

5. THE TEMPERATURE FIELD

All temperature data presented here were recorded by vortex thermometers. Temperature values were also available from two other thermometers which involved total or partial stagnation of the air, with the resulting uncertainties as to the proper correction to be applied in variable conditions of cloudiness and precipitation. In clear air the vortex temperatures agreed closely with radiosonde observations at Bermuda and with available dropsonde values in the eye. In one region, the heavy rain area of the eye wall, there is evidence that the vortex thermometer values may be unrepresentatively low by as much as 1° C. This evidence, which will be discussed more fully in a later section, is based on hydrostatic checks of the pressure field. Although this is strong evidence that the indicated temperatures are too low, the values were not adjusted in these analyses. All temperature values were corrected for the small departures from constant pressure which occurred despite considerable effort to fly each aircraft at its planned indicated pressure altitude.

The main analytical principle used in the analysis of the horizontal temperature fields shown in figures 5, 6, and 7* was to avoid areas of large temperature advection;

*The reader may wish to note both for these and subsequent figures, that the visible wall cloud extended no farther toward the center of the eye than the indicated distances:

A flight .... 19.5 n. mi. on the west and 15.5 n. mi. on the east
B flight .... 17.5 n. mi. on the west and 19.9 n. mi. on the east
C flight .... 26.1 n. mi. on the west and 4.3 n. mi. on the east

The C flight measurements are not necessarily indicative of the wall cloud proper—certainly on the east side the early entrance into overcast was due to the pronounced cirrus overhang.

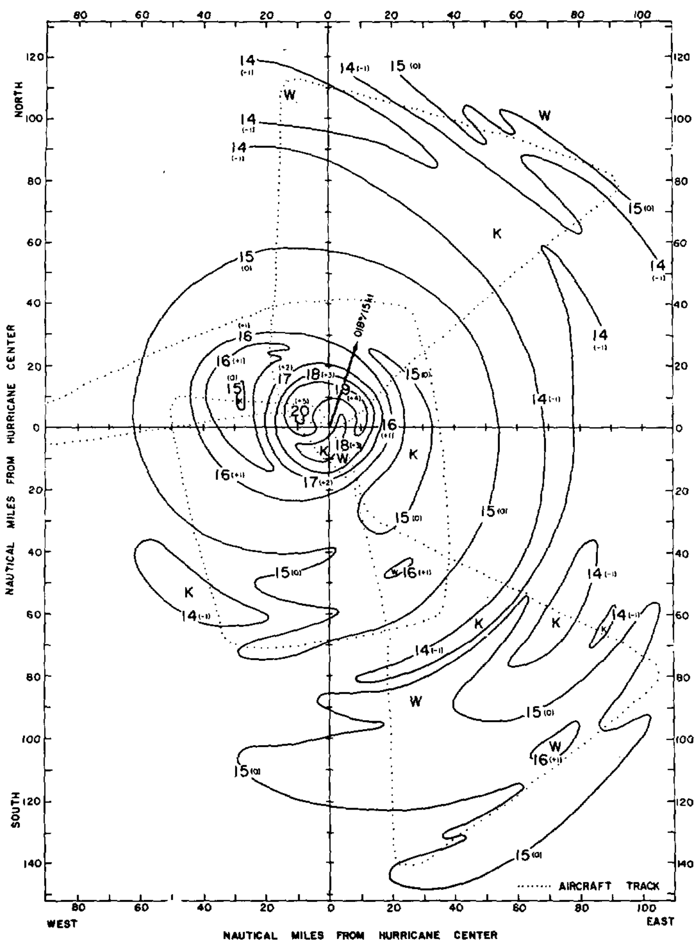

FIGURE 5.—Temperature analysis at 800 mb. Large labels indicate values in degrees Celsius, smaller parenthetical labels indicate anomaly from mean tropical conditions.

i.e., to draw the isotherms closely parallel to the winds. Wherever two or more adjacent radial legs of the flight path showed higher or lower temperatures at about the same distance from the center that feature was carried through the data-void region between the observations. One cannot be certain that such extensive narrow belts of warmer and colder air really existed (the temperature changes could be as great along the wind as normal to the flow, for example), but it is the most reasonable synoptic scale interpretation of the weak temperature gradients which existed outside the eye region.

Near the eye the only questionable feature is the annular belt of lower temperatures coincident with the heaviest rain, which was mentioned earlier. At 800 mb. and 560 mb. the largest temperature gradients occurred just inside this cool zone and the highest temperatures were recorded just inside the cloud wall. At the lowest level the eye was essentially cloud-free inside the 17° C. isotherm, and at the intermediate level, inside the 3° C. isotherm. This tendency for the highest temperatures to occur in the clear air just inside the wall cloud has also

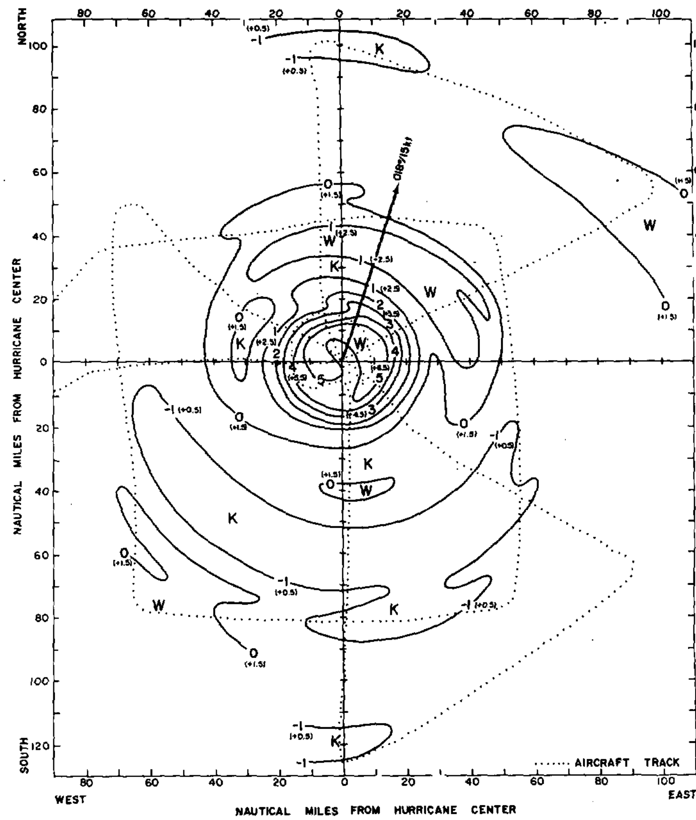

FIGURE 6.—Temperature analysis at 560 mb.

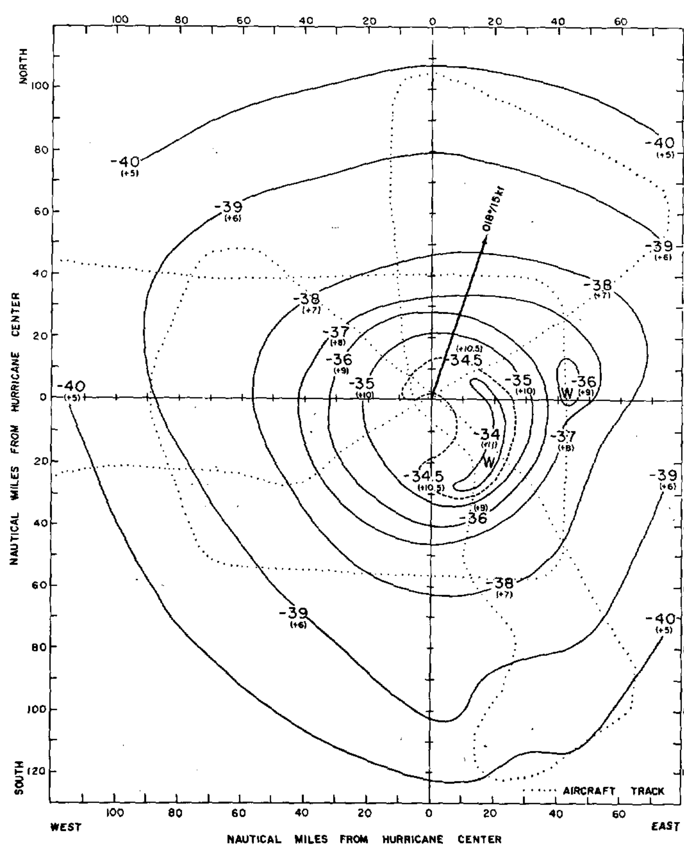

FIGURE 7.—Temperature analysis at 240 mb.

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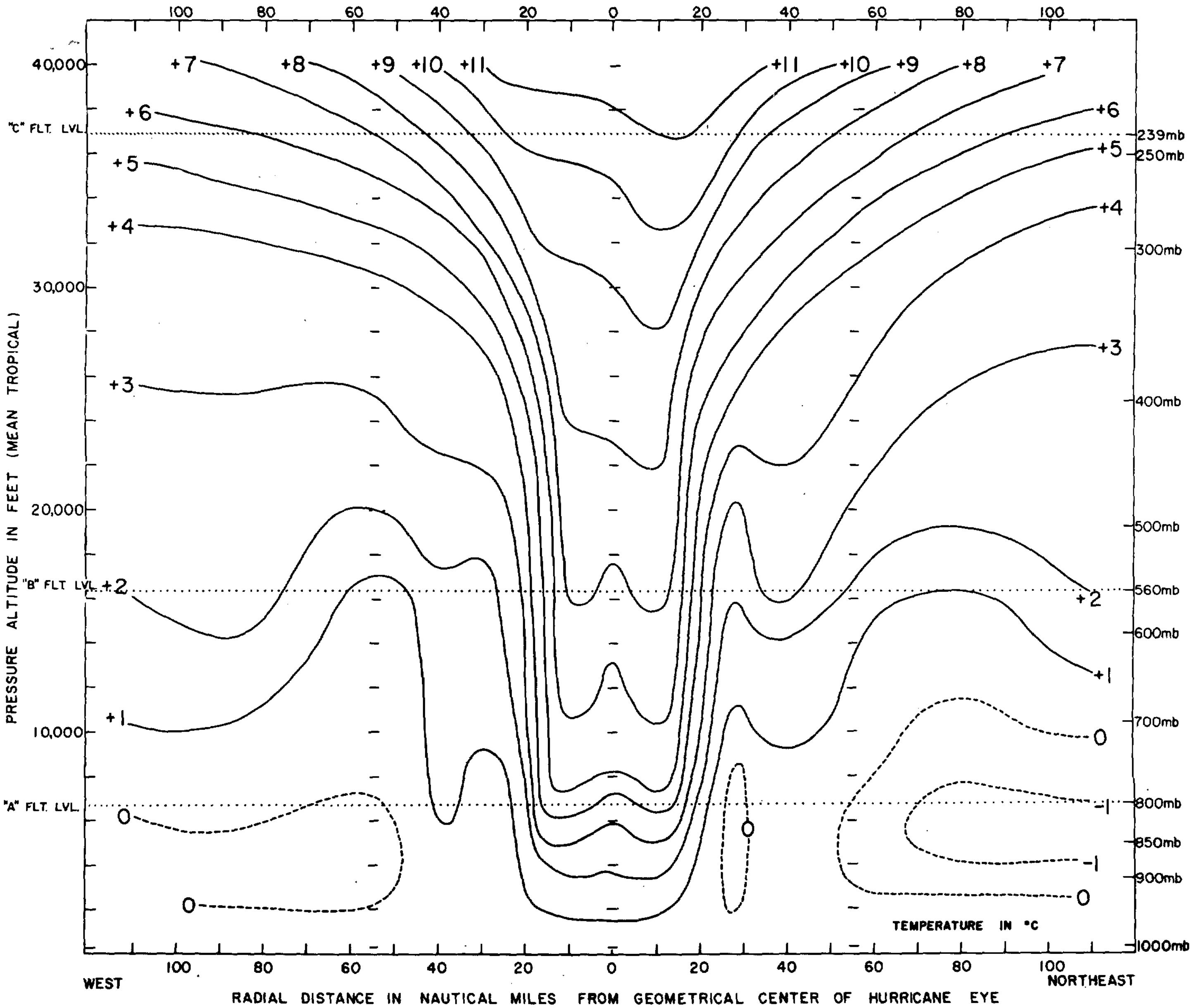

FIGURE 8.—Vertical cross-section of temperature anomaly from mean tropical atmosphere along first traverse of hurricane Cleo.

been observed at lower and intermediate levels in other hurricanes. At the highest level the maximum temperature gradients were less than at the lower two levels and occurred at a radius almost twice as large. Thus, the area of warmer air was approximately four times larger at the highest level than at the lower levels. The highest temperatures at this level occurred not in the clear air but in the cirrus overhang east and south of the eye.

It should be noted that two labels for each isotherm appear in figures 5, 6, and 7. The larger labels give the values in degrees Celsius and the smaller parenthetical labels give the anomaly of temperature from a standard tropical atmosphere typical of the hurricane season [6]. Note that at the two lower levels positive anomalies are confined mostly to the eye region and portions of the surrounding wall cloud. Both the magnitude and areal extent of the positive anomalies increase upward with the result that at the highest level one finds positive values everywhere within 120 n. mi. of the center, ranging in value from +5° C. to a maximum of slightly more than +11° C. This distribution of temperature anomaly from average tropical conditions will be stressed further in the vertical cross-section of temperature presented below.

The following procedure was used to prepare a vertical cross-section of temperature along a diameter of the storm. Temperature values at the three flight altitudes were first plotted vs. radial distance. Then, beginning inside the eye where supplemental dropsonde data below the 700-mb.

level were available from the Air Force reconnaissance plane, vertical temperature soundings were constructed from the surface to the upper flight level at intervals of 10 n. mi. radial distance, and in special regions such as the wall cloud. Admittedly, uncertainties exist in the construction of such soundings, but various techniques employed insured results which are reliable as to their principal features.

First, in addition to the three values available at each radius from the aircraft, the surface temperature was fixed at 25° to 26° C. by the sea surface temperature. In addition the constructed soundings were made to agree hydrostatically with the "D"-value data. In only one region was it impossible to obtain hydrostatic consistency between recorded temperatures and "D" values. This was in the region of heavy rain in the wall cloud which, it has been noted, coincided with temperatures near the minimum values recorded in the storm area. Neither the temperatures nor the "D" values have been altered in the analyses presented here, but it is our opinion that it is the temperature values which are in error. It is not possible to account for the hydrostatic departures on the basis of reasonable vertical accelerations. Thus, mean temperatures for the layers are correct (with one exception just discussed) and the temperatures at intermediate levels are in error only insofar as incorrect lapse rates were chosen for the layer.

From the surface to 800 mb. little error can result from lapse rates slightly in excess of the moist adiabatic; for the next layer (800 to 560 mb.) a smooth continuation of the lower lapse rate was found to fit the observed temperatures at 560 mb. and to give hydrostatic thicknesses consistent with the observed "D" values. The upper level (560 to 240 mb.) was the thickest and allowed greater subjectivity in the choice of lapse rates. At all radii, to obtain agreement with the observed temperatures at the highest level it was found necessary to construct lapse rates considerably less than moist adiabatic especially in the upper portion of the layer. It is possible that an actual stable layer (perhaps even an inversion) may have existed in the layer from about 400 to 300 mb. at the entrance to the layer of outflowing warm air aloft, but no attempt was made to incorporate such a feature in the constructed soundings. Rather, the lapse rate was continued in as smooth a manner as possible consistent with the observed temperatures and the hydrostatic thickness. With the use of these general principles it was found that different individuals constructed very similar soundings.

With the possible shortcomings of such a reconstruction in mind, the results for the first traverse of the hurricane are presented in figure 8 in terms of the anomaly of temperature from mean tropical values. There can be little doubt as to the main features shown by this diagram. Details such as the temperature minima at radial distances of about 30 n. mi. may be unreal as pointed out previously, and the distribution of temperature anomaly with height within the layers between aircraft data may differ slightly from the analysis of figure 8. However, the essential features of the anomaly pattern show no significant positive values below the 600-mb. level except inside the eye and the inner portion of the wall cloud, and an increase and horizontal spreading of positive anomalies with height, cannot be denied. Important consequences of this distribution in relation to the pressure field will be discussed in a later section.

The temperature anomalies shown in figure 8 must be produced by physical processes within the hurricane and at the air-sea interface which act upon air of initially average tropical characteristics. It is pertinent to inquire what insight can be gained into these physical processes, and their distribution within the hurricane, from considerations of the anomaly values and patterns.

The lack of significant positive anomalies below about 15,000 ft. outside the eye wall immediately eliminates the possibility of large amounts of moist-adiabatic ascent of surface air in that region. Such ascent would result in positive temperature anomalies at all radii of figure 8. Some such ascent does occur in the convective cloud bands, but its warming contribution is overwhelmed by mixing with the environment plus evaporational and contact cooling from falling rain. Thus, some negative temperature anomalies actually occur below the 700-mb. level beyond 50 n. mi. Significant positive anomalies first appear in the wall cloud, but even these are somewhat smaller than would result from moist-adiabatic ascent of surface air parcels. These departures from undilute moist-adiabatic ascent must be ascribed either to some degree of mixing or to the effects of contact cooling from falling rain. In the wall cloud region at the highest level the temperature anomalies are, however, consistent with the values to be expected from moist-adiabatic ascent of surface air parcels. It appears that two factors may contribute to the absence at the upper level of the observed departures from moist-adiabatic ascent noted at lower levels: first, most of the air at the upper level may have risen in undilute "hot towers" as suggested by Riehl and Malkus [7] either in the wall cloud or in outer convective bands; or, second, release of latent heat of fusion as a result of freezing of liquid water may have heated the air in the higher levels. Because of the lack of information on liquid water content above the freezing level, precise checks of this effect cannot be made. The spreading and decrease in positive temperature anomaly outward from the eye wall at the highest level is simply accounted for in terms of the outflow of air which has ascended with addition of latent heat in the eye wall. As the air flows outward the vertical extent decreases and, as it mixes with environmental air at this level, the temperature anomaly diminishes. Radiation losses may also be significant.

Inside the eye several additional factors must be introduced to account for the observed properties of the air. First, the observed high moisture content (presented in detail in the next section) rules out the possibility that

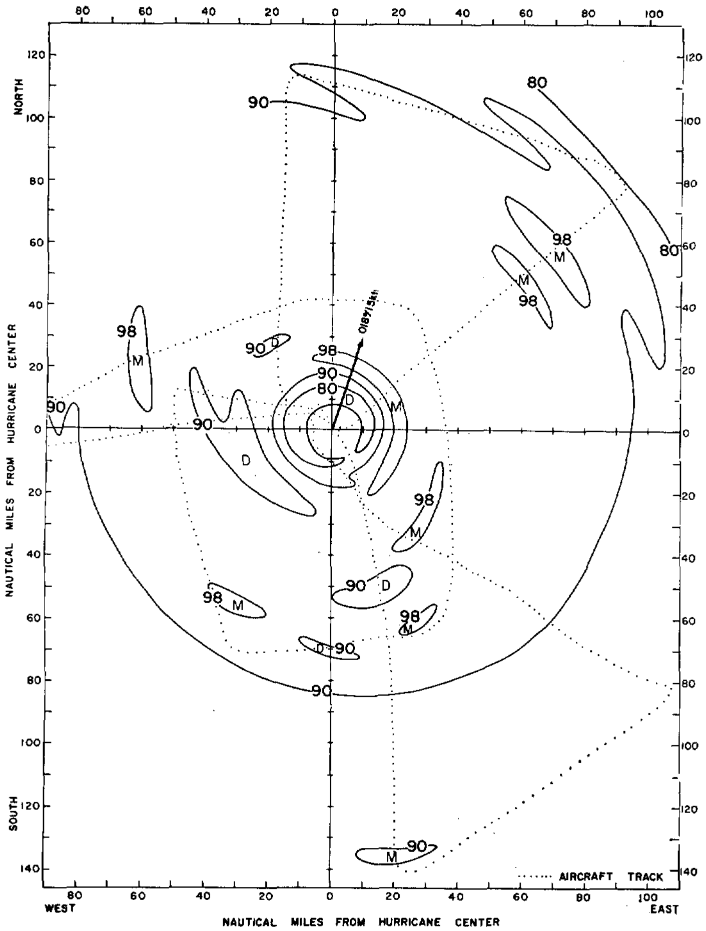

FIGURE 9.—Analysis of relative humidity at 800 mb.

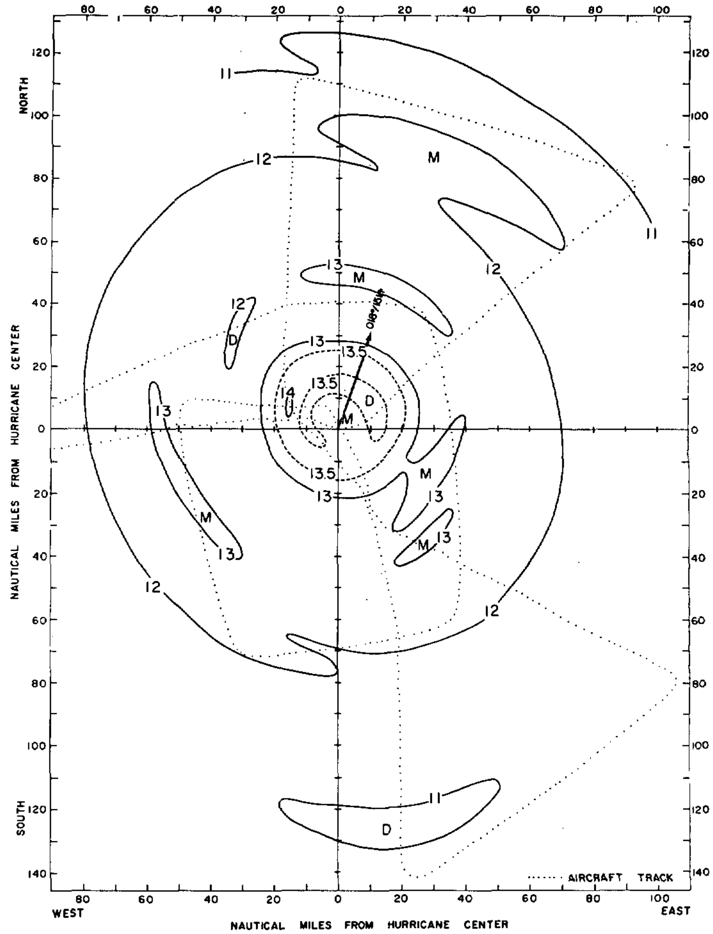

FIGURE 10.—Analysis of mixing-ratio at 800 mb.

this is solely air which has descended dry adiabatically from the upper troposphere. However, some dry adiabatic descent is required to explain the temperature anomalies in excess of values which could be due to moist adiabatic processes. The relatively cloud free condition inside the eye is, of course, the strongest evidence of descent. Qualitatively, then, the observed conditions of temperature and moisture inside the eye can be accounted for in terms of mixing of ascending cloudy air from the eye wall with unsaturated air within the eye, followed by re-evaporation of the liquid water contained in the wall-cloud air, which increases the mixing ratio and reduces the temperature of the mixture, but this cooling is more than compensated for by subsequent dry-adiabatic heating as the mixture descends. Malkus [8] has investigated this problem with certain simplifying approximations.

6. THE HUMIDITY FIELD

Of all data discussed in this report the humidity values are probably least reliable. The two lower-level aircraft were equipped with infrared hygrometers designed by the Instrumental Engineering Division of the U.S. Weather Bureau. These are accurate and reliable instruments when operated in the laboratory at surface pressures; however, serious problems arose in adapting them for airborne use. Voltage fluctuations in the aircraft power supply, reference drifts during flight, and questions as to the validity of ground calibrations when the infrared measurements are made at reduced pressures, all introduced uncertainties in the humidity measurements. In particular, many values indicated excessive super-saturation if evaluated from the laboratory calibrations. A semi-empirical method was used to evaluate the humidity values from the most reliable instrument which was carried on the low-level flight. After the effects of reference drift and voltage fluctuations were eliminated, insofar as possible, the values recorded in areas of heaviest cloud and rain were taken as saturated and all other values computed with reference to these. The results, converted to values of relative humidity and corresponding values of mixing ratio, are displayed in figures 9 and 10. As might be anticipated, relative humidities were quite high everywhere in the storm at this level. The lowest values (~75 percent) occurred in the clear portion of the eye, surrounded by the strongest gradients culminating in saturated conditions in the wall cloud. *Note that* although the lowest relative humidities occurred inside the eye, the highest values of mixing ratio also occurred there

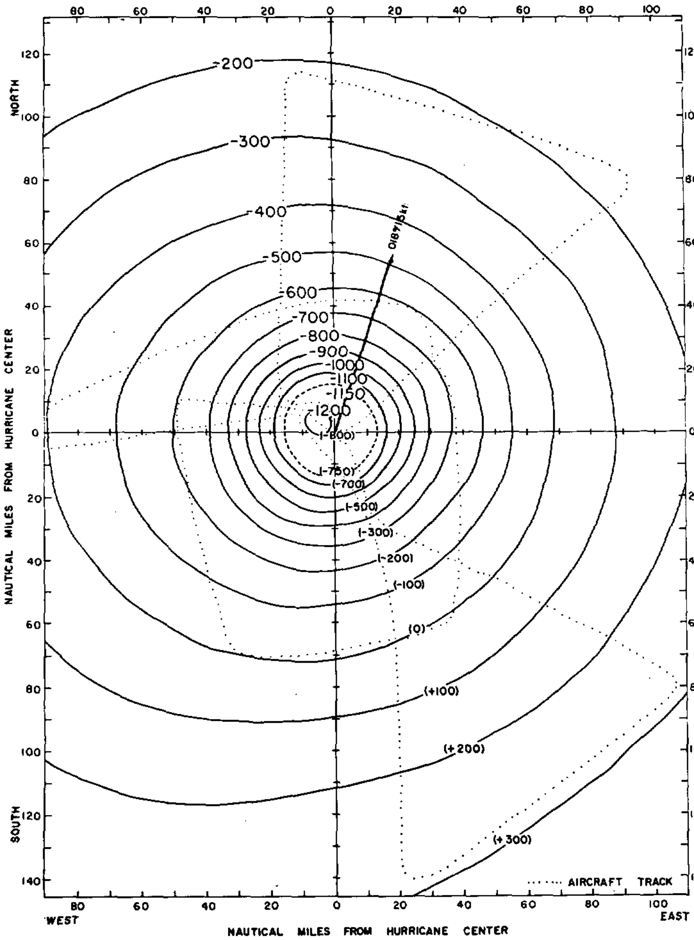

FIGURE 11.—Analysis of D values at 800 mb. Large labels indicate departures from mean tropical atmosphere, smaller parenthetical labels indicate departures from NACA standard atmosphere.

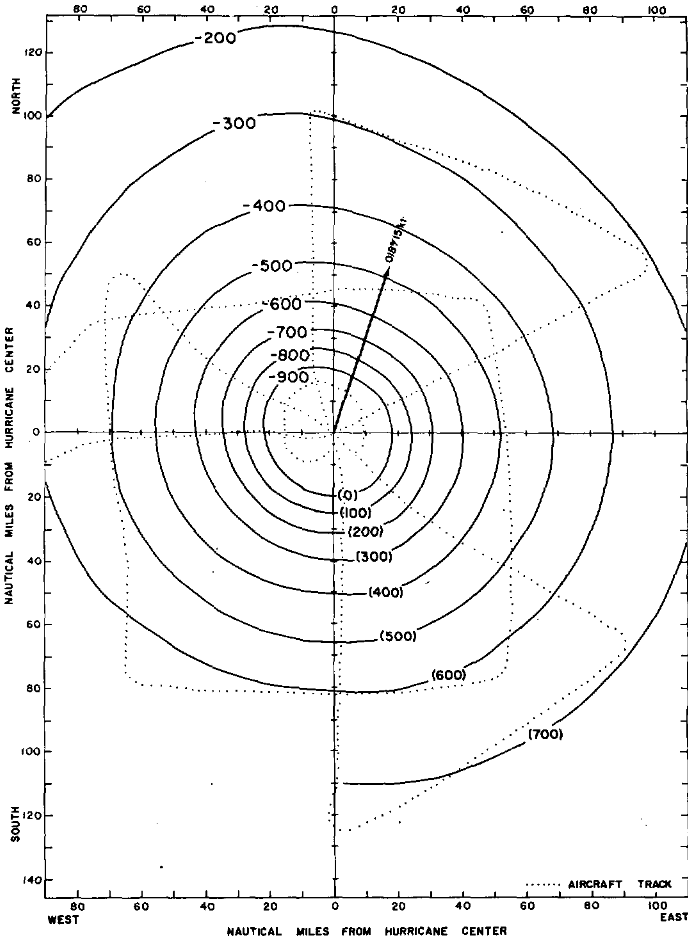

FIGURE 12.—Analysis of D values at 560 mb.

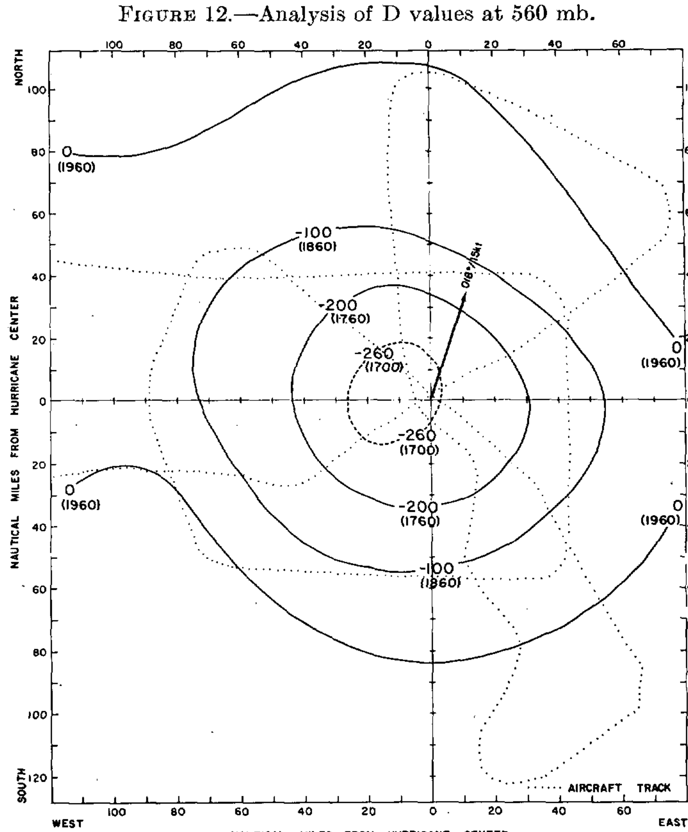

FIGURE 13.—Analysis of D values at 240 mb.

in association with the highest temperatures. Similar results (not reproduced) were found at 560 mb., but with a lower degree of confidence. No humidity data were available from the highest aircraft. It may be noted that although these uncertainties exist in the humidity values, they introduce little error into the hydrostatic computations mentioned earlier.

7. THE PRESSURE FIELD

Pressure data were obtained in the form of "D" values computed from the difference between simultaneous indications of pressure and radio altimeters. Since the former are calibrated in terms of the NACA Standard Atmosphere, the initial D values represent anomalies of pressure-height from that standard, which is highly inappropriate for average tropical conditions. Consistent with the treatment of the temperature field, the initial D values were converted to departures from the same Tropical Standard Atmosphere [6] used above.

Although it is presented and discussed separately here, the reader will realize that the analysis of the D-value data was closely related to that of the temperature field

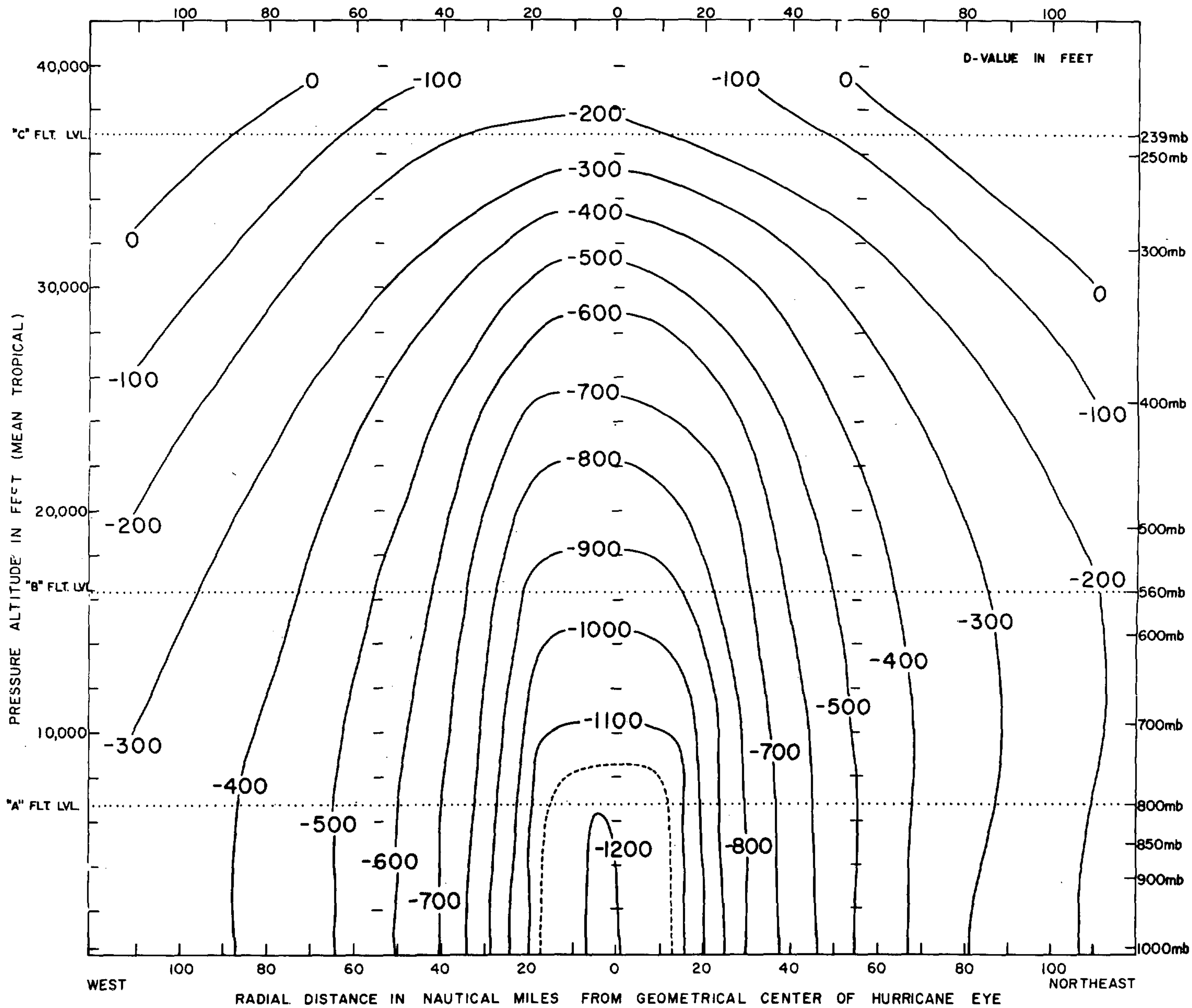

FIGURE 14.—Vertical cross-section of D values (from mean tropical atmosphere) along first traverse of hurricane Cleo.

through the hydrostatic relationship. As an example, it was found that the D values computed hydrostatically for the intermediate level were systematically lower than the recorded values. Since the D values at the lowest level were consistent with the independent dropsonde data it was decided that the recorded values at the intermediate level were systematically high, due probably to an incorrect calibration of the pressure altimeter, and a constant correction was applied at that level to bring the values into hydrostatic agreement. This, of course, in no way changes the D-value gradients. The initial recorded D values at the highest level exhibited minor irregularities which, because of the small gradients at that level, would have introduced several questionable details in the distribution if analyzed independently of the hydrostatic check. After the hydrostatic computations were made these features were smoothed out.

Analyses of the hydrostatically consistent D-value fields at the three flight levels are presented in figures 11, 12, and 13. The patterns are quasi-circular within about 120 n. mi. of the center and quite symmetrical about the center. The minimum values do not coincide with the geometric center of the eye but are systematically displaced sightly ahead and to the left. This displacement is largest at the highest level. Analogous displacements of the cyclonic singularities in the wind field occurred at each level. As would be expected, the largest negative departures of pressure-height from average tropical conditions occurred in the eye at the lowest level. These negative values decreased outward and upward, but became positive only beyond 80 to 100 n. mi. from the center at the highest level. The strongest gradients occurred in the region of the wall cloud at the two lower levels, coinciding with the strongest winds.

As an aid in visualizing the vertical structure of the pressure-height field, a vertical cross-section along the first traverse of the hurricane was prepared from the recorded D values and hydrostatic calculations from the vertical temperature soundings constructed earlier. The results are shown in figure 14.

Several interesting aspects of the hydrostatic relationship between the temperature anomalies (fig. 8) and pressure-height anomalies (fig. 14) may now be pointed out. It is generally agreed, though, as yet, not adequately verified by observations, that conditions at high levels above the hurricane (probably a little higher than the 100-mb. level) remain essentially undisturbed. On this premise, it is easily seen that, hydrostatically, the anomaly of the height of any lower pressure surface (D value) is proportional to the negative of the average temperature anomaly of the layer between that pressure surface and the undisturbed level. Thus, the large negative D values at the surface in the eye result from the positive temperature anomalies which are greatest in the upper troposphere. Furthermore, the gradient of D values in the lower layers is due to the spreading of the upper outflowing warm air and the outward decrease in temperature anomaly. The magnitude of the inward-directed pressure gradient of the inflow layer is thus determined by the characteristics of the warm air in the outflow layer; these characteristics, in turn, are primarily determined by the initial thermodynamic properties of the air in the inflow layer plus the physical processes which act upon it as it flows inward and then upward primarily in the eye wall cloud. The reader will recognize the interesting possibilities of "feedback" relationships in such a system. Further observational and theoretical work is needed to clarify these relationships, which must have a bearing on the questions of hurricane motion and formation as well as structure.

8. THE WIND FIELD

Flight-level wind data recorded on these flights are part of the information derived from the automatic navigation system (Air Force nomenclature AN/APN–82). Calibration flights and other checks show that such winds are comparable in accuracy to those obtained from standard rawinsonde equipment.

These wind data were analyzed in two ways: (1) the field of motion with respect to the earth (the actual wind), and (2) the field of motion with respect to the hurricane moving as a permanent-type system (the relative wind). The latter field, obtained by subtracting vectorially the motion of the hurricane from the former, removes all features of the field of motion which may be associated solely with the translation of the storm. Other properties of the wind field such as divergence, vorticity, and deformation remain unchanged by this subtraction. The complete isogon-isotach technique of wind analysis was carefully applied to both fields. Only very slight smoothing was required.

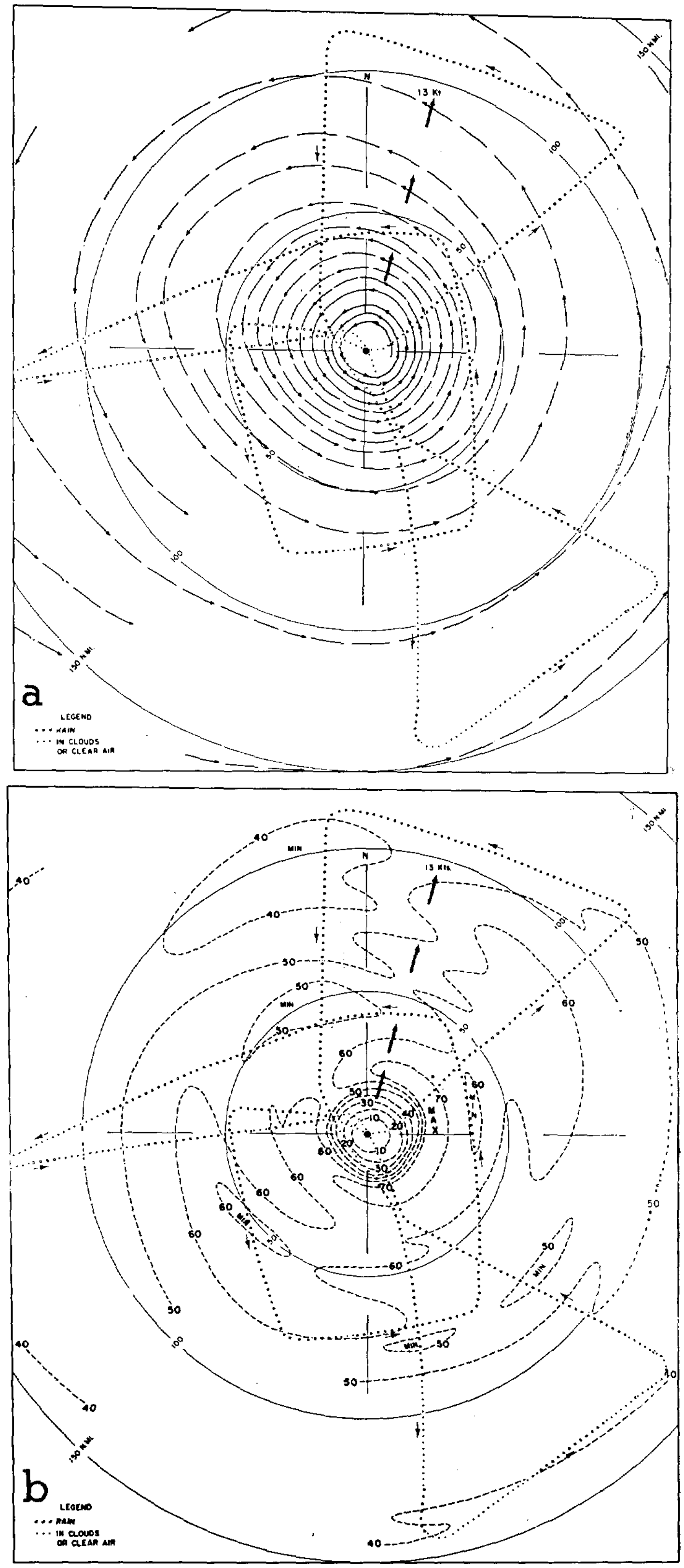

FIGURE 15.—(a) Relative streamlines at 800 mb. (b) Relative isotachs at 800 mb.

Consideration of available space precludes the illustra-

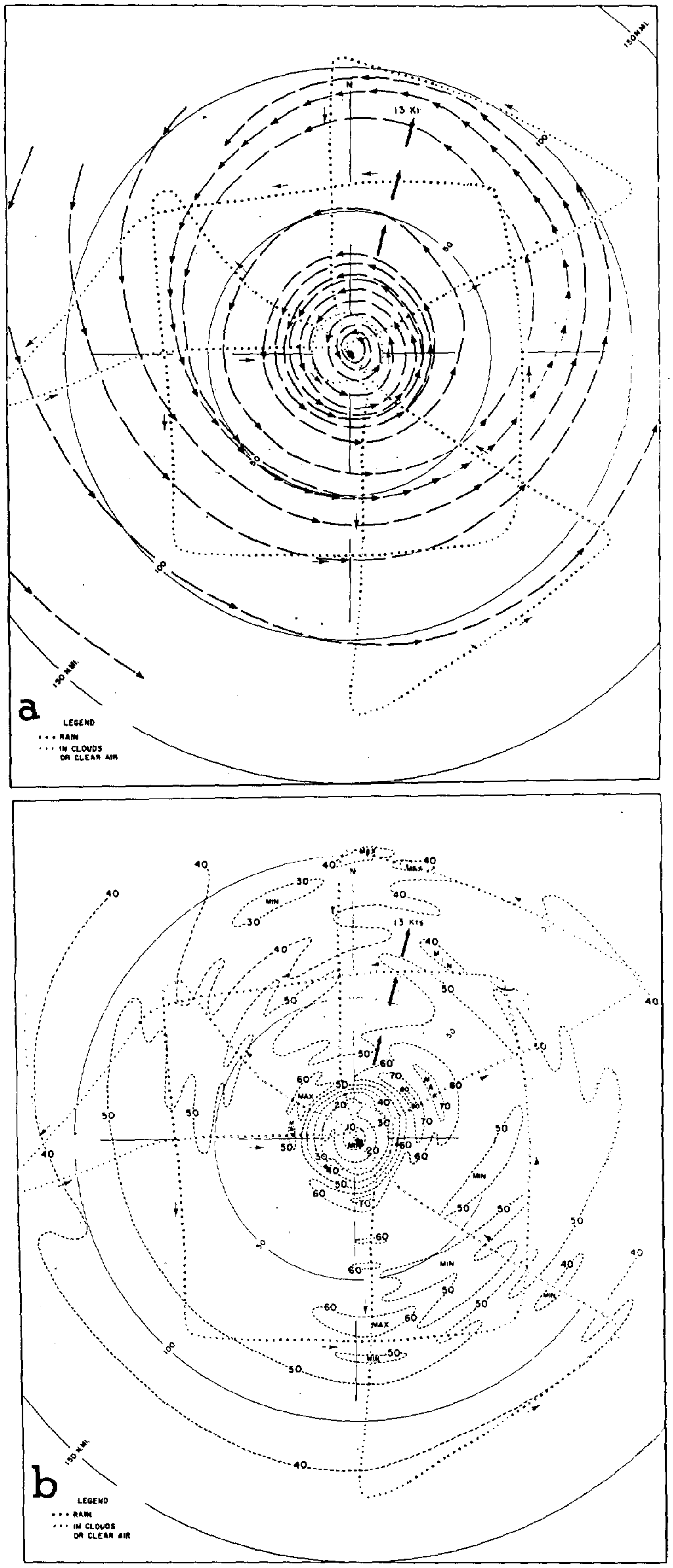

FIGURE 16.—(a) Relative streamlines at 560 mb. (b) Relative isotachs at 560 mb.

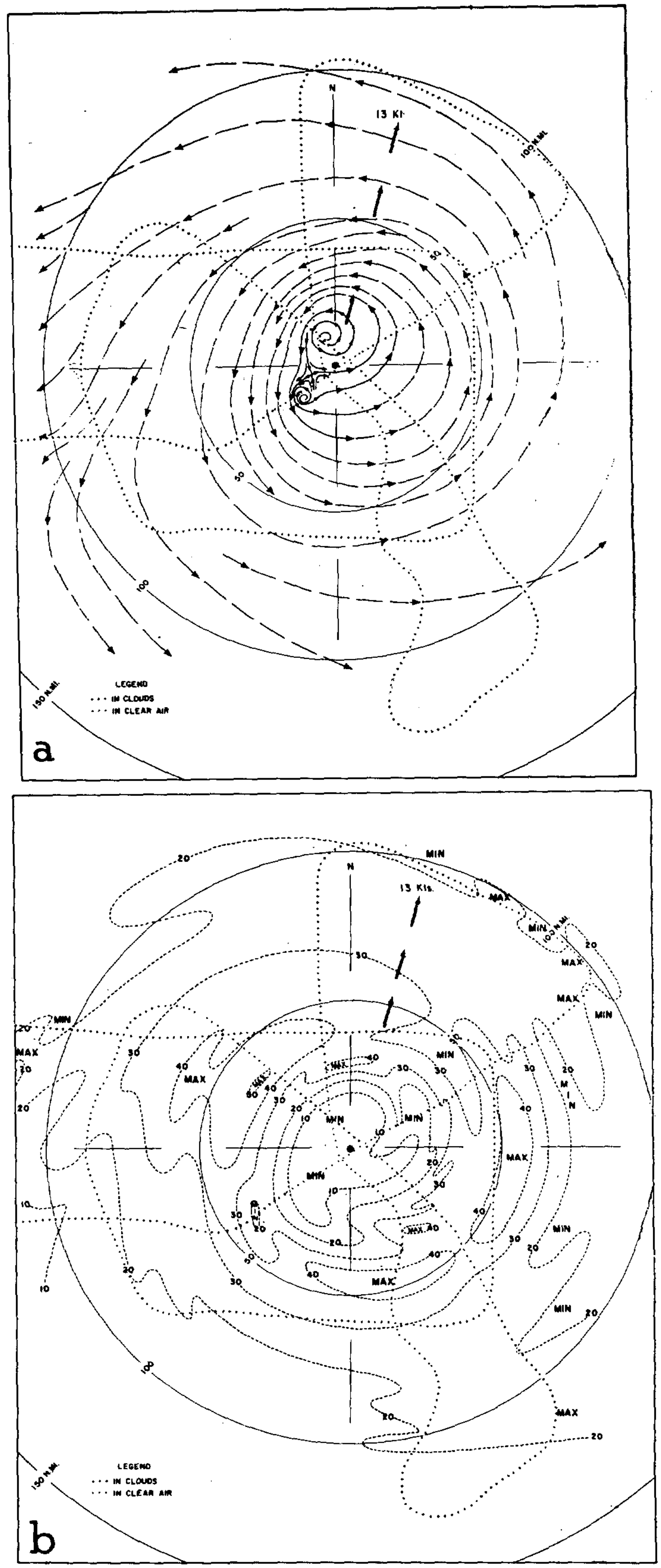

FIGURE 17.—(a) Relative streamlines at 240 mb. (b) Relative isotachs at 240 mb.

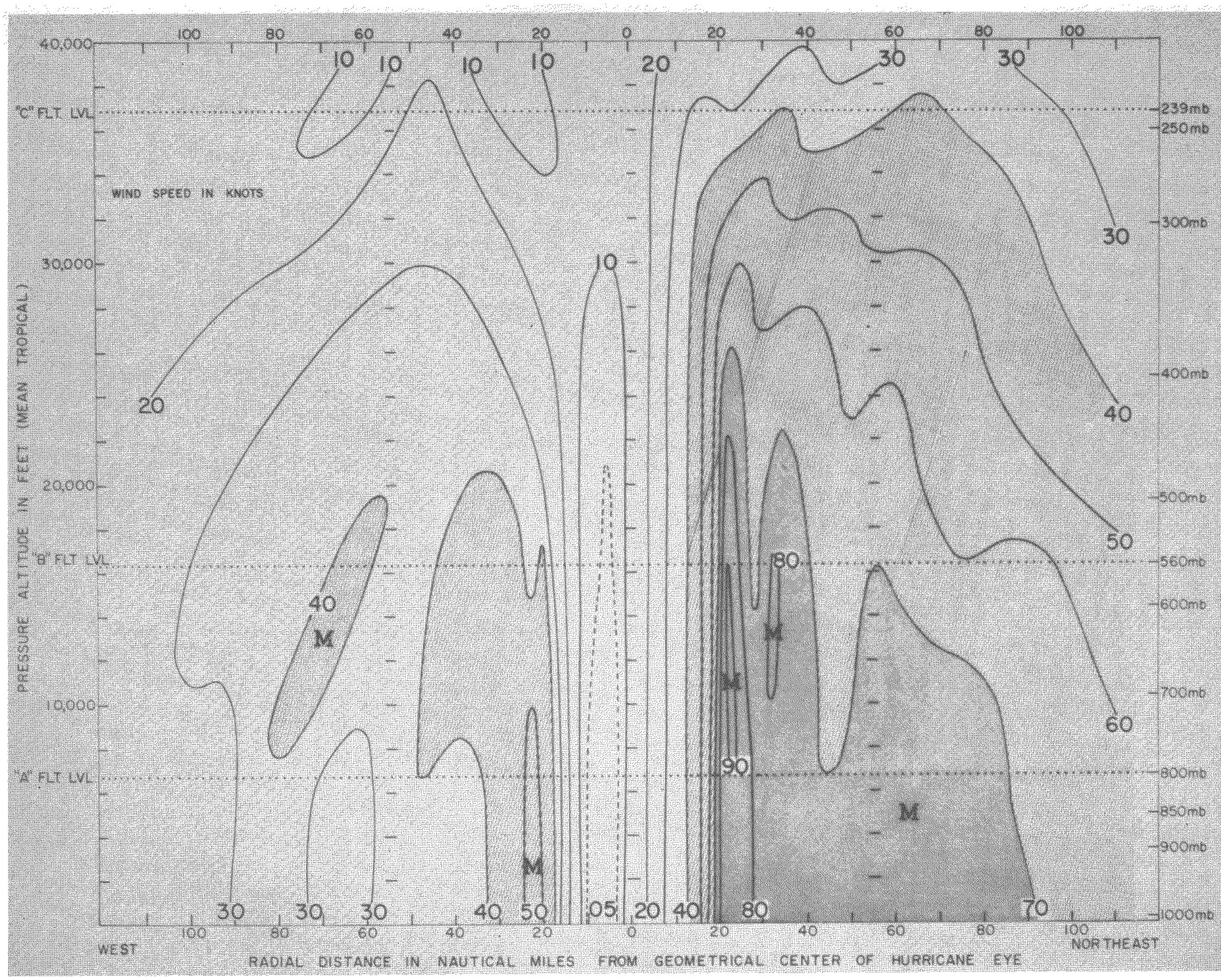

FIGURE 18.—Vertical cross-section of total wind speed (kt.) along first traverse of hurricane Cleo.

tion of all these analyses together with the auxiliary charts from which they were derived. The relative winds are perhaps a better measure of the hurricane as a perturbation, since effects of translation are eliminated, revealing the motion of the air with respect to the storm. Figures 15, 16, and 17 illustrate the relative wind fields at each flight level. Superimposed on the dominant tangential component of the flow was a small, but systematic, radial component. Maximum inflow occurred in the left-rear portions at the lowest level; this diminished upward, virtually disappearing at the highest level. Outflow was greatest in the right-front section, spreading over nearly all of the storm in the upper troposphere. A residual asymmetry appears in the relative speed field with stronger speeds to the right of the storm. The maximum speeds occurred at a larger radius at the upper level than at the two lower levels.

The characteristics of the actual wind fields may be visualized qualitatively by mentally adding to the relative winds a field of translation equal to the velocity of the storm. In general, this increases the inflow in the rear sector of the storm and the outflow ahead. Also, the degree of asymmetry in the speed field is increased with higher speeds to the right. This latter effect is illustrated by figure 18 which shows a vertical cross-section of the total wind speeds along the first traverse of the hurricane.

Relation of wind and pressure fields.—The degree of asymmetry in the wind field, especially in the speeds, may seem surprising, at first sight, in view of the highly symmetric pressure field. Since considerable confidence may be placed in these independent analyses, it was decided to test the consistency between the two. The test was carried out mainly at the lowest level where confidence in the data and their analysis was greatest, but the results are believed to be valid for the other levels as well.

For horizontal, frictionless motion, the balance of forces normal to the wind may be expressed,

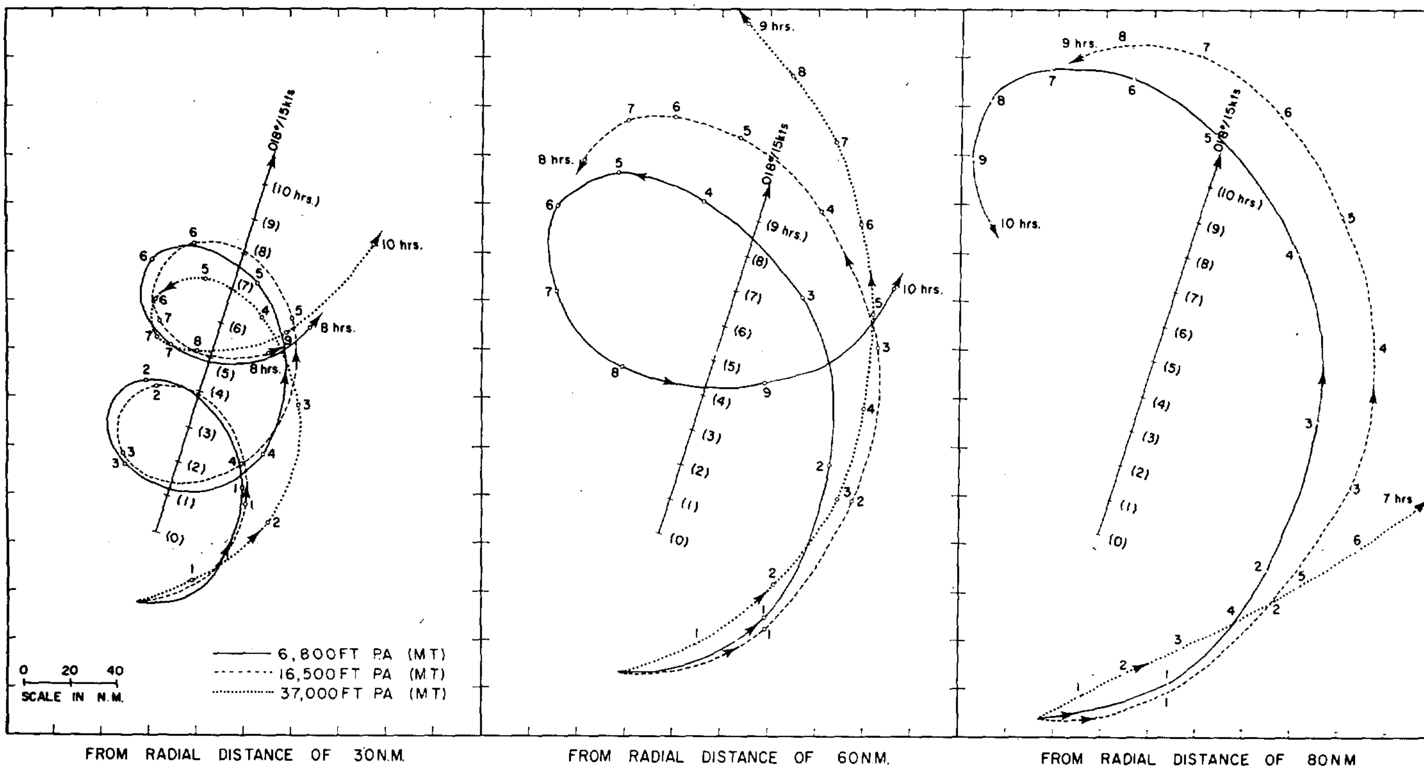

FIGURE 19.—Actual trajectories of air from initial positions to rear of storm.

$$K_T V^2 + fV = fV_g \cos \psi \qquad (1)$$

where K_T is the trajectory curvature, V is the wind speed, f is the Coriolis parameter, V_g is the geostrophic wind speed, and ψ is the angle between V and V_g. The most difficult quantity in (1) to measure is K_T. However, for a permanent-type system the problem is simplified greatly.

In that case, with the neglect of a small term involving the curvature of the normals to the streamlines, we may write

$$K_T = K_s \left(1 - \frac{c \cos \gamma}{V}\right) \qquad (2)$$

in which K_s is the streamline curvature, c is the speed of the system, and γ is the angle between the wind velocity and storm velocity. All quantities on the right-hand side of (2) can be evaluated from isogon-isotach analyses of the actual wind to yield values of K_T.

An alternate method which depends upon the same approximation of a permanent-type system was also used. When translation is added to the relative streamlines (which are also relative trajectories in this case), actual trajectories with respect to the earth are obtained. K_T may then be evaluated from these trajectories. Values of K_T measured from such families of trajectories agreed closely with the field distributions obtained from the first technique.

Figure 19 illustrates several actual trajectories of air from initial positions behind the hurricane at each level. The larger curvatures to the left of the storm are immediately apparent in this diagram. The quantitative effect of differences in K_T from the left to right sides of the hurricane will be illustrated by a sample calculation at the lowest level for a radius r=25 n. mi. Calculated values of K_T are 1/33 n. mi. to the right and 1/17 n. mi. to the left. It may be noted that this difference partly results from variations in K_s, which is smaller to the right than to the left due to inflow components in the rear of the storm versus outflow to the front, and partly from the effects of storm motion as expressed in (2). The slope of the 800-mb. surface evaluated as a finite difference over 10 n. mi. centered on r=25 n. mi. is 200 ft./10 n. mi. on both the right and left sides. The corresponding value of geostrophic wind is nearly 800 kt. Because $\psi \approx 0$ both to right and left of the center, solutions to (1) give values of the gradient wind, in this case 81 kt. to the right and 59 kt. to the left. The corresponding actual winds were about 85 and 53 kt. respectively. Similar computations at other radii and azimuths give analogous results.

Thus, the gradient wind is a good approximation to the actual wind since $\psi < 20°$ (actually the cyclostrophic wind is nearly as good because the Coriolis term is small). This statement is not in disagreement with the results of Gray [9], who studied the distribution of radial acceleration in hurricanes by means of a method which does not depend upon field analyses. His results show inward accelerations to the left and outward to the right of the center of a magnitude which, for the most part, correspond to a departure of actual from gradient winds of only

10–20 percent. Wind speeds at the lower level computed from (1) using values of K_T obtained by the above methods, and values of the right-hand term obtained from the pressure and wind analyses, agreed with the observed winds within the probable errors of the computation. This implies that the winds were nearly in gradient balance with the pressure field (actually nearly in cyclostrophic balance as the Coriolis term is small), since the crossing angle ψ did not exceed 20°. To the extent that any pattern of deviations from gradient flow could be detected, it was consistent with that reported by Gray [9]; that is, winds tended to be subgradient to the left and supergradient to the right of the storm.

Though small in magnitude, the pattern of ψ is consistent with the implied accelerations. The air accelerates toward lower pressure-heights in the left-rear sector, reaches maximum speeds on the right-hand side of the storm, then decelerates toward higher heights and lower speeds in the right-front sector. The asymmetry in the speed field is due mostly to the variation of trajectory curvature, although the smaller asymmetry of the pressure field contributes in the correct sense. Myers and Malkin [10] have discussed this same problem, but attribute the effect mostly to the asymmetry of the pressure field.

9. SUMMARY AND CONCLUSIONS

Although various consistency checks and careful analysis techniques were employed in the evaluation of these data, it is apparent that more than three aircraft would be useful for research reconnaissance. Especially needed are more observations in the surface boundary layer (1000–1500 ft.), and in the high troposphere and low stratosphere.

It is believed that the following general conclusions are justified by this study:

1. Only a small fraction of the total storm volume contains convective-scale vertical motions; the most significant area of this kind being the central eye structure, including the wall cloud.

2. The distribution of temperature anomalies from average tropical values suggests they are produced mainly by processes in this central eye region.

3. The pressure-height anomalies from average tropical values are largest in the lower troposphere where temperature anomalies are smallest. This difference in relative distribution suggests interesting interactions between the temperature and pressure fields.

4. The wind field appears to be in quasigradient balance with the pressure field. The much larger asymmetry of the wind than of the pressure distribution is associated with variations in trajectory curvature around the storm.

The degree to which these conclusions are valid for hurricanes in general depends upon the extent to which this hurricane is typical. It is not possible to assess this exactly, but it is suggested that the conclusions are qualitatively applicable to mature hurricanes with well developed eye structures.

ACKNOWLEDGMENTS

Such a data collection program necessarily involves many people. To the Air Force crews, who operated the planes; to the flight technicians, who monitored the instruments and data recording in flight; and to the ground-support personnel for all equipment, we express our gratitude. Most of the staff of NHRP was involved in some part of the data reduction and analysis; to them we also express gratitude. Special thanks are due to S. Pearce, S. Gilbert, and D. Rubsam for their contributions.

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