ON THE STRUCTURE OF HURRICANES IN THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE[1]

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ABSTRACT

A synoptic study of a number of hurricanes at the time of landfall is described with particular reference to the thermal and wind structure in the upper troposphere and lower stratosphere. It is shown that the low pressure core of the mature hurricane, before recurvature, extends not only throughout the troposphere but sometimes protrudes into the lower stratosphere up to about 27 km., the upper limit of this investigation. The upper core is found to be cold above 15 km. with temperatures occasionally 8°–10° C. below normal at the tropopause level. A peripheral ridge and a peripheral jet in the upper troposphere are described, and the possible role of these features, as well as of the cold core, in the hurricane mechanism is discussed. It is suggested that the cold core may be caused by forced ascent above the well-known warm core of the hurricane.

It is also shown that a hurricane which has recurved and become embedded in the extratropical westerlies may not have an upper cold core and its structure closely corresponds to the classical model.

Tentative schematic models of the distribution of temperature and height anomalies are indicated in the case of a mature hurricane before recurvature.

1. INTRODUCTION

The structure of hurricanes from the surface up to about 200 mb. (12 km.) has been fairly well established, thanks to the extensive reconnaissance by research aircraft during the past decade. Our knowledge of conditions above 12 km. is, however, sketchy and inadequate. It is generally assumed that the inward pressure gradient in the hurricane core reverses sign at some level between 150 mb. and 100 mb.; that the cyclonic vortex disappears above this level; and that the flow remains practically undisturbed aloft. Palmén's [10] investigation of the thermal structure of hurricanes was based upon radiosonde ascents taken at coastal stations when a hurricane crossed the Florida coast in 1946. His model of a warm core, with the tropopause bulging slightly upward over the core, has received fairly general acceptance.

Simpson [18, 19] was the first to point out that "in the upper troposphere, the core of the storm tended to be colder than the outer vortex." His findings were also based upon radiosonde ascents made in the eyes of two hurricanes which crossed Florida's coast in 1944 and 1946. He noticed, in a reconnaissance flight in hurricane Edna 1954 [19], that the streamers from a sheet of cirrostratus circled cyclonically in a broad spiral to a singular point at the center of the eye, indicating convergent cyclonic inflow even at the cirrus level.

Jordan and Jordan [5], in their study of the mean thermal structure of tropical cyclones, found a general increase in the height of the tropopause toward the central region of the storm, a progressive decrease in tropopause temperature with increase of tropopause height, and a fairly constant potential temperature. Their mean radial height profile at 100 mb. indicates a decrease in height toward the core, at this level.

Izawa [3], who made a study of the mean typhoon using wind data from 14 storms, found that though the cyclonic circulation diminishes with height, it persists in the typhoon core as a weak vortex even at 18 km., the upper limit of his investigation.

A photographic mission into the eye of typhoon Ida in September 1958 by a U–2 aircraft revealed the spectacular features of the cloud structure in hurricanes up to a level of 65,000 ft. (19.8 km.) which were discussed by Fletcher, Smith, and Bundgaard [2]. A research probe into hurricane Ginny up to 21 km. was made by a U–2 aircraft on October 22, 1964, and was studied by Penn [11]. The aircraft flew over the eye at levels of 50 mb., 115 mb., and 200 mb., and made a descent into it to about 300 mb. Although the eye region was 5°–6°C. warmer than the distant environment below 220 mb., the horizontal gradient of temperature and ozone became very weak just above the cloud tops at 190 mb. The upper troposphere over the storm appeared to be slightly colder than the coastal environment. Another U–2 probe made into hurricane Isbell in October 1964, was also studied by Penn [12] who found that the tropopause was inclined

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[1] Research conducted under ESSA grants nos. 29 and 67.

[2] On leave of absence from the India Meteorological Department.

upward into the eye and cloud-tops were found extending to 68 mb. (19 km.) to the north side of the storm.

There is thus some evidence that the hurricane affects the circulation even in the stratosphere and that it is sometimes colder than its surroundings at the top of the troposphere, instead of being warmer throughout its vertical extent. Reconnaissance into hurricanes at a number of levels above 200 mb. would provide more definite information of their structure in the upper levels. It may, however, be possible, even at this stage, to get some indication of the upper-level structure from the rawinsonde ascents made by coastal stations during the landfall of hurricanes. A synoptic-aerological study was therefore made, of the thermal and wind structure of hurricanes which crossed the United States coast during the past 10 years. Some of the results of this investigation will be presented in this article. Fuller details are given in a separate report (to be issued as an ESSA Technical Memorandum).

2. DATA AND ANALYSES

Checked rawinsonde data published by the U.S. Weather Bureau, as well as daily teletypewriter sequences, were used for the investigation. Three-hourly rawinsonde ascents made at stations affected by the hurricanes were particularly helpful in revealing short-period changes. Data were available to about 30–20 mb. (24–26 km.) in most cases.

Conventional analyses were made at various standard levels from the ground up to 25 mb. in each hurricane during different stages of development and movement. Vertical cross-sections were constructed across the storm at or near the instant of landfall. These were supplemented by graphs showing the variation with time of height and temperature at standard pressure levels at individual rawinsonde stations.

As considerable variations of temperature and wind sometimes occur in short periods, it was not found advisable to adopt compositing techniques over extended periods for these techniques may result in smoothing and in the elimination of significant singularities. Reliance was, therefore, placed on deductions based upon variations of different parameters in short periods at individual stations as well as on relevant synoptic maps. Constant-pressure maps were found useful in detecting and following small-scale Lows and Highs. Heights and their anomalies indicate the relative intensity of these features which it is not possible to determine otherwise. The horizontal sections discussed in this report refer to synoptic maps at constant-pressure surfaces.

A sample of four hurricanes in decreasing order of intensity and extent has been chosen for discussion, relating to their structure at the stage of maximum or near maximum intensity at the time of landfall. In the case of hurricane Arlene (1963), the analysis refers to a stage after recurvature when it passed over the island of Bermuda in the Atlantic Ocean.

The description and discussion are qualitative and no attempt has been made to obtain quantitative results at this stage.

3. STRUCTURE OF HURRICANE CARLA, 1961

Hurricane Carla, which struck the central Texas coast at about 2100 GMT on September 11, 1961, was the largest and most intense in the series examined in this investigation. Its lowest central pressure, as determined by aircraft reconnaissance, was 931 mb. A low pressure of 935.3 mb. was reported at Port Lavaca, Tex., at 2210 GMT, just before the instrument needle went below the scale. Peak gusts were estimated to be 175 m.p.h.

The center of the hurricane was located about 70 mi. east of San Antonio, Tex., at 1200 GMT on the 12th. It was at its maximum intensity at landfall but still remained at hurricane intensity as it approached San Antonio.

VARIATION OF HEIGHT, TEMPERATURE, AND WIND AT DIFFERENT PRESSURE LEVELS

Figure 1a shows the variation of height, temperature, and wind at San Antonio, Tex., at different standard pressure levels as the center of the hurricane passed near the station.

The following features are noticed:

(i) Heights of pressure surfaces (geopotentials) decreased at all levels as the center of the hurricane passed near the station. The curves indicate that the low pressure near the core must have extended up to about 27 km., the limit up to which observations are available.

(ii) Heights of pressure surfaces fell by about 150 m. at all levels between 200 and 70 mb. and by 250 m. at 50 mb. during the passage of the center. The height falls in the stratosphere were as large as in the lower troposphere.

(iii) Heights of pressure surfaces above 500 mb. increased from 1200 GMT on the 8th to 1200 GMT on the 9th and remained fairly constant until 0000 GMT on the 12th, after which there was an abrupt fall as the center passed near the station. The fall was more gradual in the stratosphere commencing from 1200 GMT on the 10th. There was a rapid rise at all levels between 0000 GMT on the 13th and 1200 GMT on the 14th after the storm had moved away from the station. The humps in the height curves indicate the passage of a possible peripheral ridge surrounding the hurricane core.

(iv) Temperature increased at all levels up to 125 mb. (15 km.) with the approach of the core and decreased thereafter. The maximum rise of about 5°C. occurred at 200 and 150 mb. Temperatures decreased at all levels above 125 mb. with the approach of the storm and increased thereafter. The drop was about 10°C. at 100 mb.

(v) The height of the tropopause rose gradually with the approach of the center of the storm and remained high for about 3 days after the passage of the storm. Tropopause temperature correspondingly decreased with the approach of the storm. The total fall was about 10°C.

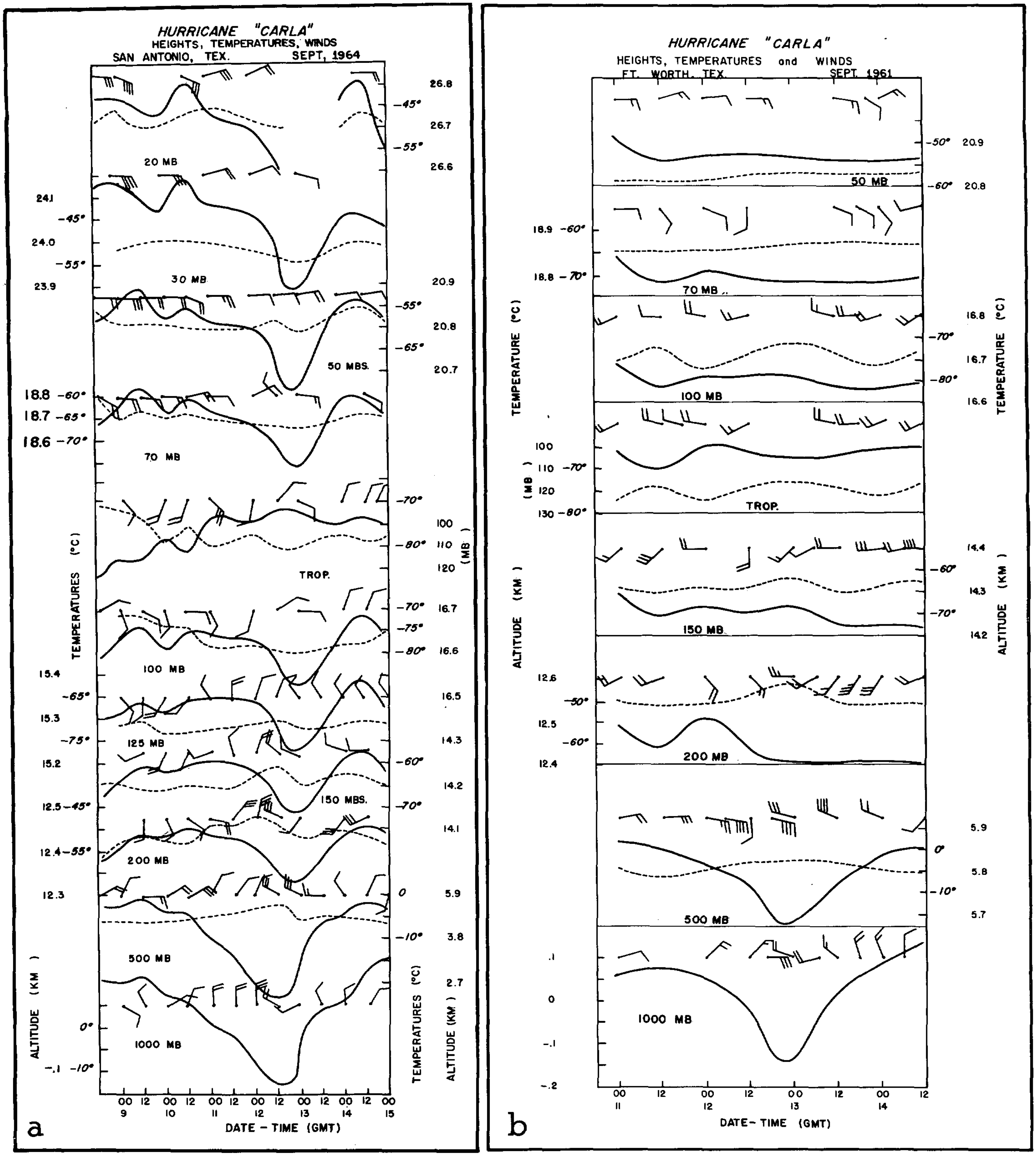

FIGURE 1.—Variation of height, temperature, and wind at standard pressure levels and at the tropopause during the passage of hurricane Carla, September 1961. (a) at San Antonio, Tex., and (b) at Fort Worth, Tex. Solid lines = heights, km. (mb. at tropopause). Dashed lines = temperatures (°C.).

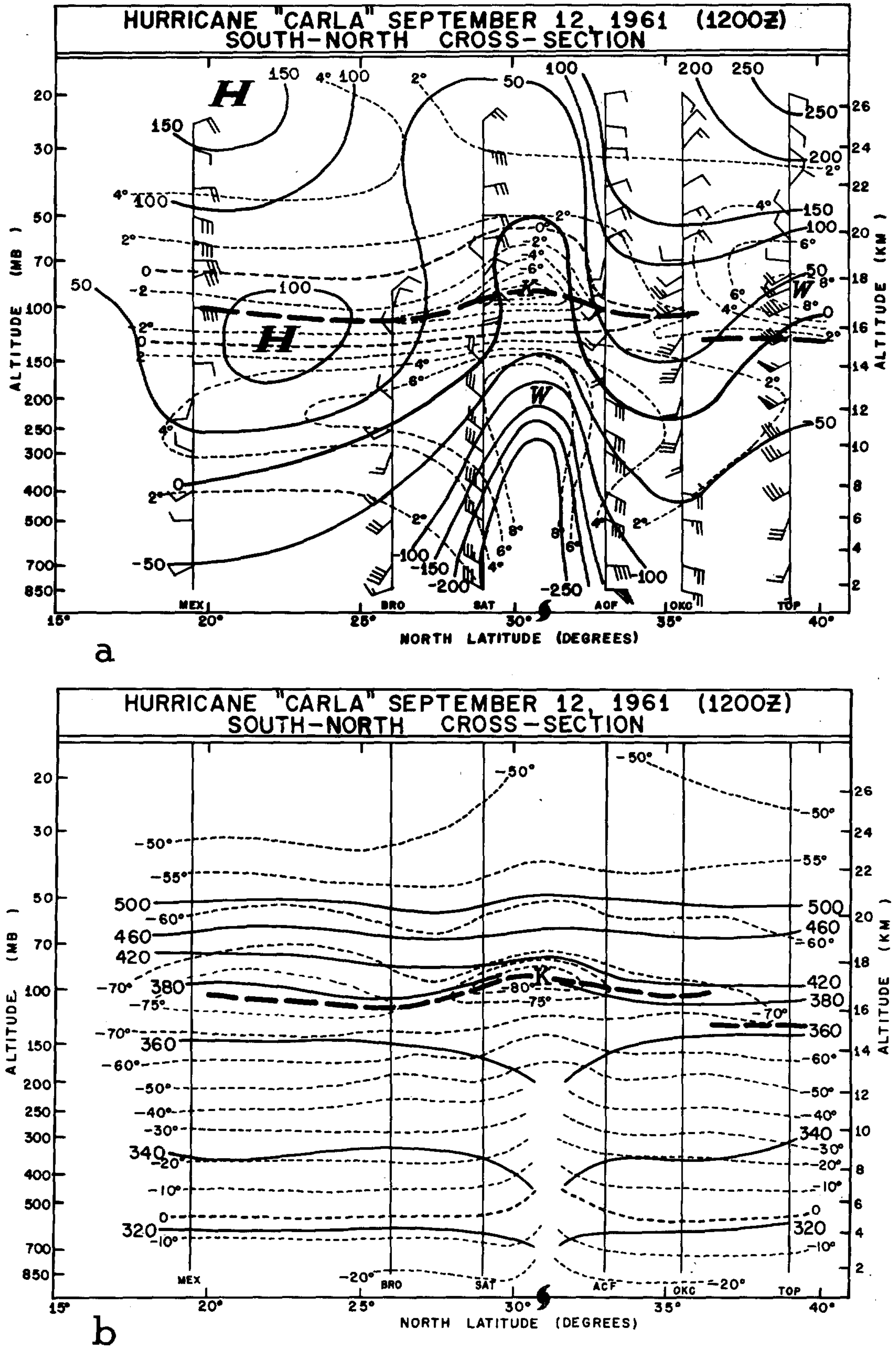

FIGURE 2.—South-to-north vertical cross-section across hurricane Carla along 97°W., September 12, 1961, 1200 GMT. (a) Solid lines = height anomalies (meters); dashed lines = temperature anomalies (°C.); thick dashed line = tropopause. (b) Solid lines are isentropes (°K.); dashed lines, isotherms (°C.).

(vi) Wind changes with height generally reflected the contour variations to about 70 mb. The cyclonic wind vortex appears to have extended to about 70 mb. (19 km.). Anticyclonic wind shifts occurred during the passage of the peripheral ridges. At 50 mb. there were no significant wind changes although heights fell sharply. This was probably due to the fact that the hurricane weakened as it passed over land near San Antonio. It is seen from curves for Fort Worth, Tex. (fig. 1b), near which the center of the hurricane passed at 0000 GMT on the 13th, that there was no fall of pressure surfaces at the station above 200 mb. Heights were fairly uniform in the stratosphere at 100 mb. and above. It appears that the stratospheric Low at 50 mb. and aloft, suggested by the height falls at San Antonio on the 12th and 13th, remained to the south of the station and filled without passing to the north of it. Consequently winds at 50 mb. and above did not change at the station, although the heights rose during the weakening stage of the hurricane.

VERTICAL CROSS-SECTIONS

The vertical cross-sections along roughly the 97° W meridian across the hurricane at 1200 GMT on September 12 are given in figures 2a and b. Figure 2a gives the anomalies of heights and temperatures computed from Jordan's [4] mean West Indies atmosphere for September. Figure 2b gives the isotherms and the isentropes for the same cross-section. Figures 3a and b present similar details in the vertical cross-section in a west-to-east direction, roughly along latitude 30° N. Data at the nearest stations have been projected to the appropriate meridian or parallel. Where data are missing at any station at the upper levels, the data at the nearest station have been used. The following large-scale synoptic features are evident.

(i) The low-pressure core [3] of the hurricane extended to the upper limit of the cross-section—about 27 km.

(ii) Height anomalies were generally negative below 8–10 km. with magnitudes exceeding 250 m. in the core. They rapidly decreased with height in the core to nearly zero at about 20 km. above which they were positive but less than 50 m. Positive height anomalies occurred outside the core above 8–10 km. The greatest positive anomalies in the upper troposphere were about 100 m. and occurred in the peripheral ridge between 14 and 16 km. (fig. 2a).

(iii) Temperatures were above normal in the hurricane up to about 125 mb. (15 km.). They were below normal aloft between 16 and 20 km. The zone of below normal temperatures extended horizontally to the southern limit (20° N.) of the cross-section (fig. 2a) and there was a sharp cutoff at about 35° N. In the E-W cross-section they extended over a broad band from 88° W. to 107° W. The highest positive anomalies exceeding 8° C. occurred near the core region between 10 and 12 km. Highest negative anomalies, also exceeding 8° C., occurred in the core near the tropopause (17 km.). Positive anomalies extended outside the core between 8 and 16 km. The core remained colder than its surroundings from 16 to 20 km. The temperature distribution indicates a warm core up to about 15 km. and a cold core aloft.

(iv) Isotherms bulged upward near the warm core up to about 15 km. (fig. 2b). A cold pool with temperatures of −80° C. or lower existed between 16.5 and 17.5 km. Isotherms bulged upward near the upper cold core.

(v) Isentropes sloped downward in the tropospheric core and bulged slightly upward near the stratospheric core. The tropopause was nearly isentropic, with a potential temperature of about 380° K. A layer of nearly constant potential temperature existed in the core just below the tropopause.

(vi) The tropopause bulged upward near the core and was coldest there (−80.5° C.). It sloped up by about 2 km. from the peripheral ridge to the center of the hurricane.

(vii) Winds near the core were disturbed up to about 19 km., indicating that the cyclonic wind vortex might have extended up to 19 km. Aloft, stratospheric winds were mainly easterly with slight changes in direction and speed. The low pressure area in the core seems to become diffuse above 20 km. and probably lay as an extended Low to the south of San Antonio.

HORIZONTAL SECTIONS

Figure 4 gives the contours and isotherms at standard pressure levels from the surface to 70 mb. (19 km.) and isobars and isotherms at the tropopause level at 1200 GMT on September 11, 1961, when the hurricane was out at sea and was at its maximum intensity. The maps represent conditions 24 hr. earlier than the vertical cross-section in figures 2 and 3. The corresponding vertical cross-sections have not been reproduced as they were essentially similar to those in figures 2 and 3. These synoptic maps reveal only large-scale features.

The lower troposphere.—In the lower troposphere (figs. 4a and b) the cyclonic circulation had a diameter of about 1,000 mi. and was surrounded by a diffuse ridge. It was warm, as usual, with temperatures near the core 5°–7°C. above normal [4] at 500 mb. The eye temperature was probably 12°–13°C. above normal at this level, judging from aircraft measurements of 12°C. at 620 mb.

The eye of the hurricane was about 15 mi. across, as determined by aircraft reconnaissance. Wind speeds at the eye-wall were nearly 100 kt. and gradually decreased to 55 kt. at 100–150 mi. from the center. They continued to blow at 50 kt. up to 300 mi. from the center. Persistence of high wind speeds over a considerable area was a prominent characteristic of this hurricane.

The upper troposphere.—The diameter of the cyclonic vortex diminished, as usual, with height but the low pressure area near the core persisted throughout the upper troposphere (figs. 4c–f). The peripheral ridge surrounding the core extended inward and upward with height. The outer rim of the peripheral ridge was located about 1,000 mi. away from the center and lay almost above the axis

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[3] The term "core" used in this article refers to the central region of the storm, surrounding the eye. No conclusions are drawn regarding the characteristics of different parts of the core, such as the eye, the eye-wall, etc., because of the synoptic nature of the data used.

[4] The term "normal" in this article refers to the monthly West Indies normal of Jordan [4] and not to the normal conditions at the station or locality where the storm was actually located.

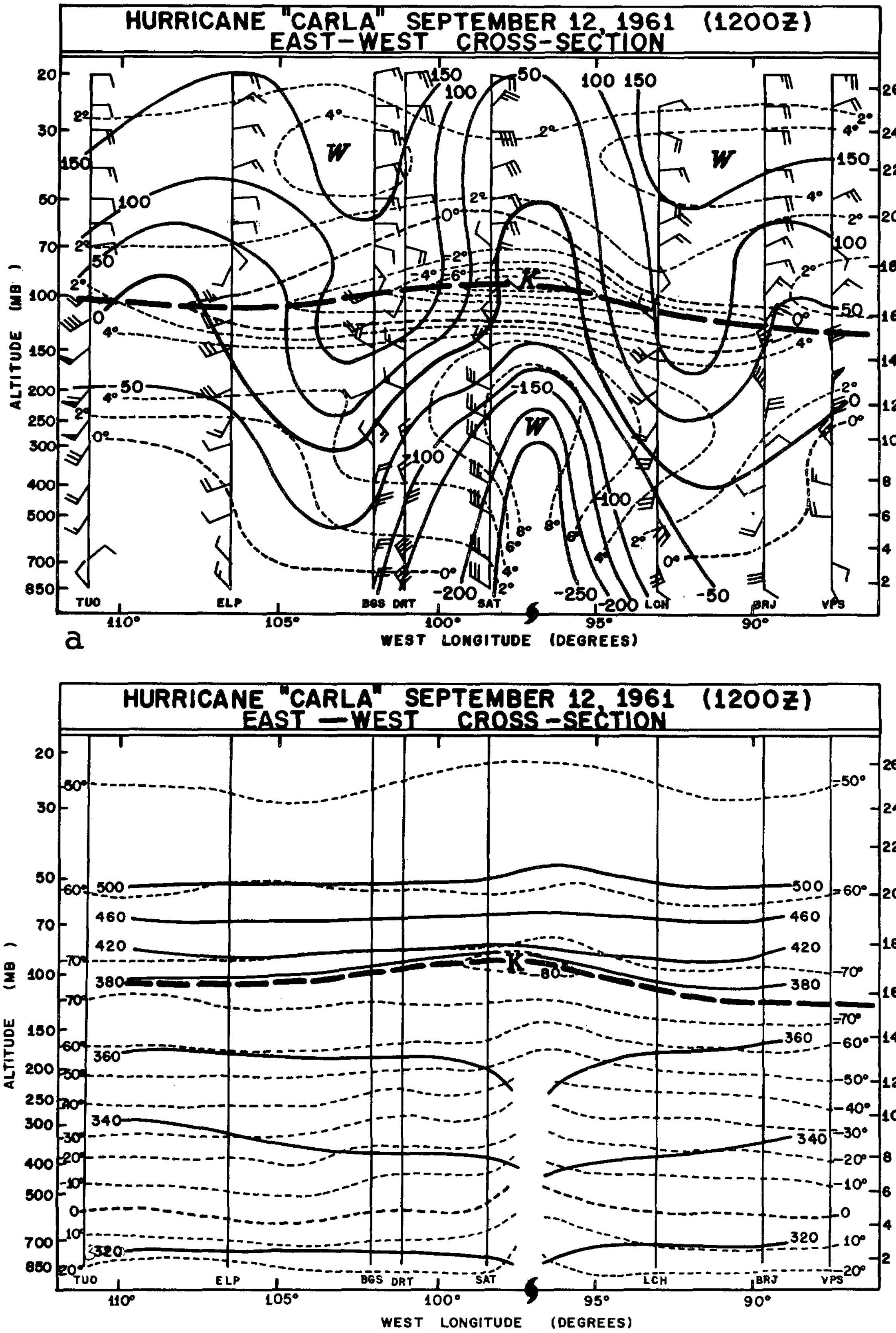


FIGURE 3.—(a) West-to-east vertical cross-section along latitude 30°N. during passage of hurricane Carla, September 1961.

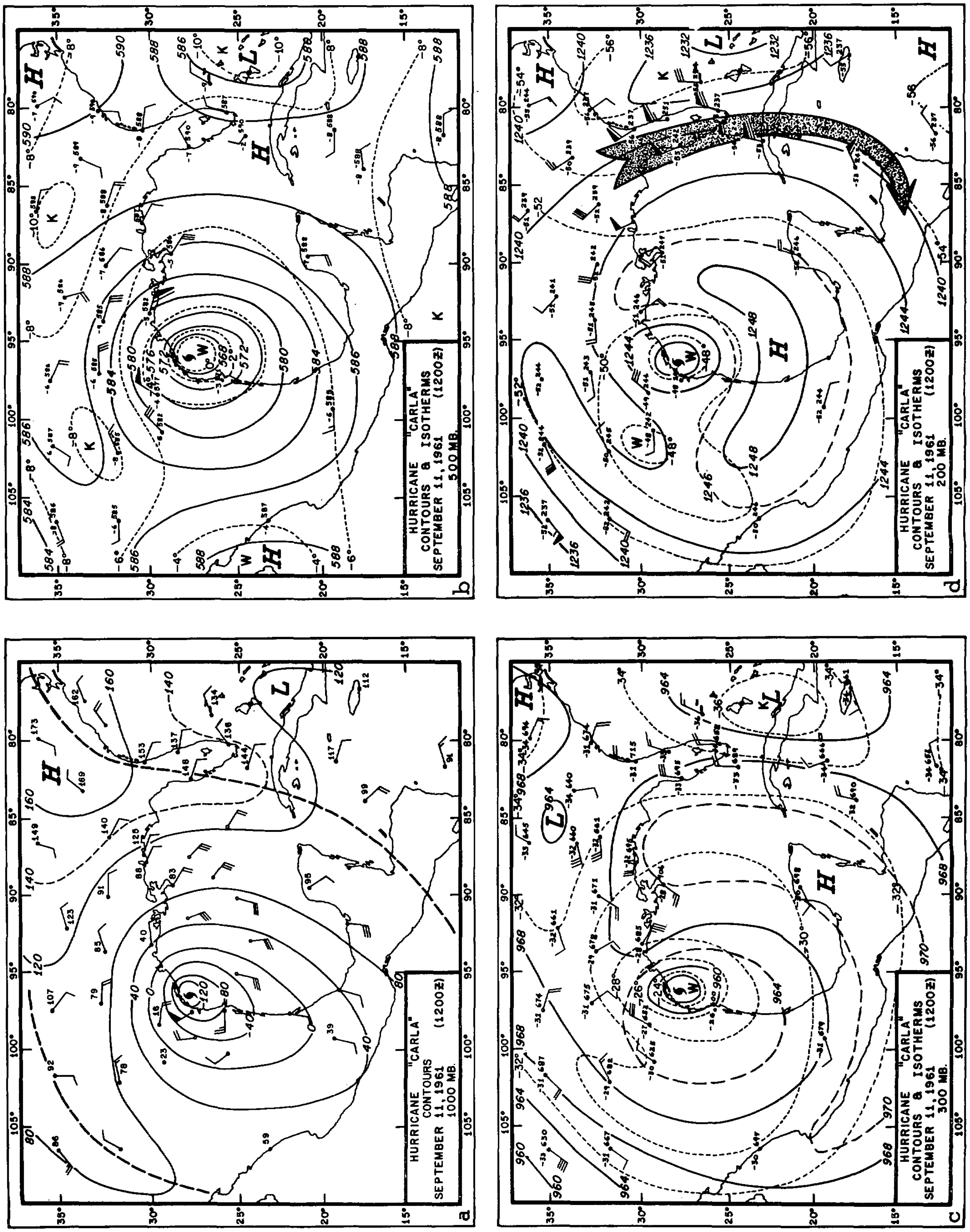
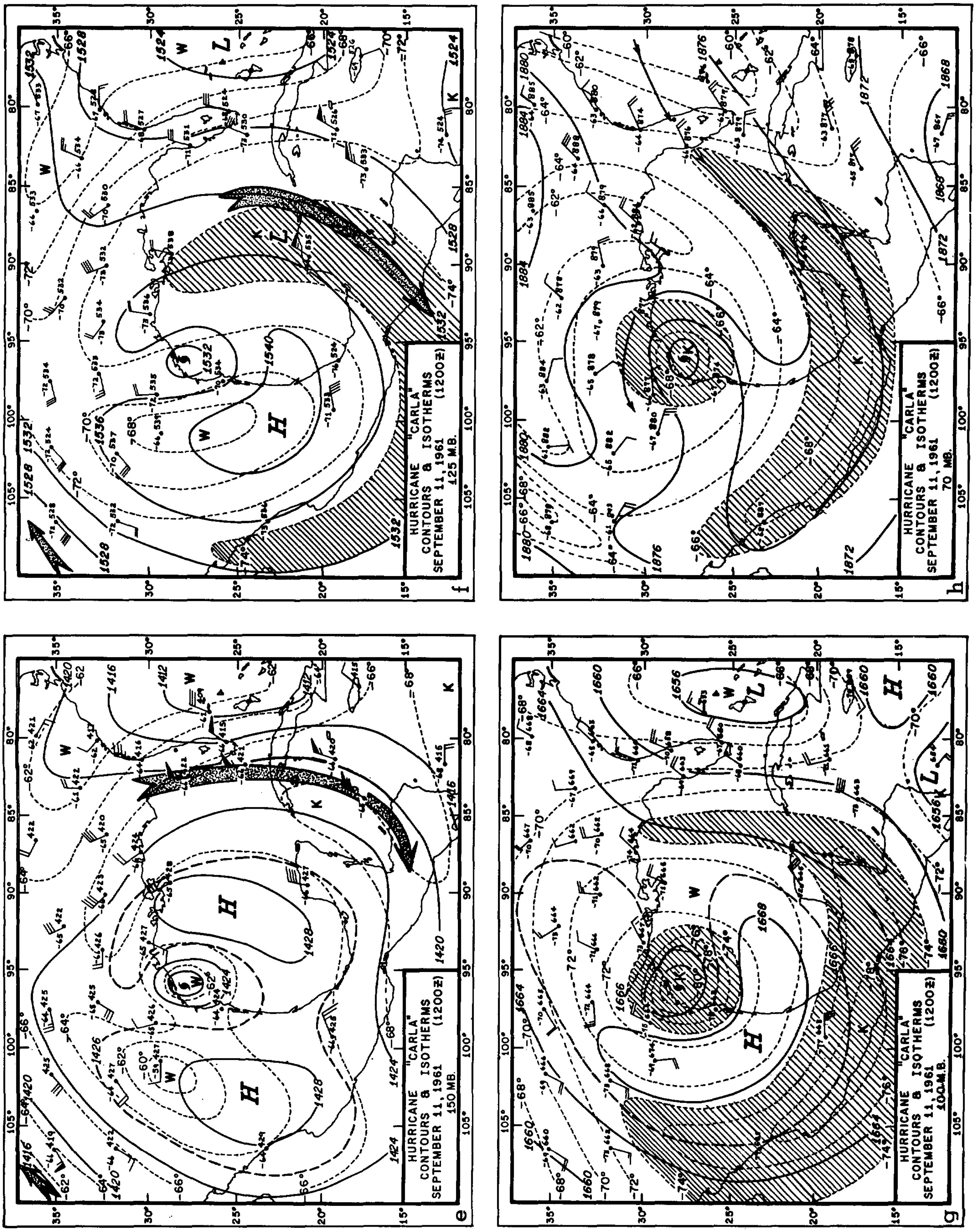


FIGURE 4.—(a)-(d). (Continued; see page 549 for caption.)



HURRICANE "CARLA" CONTOURS & ISOTHERMS SEPTEMBER 11, 1961 (1200Z) 150 MB.

HURRICANE "CARLA" CONTOURS & ISOTHERMS SEPTEMBER 11, 1961 (1200Z) 125 MB.

HURRICANE "CARLA" CONTOURS & ISOTHERMS SEPTEMBER 11, 1961 (1200Z) 100 M.B.

HURRICANE "CARLA" CONTOURS & ISOTHERMS SEPTEMBER 11, 1961 (1200Z) 70 MB.

FIGURE 4.—(e)-(h). (Continued; see page 549 for caption.)

of the diffuse ridge surrounding the hurricane at the surface.

Temperatures were above normal in the entire hurricane circulation (core as well as ridge) up to about 150 mb. Those near the core were 6°–8°C. above normal. Temperatures decreased outward, near the rim of the peripheral ridge, between 300 and 200 mb. (figs. 4c–d) and the gradient reversed with height aloft. Consequently, strong winds with speeds of 60–70 kt. developed at the outer rim between 200 and 150 mb., particularly to the east and northwest.

While the wind speeds diminished rapidly with height near the core, they increased to jet intensities at the outer rim of the peripheral ridge.

The level of reversal of thermal properties in the hurricane was 125 mb. (about 15 km.). Temperatures were neither high nor low near the core at this level. A warm pool was located to the left of the core (facing the direction of motion of the storm) at this level and a cold pool to the right (fig. 4h). Isotherms over the central part of the hurricane were oriented roughly parallel to the direction of motion.

The lower stratosphere.—The core of the hurricane was still in the troposphere at 100 mb., while the rest of the circulation was in the stratosphere. Figures 4g and h illustrate the structure at 100 mb. and 70 mb., respectively. The low-pressure area near the core expanded considerably at 100 mb. and was slightly elongated along the direction of motion of the storm. The upper tropospheric peripheral ridge persisted at 100 mb. but merged with the stronger seasonal ridge near the United States at 70 mb. and aloft. Normal stratospheric easterlies prevailed at 50 and 25 mb., except possibly near the vicinity of the core of the storm where low pressures persisted.

The thermal structure at 100 and 70 mb. was spectacular. The hurricane core was cold, with temperatures below normal by 6°C. or more at 100 mb. It was surrounded by a ring of above normal temperatures beyond which lay another ring of colder air along the southern rim of the peripheral ridge.

The tropopause surface.—Figure 4i illustrates the topography (mb.) and temperatures (°C.) at the tropopause level. The tropopause surface bulged upward over the central region of the hurricane; the tropopause dome was surrounded by alternate rings of low and high tropopause. The central dome sloped from 15 to 17 km. over a distance of 250–300 mi.

The central dome was cold, with temperatures of −82°C. or lower near the core. The temperature increased by 10°C. at the outer rim of the tropopause dome. The alternate rings of high and low tropopause were associated with low and high temperatures, respectively. Temperatures of −80°C. or lower also occurred in the southern part of the peripheral ridge. The temperature pattern closely resembled that at 100 mb. (fig. 4g).

The wind flow at the tropopause surface was anticyclonic except possibly near the core. The peripheral jet

FIGURE 4.—Contours and isotherms at standard pressure levels and at the tropopause level in hurricane Carla, September 11, 1961, 1200 GMT. Solid lines = contours in tens of meters (mb. at tropopause); dashed lines = isotherms (°C.). Cold area in the hurricane is hatched. (a) 1000 mb. (b) 500 mb. (c) 300 mb. (d) 200 mb. (e) 150 mb. (f) 125 mb. (g) 100 mb. (h) 70 mb. (i) tropopause.

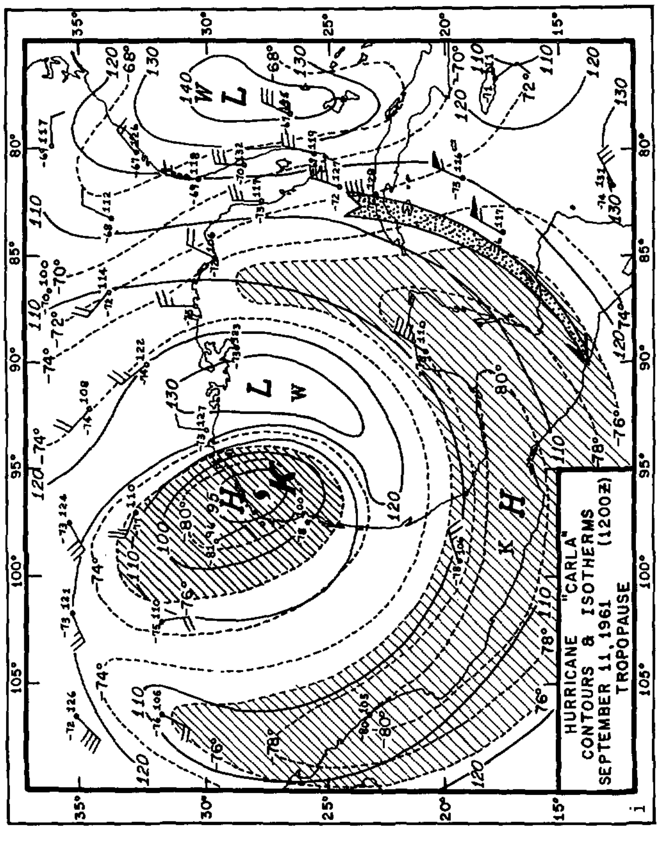


FIGURE 4.—(i). (Concluded.)

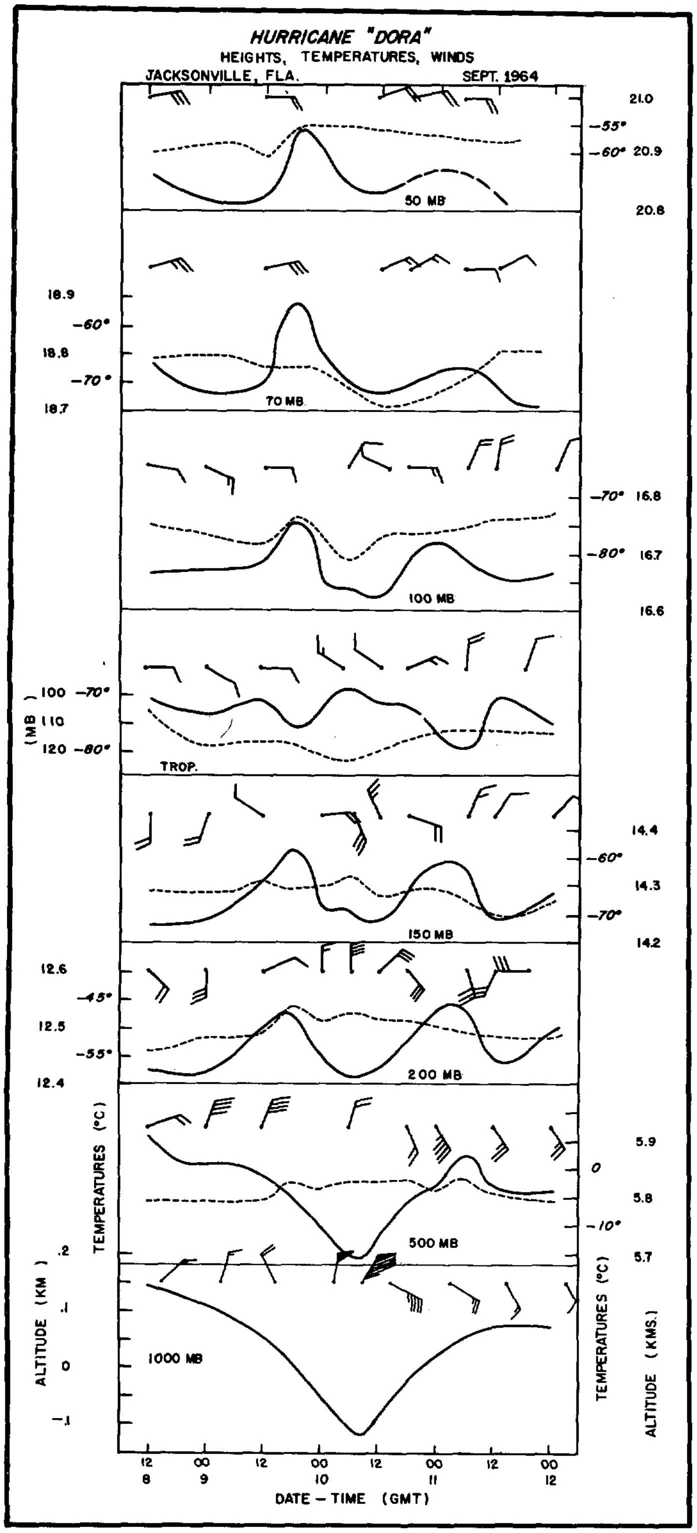


FIGURE 5.—Variation of height, temperature, and wind at standard pressure levels and at the tropopause during the passage of hurricane Dora, September 1964 at Jacksonville, Fla. Analysis as in figure 1.

was well marked, with wind speeds of 50–60 kt. at the southeast and northwest rims.

SUMMARY OF THE STRUCTURAL FEATURES OF HURRICANE CARLA

It will be convenient to summarize the salient features of hurricane Carla at this stage. The hurricane was large and deep. Its low-pressure core extended from the surface up to 27 km. (the upper limit of this investigation), possibly beyond. There was no reversal of pressure gradient at any level near the core although the pressure gradient diminished with height.

The diameter of the cyclonic wind vortex diminished rapidly above 6 km. and was at its minimum at the tropopause level of 17 km. It, however, seemed to extend into a broad trough aloft.

A peripheral ridge surrounded the low pressure vortex from the surface upward. As the cyclonic vortex shrank in diameter at the upper levels, the axis of the peripheral ridge inclined inward with height between 6 and 12 km., above which it was nearly vertical. The outer rim of the ridge in the upper levels lay roughly above the ridge axis at the surface. While the low-pressure vortex with its associated cyclonic circulation dominated the circulation in the lower levels, the peripheral ridge with its associated anticyclonic circulation dominated the upper levels up to about 19 km. The two systems were, however, interlinked and appeared to be constituent parts of the hurricane circulation.

Peripheral jets skirted the outer rim of the peripheral ridges, particularly to the east, south, and northwest. While wind speeds in the upper troposphere diminished upward in the central region of the storm, they increased upward at the periphery. The core of the jet was located roughly above the axis of the surface peripheral ridges enveloping the hurricane circulation. The altitude of the jet core was about 12 km. in the northwestern and 14–15 km. in the southern sector.

The core of the hurricane was warmer than its surroundings below 15 km. and colder than its surroundings aloft. Maximum positive anomalies of temperature occurred near the core between 10 and 12 km. and maximum negative anomalies between 16 and 17 km. Temperatures in the peripheral ridge were above normal above 6 km.

The tropopause bulged upward and was coldest near the core. It dipped downward and was warmest at the axis of the peripheral ridge. Alternate rings of warm and cold air surrounded the cold core at this level.

Potential temperatures increased in the tropospheric core of the hurricane and decreased in the stratospheric core. A layer of nearly constant potential temperatures, 1 or 2 km. thick, existed near the cold core below the tropopause.

The layer of transition between the warm and cold cores was situated at about 125 mb. (15 km.) and had a warm pool to the left of the hurricane core and a cold pool to the right, with isotherms running roughly parallel to the direction of motion of the storm.

4. STRUCTURE OF HURRICANE DORA, 1964

Hurricane Dora, August 28–September 16, 1964, also was a large hurricane, about 800 mi. in diameter at the surface. Its eye crossed the coast about 6 mi. north of St. Augustine, Fla., at 0620 GMT on September 10. Moving westward, it was located within 30 mi. of Jacksonville, Fla. at about 0900 GMT. St. Augustine remained in the eye between 0715 and 0830 GMT and recorded the lowest pressure of 966 mb. at 0800 GMT. Jacksonville Naval Air Station recorded a low pressure of 977.7 mb. and gust of 81 m.p.h. at 0855 GMT. Six-hourly rawinsonde observations are available for Jacksonville.

Figure 5 illustrates the variations of height, temperature, and wind at standard pressure levels and at the tropopause over Jacksonville during the passage of the hurricane. Figure 6 gives the vertical cross-section across the storm roughly along 80°W. meridian at 0600 GMT, September 10, 1964. Figures 7 a–d give the contours and temperatures at standard pressure levels from 150 to 70 mb. The data for the hurricane circulation are for 0600 GMT and the rest for 0000 GMT.

The following is a summary of hurricane Dora's structural features:

(i) The hurricane, which was less intense and had a smaller diameter than hurricane Carla, had similar structural features. Low pressure near the core extended up to about 26 km., probably higher. The Low weakened with height and spread out above 17 km. but there was no reversal of pressure gradient in the core at any height. The cyclonic wind vortex seems to have extended up to about 17 km. where it was very small; aloft it weakened into a trough.

(ii) A peripheral ridge enveloped the cyclonic vortex from the surface upward, its axis inclining inward with height above 6 km. The outer rim of the peripheral ridge was located roughly above the ridge axis at the surface as in the case of hurricane Carla. The peripheral ridge dominated the circulation in the upper troposphere.

(iii) Peripheral jets skirted the outer rim of the peripheral ridge, to the north and south, between 12 and 16 km. The core of the northern jet was at a height of about 12 km. and that of the southern jet at 15 km. They were located almost above the surface ridge. At the western rim, however, two low-pressure cells lay in the upper troposphere above the axis of the surface ridge and seemed to inhibit the growth of jets along this part of the rim.

(iv) The hurricane had the usual warm core below 14 km. and a cold core between 16 and 20 km. Maximum positive anomalies of temperature (9°–10°C. above normal) occurred in the core below 10 and 12 km. and maximum negative anomalies (6°–8°C. below normal) between 16 and 18 km. Large negative anomalies of temperature also occurred at the southern rim of the peripheral ridge.

(v) The tropopause was elevated over the core but not to the same extent as in hurricane Carla. It was also elevated near the southern rim.

(vi) The transition layer between the warm and cold cores lay between 14 and 16 km. A warm pool was located to the left of the hurricane core at this level and a cold pool to the right with isotherms running roughly along the direction of motion of the hurricane.

5. STRUCTURE OF HURRICANE CLEO, 1964

Hurricane Cleo, August 20–September 4, 1964 was a small hurricane, the center of which passed north-northwestward over parts of Miami, Fla., at about 0700 GMT on August 27, 1964. The lowest pressure recorded at North Miami was 967.5 mb. and highest wind speeds were 100–105 m.p.h. with gusts up to 135 m.p.h.

Three-hourly rawinsonde observations were made at Miami during the passage of the hurricane, except at 0900 GMT. Figure 8 gives the variation of height, temperature, and wind at different pressure levels from 1000 to 30 mb. (24 km.).

Figure 9 depicts the south-north vertical cross-section of the hurricane roughly along the 80°W. meridian at 0600 GMT on the 27th. The observations for stations south of 20°N. are for 1200 GMT. The center of the hurricane was located about 25 mi. southeast of Miami.

As the center of hurricane Cleo passed close to Miami rather rapidly and frequent observations were made available, the vertical time-section for Miami was useful in revealing the vertical structure of the hurricane in some detail. Figure 10 illustrates the vertical time-section over Miami between 1200 GMT of the 26th and 0000 GMT of the 28th. The approximate distance of the center of the hurricane from Miami is indicated in the diagram. The section extends over a distance of about 400 mi. covering the entire storm circulation and observations are spaced nearly 30 mi. apart. The time-section roughly corresponds to a space-section, with north to the left of the diagram and south to the right, strikingly similar to figure 9 reversed. (No data are available within 25 mi. of the eye center.)

Figure 11 presents the contours and isotherms at standard pressure levels from 125 to 70 mb. and isobars and isotherms at the tropopause level at 0600 GMT on August 27, 1964. Data within the hurricane circulation relate to 0600 GMT and the rest are for 1200 GMT.

Hurricane Cleo's structural features were as follows:

(i) The hurricane, though comparatively small, had a structure essentially similar to that of hurricanes Carla and Dora. The relative low pressure near the core extended up to 27 km., probably higher. A peripheral ridge enveloped the hurricane from the surface upward with its axis inclined inward with height above 6 km., and dominated the hurricane circulation between 8 and 16 km. It was, however, asymmetrically developed, being located mainly to the east of the hurricane.

(ii) The core of the hurricane was warm, as usual, up to 13 km. and cold above 14 km. Maximum positive and negative anomalies of 5°–6°C. occurred near the core at 10–12 km. and 15–16 km., respectively. The characteristic pattern of isotherms in the transition layer (near 150 mb.

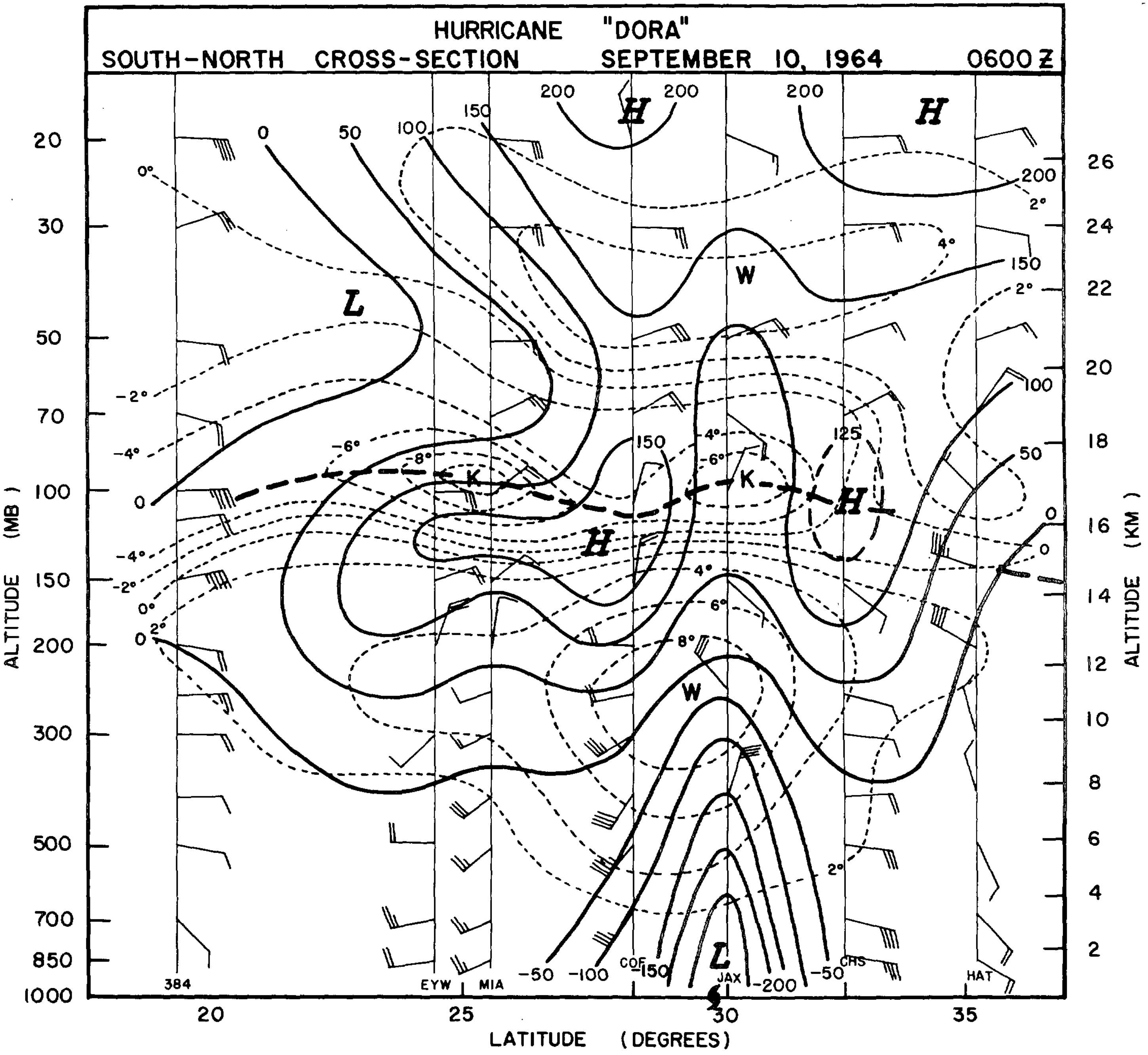


FIGURE 6.—South-to-north vertical cross-section across hurricane Dora along 80° W., September 10, 1964, 0600 GMT. Analysis as in figure 1.

in this case) running almost parallel to the direction of motion of the hurricane, with warm air to the left and cold air to the right, was seen in this case also.

(iii) The tropopause was comparatively lower than in other hurricanes, but its topography and temperatures were essentially similar. It bulged upward and was coldest near the core and dipped downward and was warmest at the axis of the peripheral ridge. It was again elevated at the outer rim of the peripheral ridge and low temperatures comparable to those in the core were seen at the southern rim as in other hurricanes.

(iv) Peripheral jets with wind speeds of 40–50 kt. appeared at the outer rim of the peripheral ridge, to the northwest and southeast. The jets were located roughly above the axis of the peripheral ridge at the surface, as in the other hurricanes.

6. STRUCTURE OF HURRICANE ARLENE, 1963

Hurricane Arlene, July 31–August 11, 1963, the last in this series, is the only one for which an eye-sounding was available. Some features of this sounding have been discussed by Stear [20].

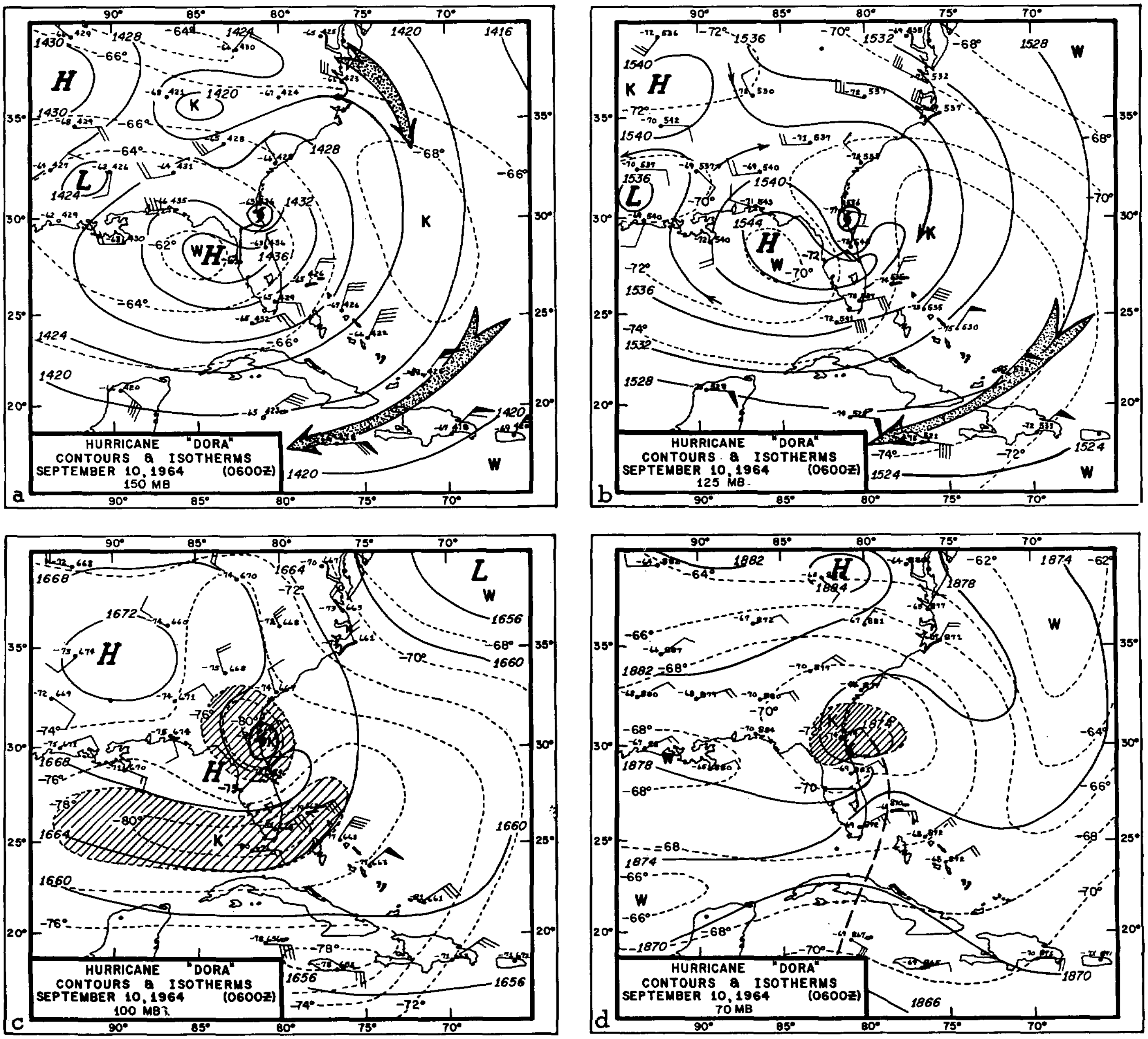


FIGURE 7.—Contours and isotherms at standard pressure levels during passage of hurricane Dora September 10, 1964, 0600 GMT. (a) 150 mb (b) 125 mb. (c) 100 mb. (d) 70 mb.

The hurricane was located at a fairly high latitude, 32°N., as it passed northeastward over Bermuda after recurvature and was embedded in the zonal westerly flow.

Figure 12 presents the variation of height, temperature, and wind at different standard pressure levels at Kindley Air Force Base, Bermuda, from 0000 GMT on the 9th to 1200 GMT on the 10th. As observations are not available for a vertical cross-section in space, a vertical time-section (*fig.* 13) has been prepared for Kindley AFB as the center of the hurricane passed over the station. Six-hourly observations have been plotted from right to left on the figure and distances of the station from the center of the hurricane have been indicated at each observation. The vertical time-section roughly represents a cross-section across the hurricane in a SW–NE direction, SW to the left of the diagram and NE to the right. Figure 14 gives the contours and isotherms at standard levels from the surface up to 70 mb. at 1600 GMT on August 9, 1963. The data for Bermuda are for 1600 GMT and those of the continental stations for 1200 GMT. Ships' data at the surface are for 1800 GMT in figure 14a.

The hurricane, which was very small compared to

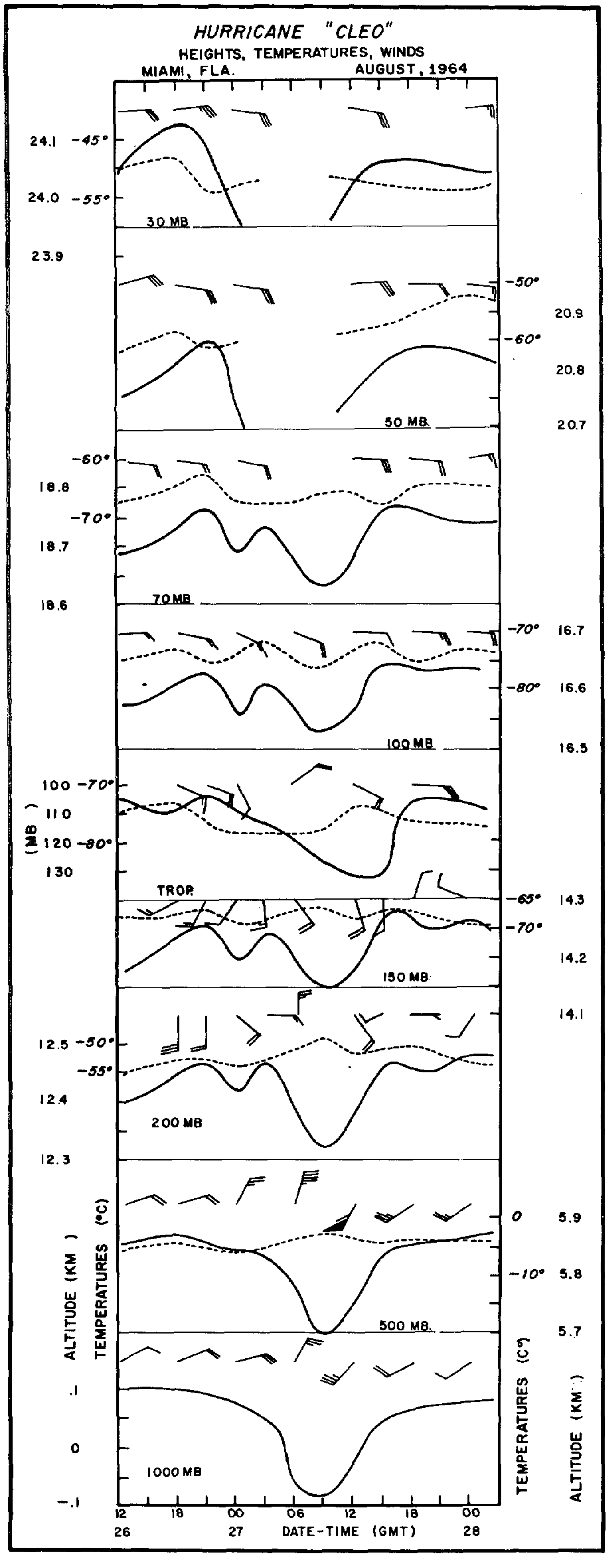


FIGURE 8.—Variation of height, temperature, and wind at standard pressure levels and at the tropopause during the passage of hurricane Cleo, August 1964 at Miami, Fla. Analysis as in figure 1.

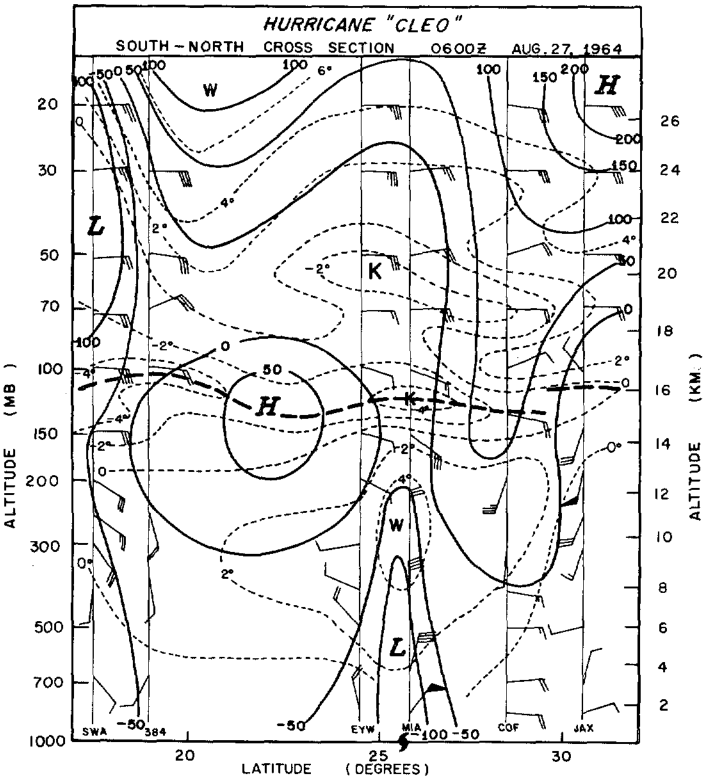


FIGURE 9.—South-to-north vertical cross-section across hurricane Cleo along 80°W. September 27, 1964, 0600 GMT. Analysis as in figure 2.

others discussed in this article, exhibited certain features which were similar to the others and some which were quite different. Its core was warm up to about 10 km., as in other hurricanes. Unlike the others, its low-pressure core did not appear to extend higher than about 11 km. and the pressure gradient reversed sign at 14 km. and higher. There was no peripheral ridge or jet and no cold core as in other hurricanes. The tropopause bulged slightly over the hurricane without a corresponding change of temperature. Hurricane Arlene's structure corresponded to the classical pattern [13]. It differed from the other hurricanes in an important aspect, viz, absence of a cold core above the warm core.

7. GENERAL CHARACTERISTICS OF HURRICANE STRUCTURE AT UPPER LEVELS

From the preceding analyses, it is possible to describe the following general characteristics of some mature hurricanes prior to their recurvature into the extratropical westerlies:

(i) The low-pressure core seems to extend throughout the troposphere and into the stratosphere up to about 27 km., possibly higher. This is probably a feature common to many, if not all, mature hurricanes. In intense hurricanes the closed core may extend to higher levels than in weak hurricanes. The pressure gradient in the core rapidly

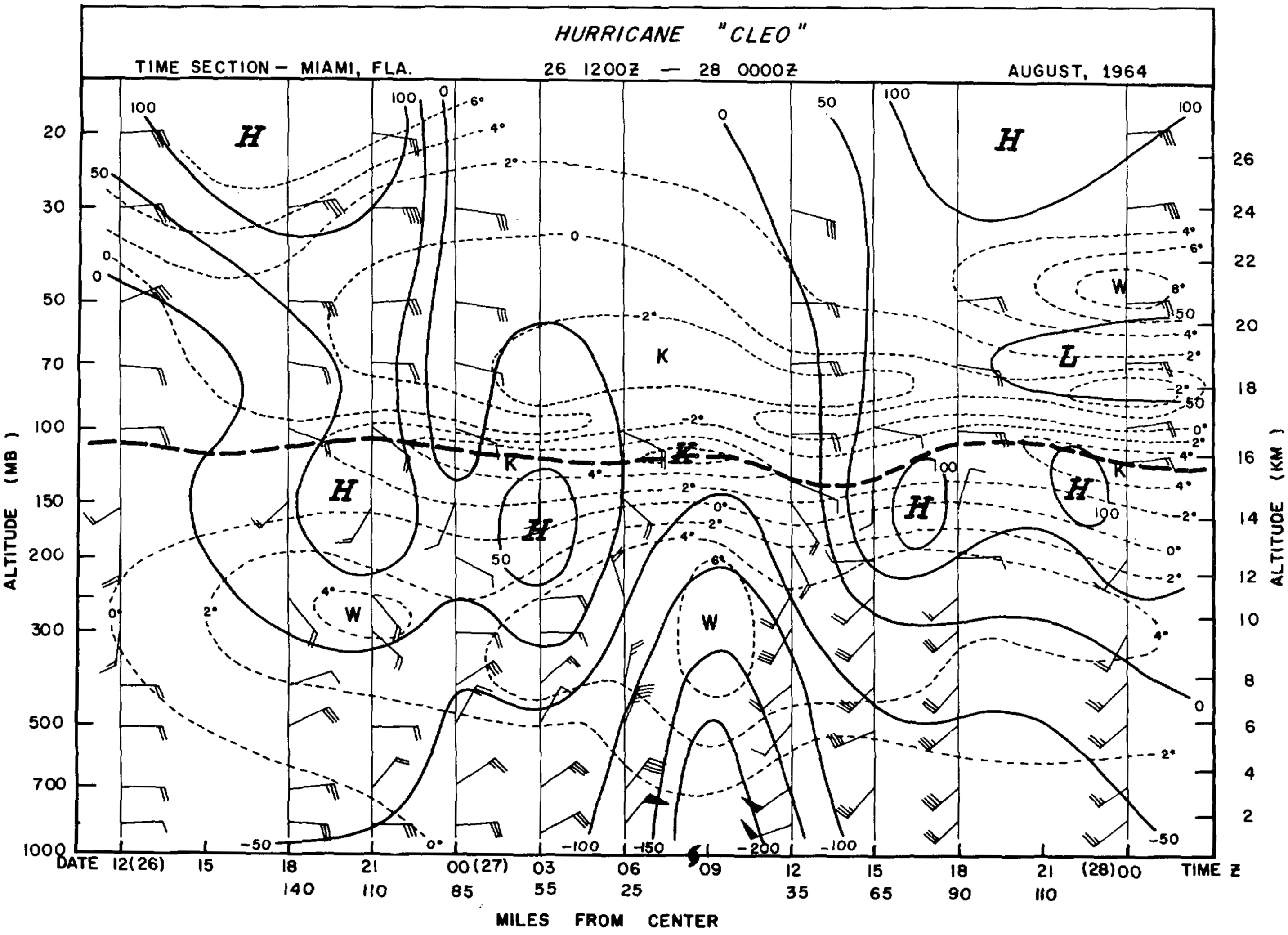


FIGURE 10.—Vertical time section during the passage of hurricane Cleo at Miami, Fla. Distance from center of hurricane (in miles) indicated at each time of observation. Other analysis as in figure 2.

decreases with height above 6 km. but a weak and diffuse Low or a trough seems to persist even in the stratosphere. The pressure gradient near the core does not appear to reverse with height at any level in the upper troposphere, as has often been assumed.

(ii) A peripheral ridge surrounds the core of the hurricane vortex at all levels from the surface upward. The axis of the ridge slopes inward with height above 6 km. and approaches closest to the center between 12 and 16 km. The peripheral ridge consequently dominates the hurricane in the upper troposphere. Its outer rim[5] in the upper troposphere seems to be situated roughly above its axis at the surface. The ridge weakens in the stratosphere but may be present up to 25 km. or even higher in some intense hurricanes. The ridge appears in many cases to be asymmetrically developed, with respect to the hurricane core.

(iii) The hurricane has a warm core below 15 km. and a cold core aloft. Highest and lowest temperature anomalies generally seem to occur at 8–12 km., and near the tropopause level (16–17 km.), respectively. The magnitude of the temperature anomalies, however, varies with the intensity of the hurricane, being larger in strong hurricanes than in weak ones. While both positive and negative anomalies are influenced by the hurricane intensity, negative anomalies in the cold core seem to be determined also by ambient conditions. Large negative anomalies may thus occur sometimes even in weak hurricanes and smaller negative anomalies in stronger hurricanes.

(iv) Temperatures in the peripheral ridge are above normal between 5 and 15 km. and nearly normal or below normal between 15 and 20 km. A strong temperature gradient with temperatures decreasing outward seems to exist along the outer rim of the ridge between 8 and 12 km., above which the gradient reverses sign. The southern rim

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[5] The outer rim of the upper peripheral ridge can often be determined by the presence of an upper tropospheric trough or Lows beyond it. In some cases the appearance of a strong jet may delineate this rim.

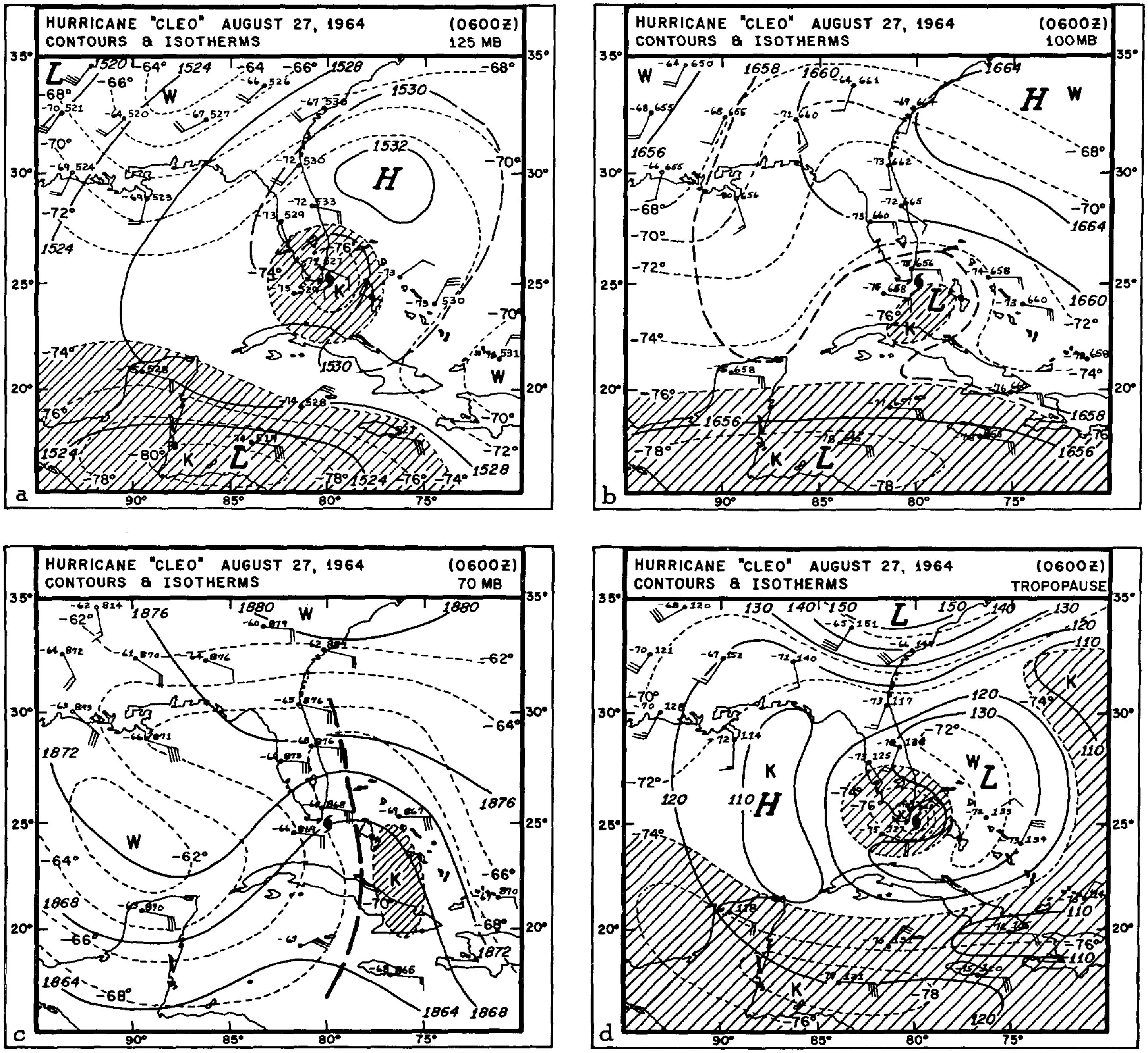

FIGURE 11.—Contours and isotherms at standard pressure levels and at the tropopause in hurricane Cleo, September 27, 1964, 0600 GMT. (a) 125 mb. (b) 100 mb. (c) 70 mb. (d) tropopause.

is generally cold above 14 km. with temperatures comparable to those in the cold core at the tropopause level. In a more or less symmetrical hurricane, rings of warm and cold air seem to surround the cold core at and near the tropopause level (16–17 km.).

(v) The tropopause generally bulges upward and is coldest near the hurricane core, the bulge being more prominent in intense hurricanes than in weak ones. It lowers and is warmer at the axis of the peripheral ridge and again rises and becomes colder at the outer rim of the peripheral ridge. The temperature gradient between the axis of the peripheral ridge and the core may be as much as 10°–12°C., in some cases, at the tropopause level.

(vi) There is a typical thermal structure at the transition layer (14–15 km.). A pool of above normal temperatures is often located to the left of the core (facing in the direction of motion) and below normal temperatures to the right, with isotherms running roughly parallel to the direction of motion of the hurricane.

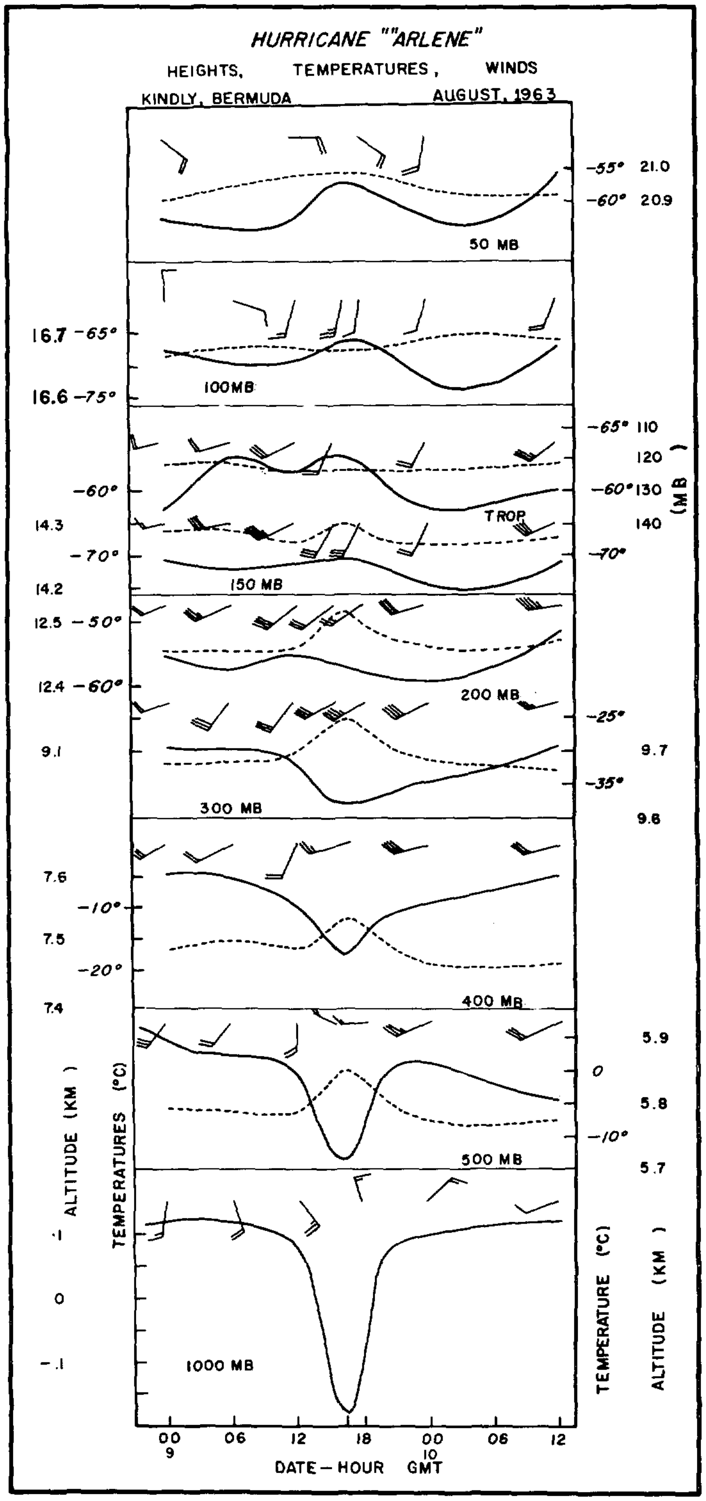

FIGURE 12.—Variation of height, temperature, and wind at standard pressure levels and at the tropopause during the passage of hurricane Arlene, August 1963, at Kindley Air Force Base, Bermuda. Analysis as in figure 1.

(vii) The cyclonic wind vortex has its maximum diameter at the surface and remains nearly unchanged up to about 6 km. It diminishes rapidly with height above 6 km., being smallest at the tropopause level. Even in large hurricanes whose surface diameter is about 1,000 mi., the diameter of the upper cyclonic vortex seems to dwindle to less than 100 mi. near the tropopause level. It, however, appears to expand outward above this level and may continue as a weak circulation up to about 19 km. in intense hurricanes, above which it degenerates into a trough or a wave in the prevailing easterlies.

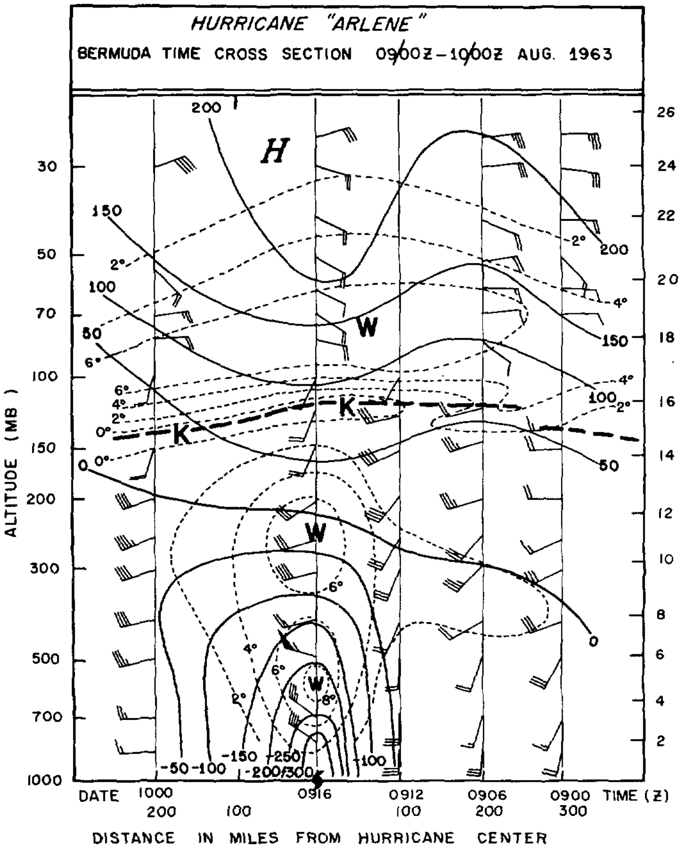

FIGURE 13.—Vertical time-section during passage of hurricane Arlene at Kindley AFB, Bermuda. Analysis as in figure 10.

(viii) Anticyclonic flow dominates the hurricane circulation above 6 km. It is generally broken up into two or more anticyclonic vortices which, in most cases, are asymmetrically situated with respect to the inner cyclonic vortex. The centers of the anticyclonic vortices are located along the axis of the peripheral ridge and the anticyclones reach maximum intensities between 12 and 16 km. In intense hurricanes, the anticyclonic flow patterns may extend even to about 20 km. in the lower stratosphere.

(ix) A peripheral jet is often formed at the outer rim of the peripheral ridge with wind speeds reaching 60–80 kt. between 12 and 15 km. in intense hurricanes. The jet is not uniformly located at the rim and does not seem to develop in those situations in which cyclonic vortices skirt the rim. The concentration of kinetic energy at the inner and outer boundaries of the inflow and outflow currents in the lower and upper troposphere, respectively, seems to be a spectacular feature of the hurricane circulation.

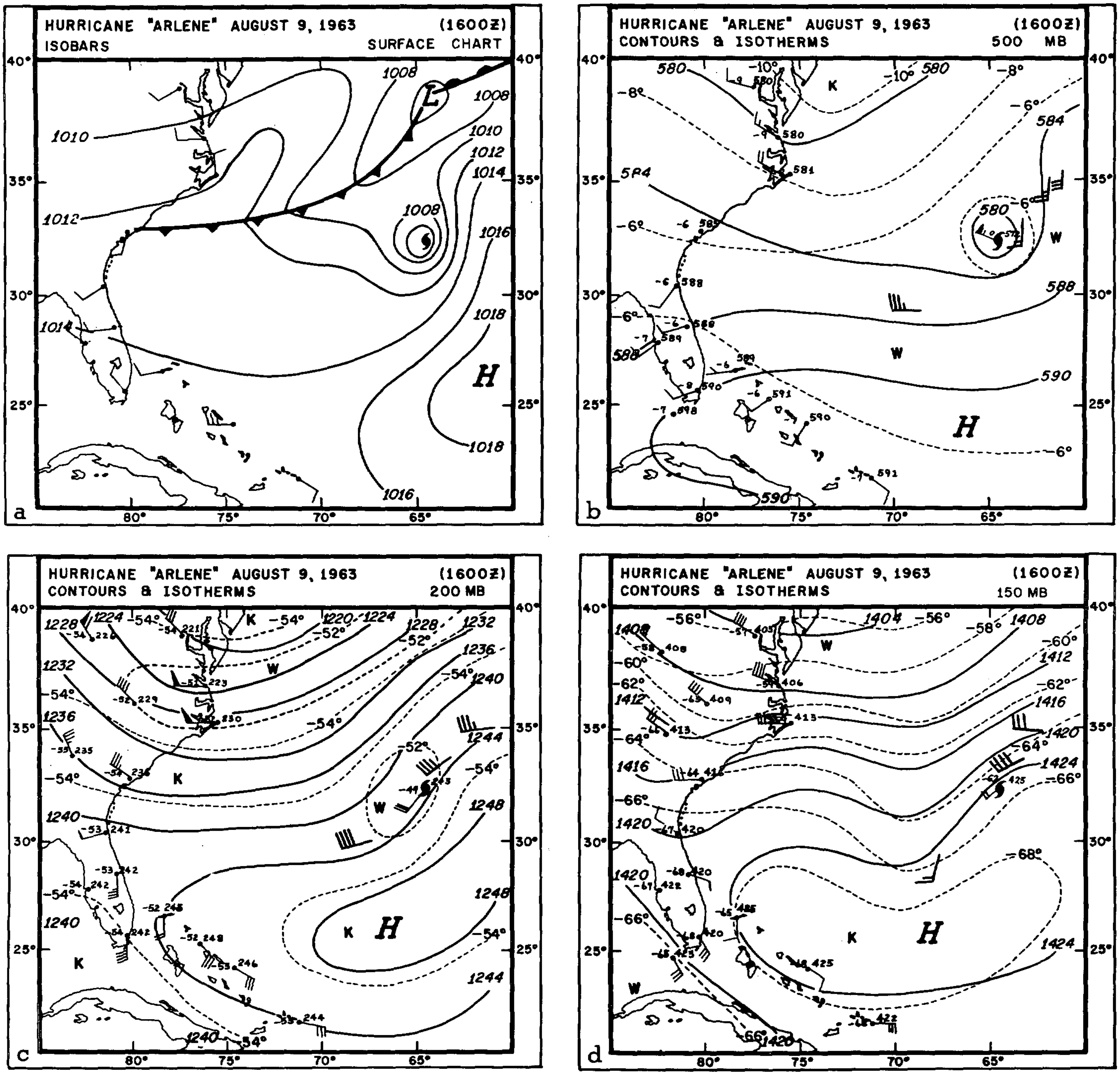

FIGURE 14.—Contours and isotherms at standard pressure surface in hurricane Arlene, August 9, 1963, 0600 GMT. Solid lines = contour. in tens of meters (mb. for isobars in a); dashed lines = isotherms (°C.). (a) Surface (b) 500 mb. (c) 200 mb. (d) 150 mb. (continued).

8. EXCEPTIONS TO GENERAL CHARACTERISTICS

THE CASE OF HURRICANE ARLENE

The structure of hurricane Arlene has already been mentioned as an exception to that of other hurricanes. However, hurricane Arlene is the only case among the storms examined during this investigation in which the structure of the hurricane was quite similar to the classical model. It is interesting to examine why hurricane Arlene was an exception to the general pattern and still it agreed with the model often accepted as applicable to hurricanes in general.

It has been pointed out that hurricane Arlene had recurved into the extratropical westerlies and was embedded

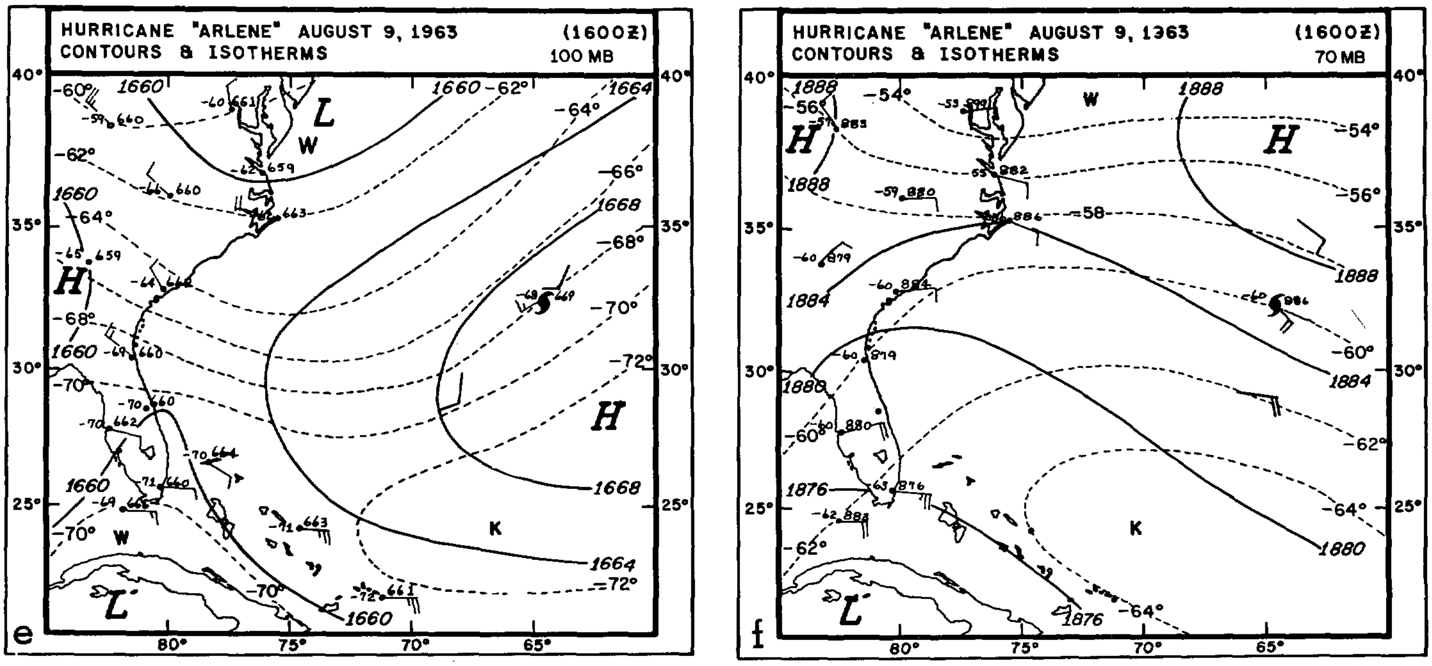

FIGURE 14.—(Concluded). (e) 100 mb. (f) 70 mb.

in them at the time of analysis. If the observed changes occurred after recurvature, it should be possible to observe similar effects in other recurved hurricanes. For this purpose the case of hurricane Carla was examined after it recurved into the extratropical westerlies on September 13, 1961, and weakened into a tropical storm over land. High-level data were not available in the case of other hurricanes which recurved over sea. Figure 1b gives the variations of height, temperature, and wind at different levels over Fort Worth during the passage of hurricane Carla close to the station. The similarity of the curves in figure 1b and those for hurricane Arlene (fig. 12) is evident. While heights fell up to 500 mb. with the approach of the center of the storm and rose thereafter, the height of the 200-mb. surface increased during the passage of the forward peripheral ridge, decreased with the approach of the core, and remained fairly uniform during and after the passage of the core. At 150 mb., the height increased slightly during the passage of the core and decreased thereafter—just the opposite of the changes observed at this surface at San Antonio 12 hr. earlier during the passage of the core (fig. 1a). The variations at higher levels were slight. Temperatures increased near and above the core at all levels up to 100 mb. The tropopause lowered slightly above the core.

Figure 15 gives the vertical cross-section across tropical storm Carla at 0000 GMT on the 13th. The hurricane had weakened into a tropical storm by this time. The low-pressure core of tropical storm Carla extended from the surface up to about 8 km., above which the pressure gradient was reversed. The core was warm. Highest positive temperature anomalies were however located between 10 and 12 km. Maximum positive anomalies of height in the troposphere were located at 14–16 km., directly above the maximum positive anomalies of temperature. The upper cold core of the hurricane seen in figure 2a was separated from the warm core and lagged above San Antonio, some 200 mi. behind the storm center. In fact, it lingered for a few days at this position after the storm moved rapidly away across the United States, so it was here in the process of shearing off.

The similarity between the structures of hurricane Arlene on August 9, 1963 (fig. 13) and tropical storm Carla on September 13, 1961 (fig. 15) is striking. The warm core extended to about 10 km. in hurricane Arlene and to about 8 km. in tropical storm Carla. The pressure gradient in the core reversed sign a few kilometers above the level of maximum positive temperature anomalies in both cases. Temperatures above the core were nearly normal at the tropopause and above normal in the stratosphere in both cases. Both storms were under the influence of extratropical westerlies. The structure of hurricane Arlene on August 9, 1963, may be that of hurricanes after recurvature and when they are embedded in the extratropical westerlies. It is possible that, like hurricane Carla, hurricane Arlene also had an upper cold core before recurvature and that, as in hurricane Carla, the upper cold core became separated from the warm core during the recurvature of the hurricane.

9. DISCUSSION

It may be seen from the generalizations in the preceding section, that the mature hurricane, before recurvature, seems to extend throughout the troposphere and even into the lower stratosphere. Apart from the well-known warm core, it has an upper cold core above 15 km. and

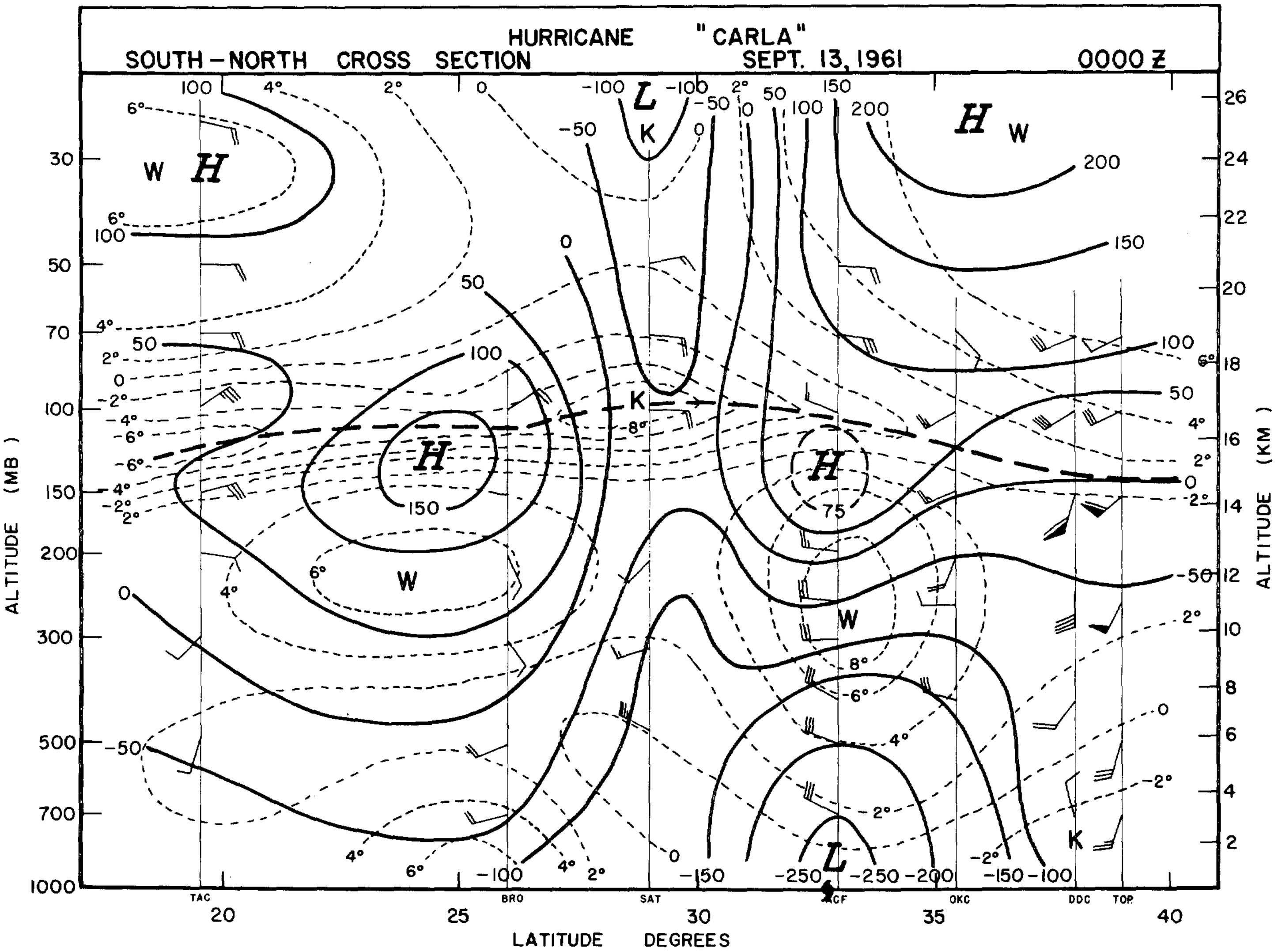

FIGURE 15.—South-to-north vertical cross-section across hurricane Carla, September 13, 1961, 0000 GMT. Analysis as in figure 2.

an upper peripheral ridge extending well beyond the limit of the lower cyclonic circulation. Peripheral jets often skirt along the outer rim of the peripheral ridge between 12 and 15 km. The possible reasons for these upper-level features and their likely role in the hurricane mechanism, will be examined qualitatively.

THE UPPER COLD CORE

The upper cold core is a spectacular feature in the system otherwise dominated by the warm core. It is well known that the tropical disturbance from which the hurricane develops is generally cold-cored in the middle and upper troposphere and that the cold core is transformed into a warm core as the disturbance intensifies into a hurricane. Apparently the upper cold core persists above the warm core, even after the formation of the latter.

An obvious mechanism supporting the upper cold core would be forced ascent in the upper troposphere and lower stratosphere. In a mature hurricane, cloud towers are frequently found to rise highest near the eye-wall. Air parcels ascending vigorously because of buoyancy in undilute "hot-towers" at the eye-wall do not come to an abrupt stop at the level of density equalization but would have a tendency to overshoot. Ascent above this level should result in lower temperatures in the ascending columns than outside. The "hot-towers" would develop "cold-tops" and the cold air flowing out of these tops could produce the cold core at the upper levels of the hurricane. The cold air would have a tendency to sink to lower levels and warm up, but as long as intense convection was maintained, it would be replenished almost continuously. In recent years, interesting observational, theoretical, and experimental evidence has been obtained about the existence of penetrative cumulus convection above the tropopause level.

Observational evidence.—Malkus [8] cited a spectacular case of cumulonimbus development in the inner rain area and at the eye-wall of hurricane Daisy on August 27, 1958, in which the tallest towers were found by radar measurements to have grown to 60,000 ft. (18.3 km.), which is almost certainly above the tropopause. The U–2 reconnaissance flight above typhoon Ida on September 25, 1958, [2] found that the cloud tops extended to 65,000 ft. (19.8 km.) at the eye-wall. An overhanging upper lip of the wall cloud protruded into the eye at 60,000 ft. and the air appeared to cascade down from this level. Another U–2 flight over hurricane Isbell on October 14, 1964, [2] found that cloud tops at the north side of the storm reached 68 mb. (19 km.). In all these cases, it may be presumed that penetrative convection of cumulonimbus towers must have occurred above the tropopause level with overshoots ranging from 1 to 3 km.

Theoretical aspects.—Extending Levine's [7] model of bubble convection in the context of development of cumulonimbus towers in the inner rain area of hurricane Daisy, 1958, Malkus [8] calculated a number of interesting parameters for these towers. Assuming a virtual temperature excess $\Delta\theta_b$ of 1°C. at the base of the cloud (proportional to buoyancy), she found that large towers with base radii greater than 2 km. would have no difficulty in reaching the tropopause level. With $\Delta\theta_b = 1.5$°C., and radius of cloud element 3 km., the maximum height would be 17.3 km., the rate of ascent of the cloud tower at the level of density equalization would be about 15 m./sec., and the overshoot 3.1 km. The negative $\Delta\theta$ (virtual potential temperature anomaly relative to environment) at the top of the tower would be -12.5°C. The corresponding temperature anomaly would be -6°C., which agrees with the order of magnitude of negative anomalies in the upper cold pools studied in this investigation.

Calculations near the tropopause layer indicated that the length of overshoot of the cloud tower above the tropopause is directly proportional to the rate of ascent at the tropopause (as is to be expected) and that the penetration is not affected by variations in the static stability of the tropopause layer. A rate of rise of 20 m./sec. at the tropopause is required for an overshoot of 1 km. above the tropopause.

Experimental evidence.—Saunders [16] demonstrated penetrative convection in stably stratified fluids by a spectacular laboratory experiment. Applying the laboratory results to the case of penetration of convective clouds into the lower stratosphere, he found a direct relation between the approach velocity of the cloud top at the tropopause and the degree of penetration into the stratosphere. An ascent rate of 7.8 m./sec. is required at the tropopause level for a penetration of 1 km. The "parcel" method indicates an ascent rate of 17 m./sec., and the "bubble" method 20 m./sec. Considering the fact that the vertical velocity at the core of the "thermal" in Saunders' experiment was twice the rate of advance of the cap of the thermal, the 17 m./sec. speed needed for the 1 km. penetration could occur near the core of the rising cloud element.

In a photographic and radar study of convective clouds over Florida, Saunders and Ronne [17] found meteorological evidence for the proportionality between the vertical velocity of the cap of the cumulus tower at the tropopause and the length of its penetration into the lower stratosphere. In five cases observed by them, the ascent rates at the tropopause ranged between 10 and 25 m./sec., and the corresponding stratospheric penetration between 1 and 3 km.

From the foregoing evidence, it is clear that convective cloud towers of sufficient width (>2 km. at the base) can rise near the eye-wall beyond the level of density equalization between the cloud and its surroundings. If they approach the tropopause with a speed of 20 m./sec., they should be able to penetrate it to a distance of 1 km. The maximum updraft required in the hurricane for producing the required upward speed at the tropopause is 50 m./sec. No direct measurements of such strong updrafts are available but indirect radar and pilot evidence seems to support the suggestion that updrafts of 40–50 m./sec. may occur in at least some hurricane eye-walls (Malkus [8]). It may therefore be reasonably inferred, at this stage, that the low temperatures in the upper levels of intense hurricanes may be caused by penetrative convection of cloud towers from the warm core, above the level of density equalization.

The presence of an upper cold pool would have some dynamic consequences on the hurricane circulation in the upper levels. The inward pressure gradient in the low pressure core of the hurricane, which diminishes with height in the warm core, would not be wiped out and reverse sign at the higher levels as is usually assumed, but would persist and may even slightly increase in the upper cold core. It is therefore not surprising that the low-pressure cores of most mature hurricanes studied in this investigation seemed to extend well into the lower stratosphere. Since the wind speeds in the upper cold core are generally weak, the centrifugal force of rotating particles may not be able to counterbalance the pressure gradient force directed inward from the peripheral ridge which is well formed at the upper levels. There may therefore be net inflow rather than outflow near the core above 150 mb. Simpson's [19] observation of cyclonic inflow of cirrus streamers at the top of hurricane Edna 1954 seems to be significant in this connection.

The vertical circulation in the upper cold core seems to be of an "indirect" type, with inflow from the peripheral ridge being forced to ascend at the eye wall and outflow from the top of the cloud towers pushing its way into the lower stratosphere. The mature hurricane thus seems to consist of two vertical circulation cells, a "direct" cell in the troposphere below 15 km. with warm air rising at the eye-wall and an indirect cell aloft with cold air forced to rise near the eye-wall.

THE UPPER PERIPHERAL RIDGE AND THE PERIPHERAL JETS

The existence of upper tropospheric anticyclones aiding outflow from the hurricane has been known for a long time

[6]. The inward pressure gradient in the hurricane decreases with height and is generally assumed to reverse sign at some level between 14 and 16 km., causing outflow from the eye-wall as well as from the outer rainbands [13]. It is, however, seen in this investigation that the upper tropospheric ridge seems to remain peripheral to the cyclonic vortex at all levels. Even though the axis of the ridge slopes inward with height above 6 km., it does not appear to overlie the core at any level. The reversal of the pressure gradient in the upper troposphere, therefore, seems to aid outflow from the outer rainbands, not from the eye-wall. The outflow from the eye-wall, which is maintained by the imbalance between the centrifugal force of rotating particles and the inward pressure gradient force, may be operative up to 13 or 14 km., the upper limit of strong tangential velocities near the core.

A significant feature of the anomaly patterns in the upper peripheral ridge is the occurrence of positive anomalies of heights of isobaric surfaces, with maxima along the ridge axis. The height anomalies in the lower troposphere are negative, with maximum negative values in the hurricane core. The corresponding pressure anomalies at different levels are therefore positive in the upper troposphere and negative in the lower troposphere. The anomaly patterns indicate pressure excess (relative to the normal atmosphere) at the upper levels of the hurricane and pressure deficit at the lower levels, associated with the transport of mass from the lower to the upper levels of the storm by the eye-wall and the outer rainbands.

As mass entering the circulation at the lower levels is continuously transferred into the upper levels, a compensatory descent is called for in steady-state conditions. Descent between the rainbands or just outside the hurricane circulation seems improbable, as such descent would reverse the temperature gradient in the storm. Either the mass outflow should be altogether removed from the hurricane circulation or it should be returned to lower levels at some distance away from the hurricane where the outflow has a chance to cool and sink without upsetting the thermal gradient in the hurricane. The structure of the upper peripheral ridge in a mature hurricane seems to indicate a mechanism of the latter type. The reversal of the pressure gradient in the ridge would force the air rising in the rainbands to move outward from the hurricane circulation. The ridge is extensive and its outer rim is located at a considerable distance from the limit of the lower cyclonic vortex. The outflow in the upper levels would be cooled not only by radiation during its transport outward in the upper anticyclonic eddies but also by mixing with the cooler environmental air at the outer rim. The existence of a strong temperature gradient and peripheral jets at the outer rim of the upper peripheral ridge has been pointed out earlier (iv, section 7). The hurricane outflow, after cooling, may return to lower levels by slow subsidence at the outer rim, as evidenced by the sharp outer edge of the cloud canopy in satellite pictures (Fett [1]). The location of a diffuse high-pressure ridge surrounding the hurricane at lower levels with its axis almost beneath this upper rim, and the sharp outer edge of the cloud canopy revealed by satellite pictures seem to indicate descent of air near the outer rim of the peripheral ridge.

Apart from mass, heat is also transported into the upper peripheral ridge from the eye-wall and the rainbands. Temperature anomalies in the ridge are positive, with maxima in the hurricane core. As heat is continuously released at the eye-wall and the rainbands, it has been recognized for a long time that there should be some mechanism for removing the excess heat from the outer circulation of the storm in order that the hurricane core be maintained at a higher temperature with respect to its surrounding circulation. The mechanism for removal of excess heat is generally assumed to be external to the hurricane. While such an external agency can be seen in a hurricane like Arlene, 1963, which was embedded in a broad zonal current, it is not readily discernible in a hurricane like Carla, 1961, which developed an extensive upper peripheral ridge of its own reaching the top of the troposphere. Heat is released by the cloud towers into this peripheral ridge and any mechanism to remove the excess heat should be found within the ridge or in its close vicinity.

A variety of processes may be responsible for disposal of excess heat transported into the upper peripheral ridge. Part of it may be converted into the potential energy of the ridge itself. Part may be advected to the outer rim of the upper peripheral ridge where it may be transferred to the environmental air by mixing and also converted into kinetic energy in the peripheral jets. The rest may be lost to space by radiation.

The upper peripheral ridge and the peripheral jets seem to be built-in mechanisms in a mature hurricane for disposal of excess mass and heat transported from the lower to the upper levels. A number of energy conversion processes seem possible in the ridge. Quantitative determinations will, however, be needed to assess the processes at work in the actual hurricane.

RADIATION FROM THE CLOUD CANOPY

Riehl [15] drew attention to the importance of suppression of outgoing long-wave radiation by the cold cloud canopy of a hurricane and considered that the resultant internal warming would be important during the developing stage. If we assume an effective radiation (equivalent blackbody) temperature (ERT) of −70°C. at the cloud canopy as indicated by TIROS III satellite over hurricane Anna, July 1961, and −17°C. for the normal tropical atmosphere. The fluxes of heat are 0.14 cal. cm.$^{-2}$ min.$^{-1}$ from the canopy and 0.35 cal. cm.$^{-2}$ min.$^{-1}$ from the surrounding atmosphere. The heat conserved by the suppression of outgoing radiation by the cloud canopy would be nearly 300 cal. cm.$^{-2}$ day^{-1}. Rhiel estimated that the resulting warming would be about 1°C. in 24 hr.

The above effect should be operative even in intense hurricanes as a thick cirrus canopy is present over them. The ERT near the upper cold core of a mature hurricane may be near $-80°C$. The outward flux of heat at this temperature is 0.11 cal. $cm.^{-2}$ $min.^{-1}$ and the heat energy conserved by suppression of outgoing radiation in the cloud canopy would be about 350 cal. $cm.^{-2}$ day^{-1}. Malkus and Riehl [9] estimated that the oceanic pick-up of heat (sensible and latent) would be nearly 3440 cal. $cm.^{-2}$ day^{-1}, near the core of a mature hurricane, which is one order of magnitude higher than that available by suppression of radiation. The radiation effect therefore does not seem to be important in a mature hurricane.

STRUCTURAL CHANGES AFTER RECURVATURE

Significant differences have been observed in the upper-level structure of two hurricanes after they had recurved into the extratropical westerlies, as pointed out in section 8. The upper cold core was sheared off in one case and was not observed in the other. There was no peripheral ridge in either. The pressure gradient reversed sign above the warm core, as postulated by the classical model. The zonal westerlies in which the storms were embedded appeared to provide the mechanism for removal of the excess heat transported from lower levels.

The U–2 aircraft flight over hurricane Ginny on October 22, 1964, gave some detailed information above a hurricane embedded in the extratropical westerly flow. Although hurricane Ginny was executing a loop at the time of the U–2 flight and was actually moving southwestward, it was under the influence of the extratropical flow in the upper troposphere. The U–2 reconnaissance found that the cloud tops were confined to about 40,000 ft. (12.2 km.) in this hurricane [2]. The warm core extended up to the cloud tops. The horizontal gradients of temperature from 105 to 50 mb. were poorly defined. The temperatures at 100 mb. above and near the eye of the hurricane were about 6° C. above normal. There was no cold core above hurricane Ginny. Its structure closely resembled the classical model, as did hurricane Arlene and tropical storm Carla after recurvature.

The upper-level structure of hurricanes embedded in the extratropical westerlies thus may be sometimes quite different from that of mature hurricanes before recurvature. The upper cold core and the upper peripheral ridge may be sheared off or absent in such hurricanes and they may correspond to the classical model.

SCHEMATIC PATTERNS OF THE STRUCTURE OF A MATURE HURRICANE

Figure 16 illustrates schematically the structure of a mature hurricane, before recurvature. The cross-sections extend to 24 km. and represent conditions in the troposphere and lower stratosphere. Figure 16a represents the distribution of anomalies of height and temperature at different isobaric surfaces and figure 16b the distribution of isotherms and isentropes. Numerical values have not been indicated in the diagrams. The zero isopleth in figure 16a separates positive anomalies from negative anomalies. The tropopause has been indicated by a thick dashed line in both figures. The schematic patterns represent the generalizations listed in section 7.

10. CONCLUSION

This examination of the synoptic structure of some hurricanes in the upper troposphere and lower strato-

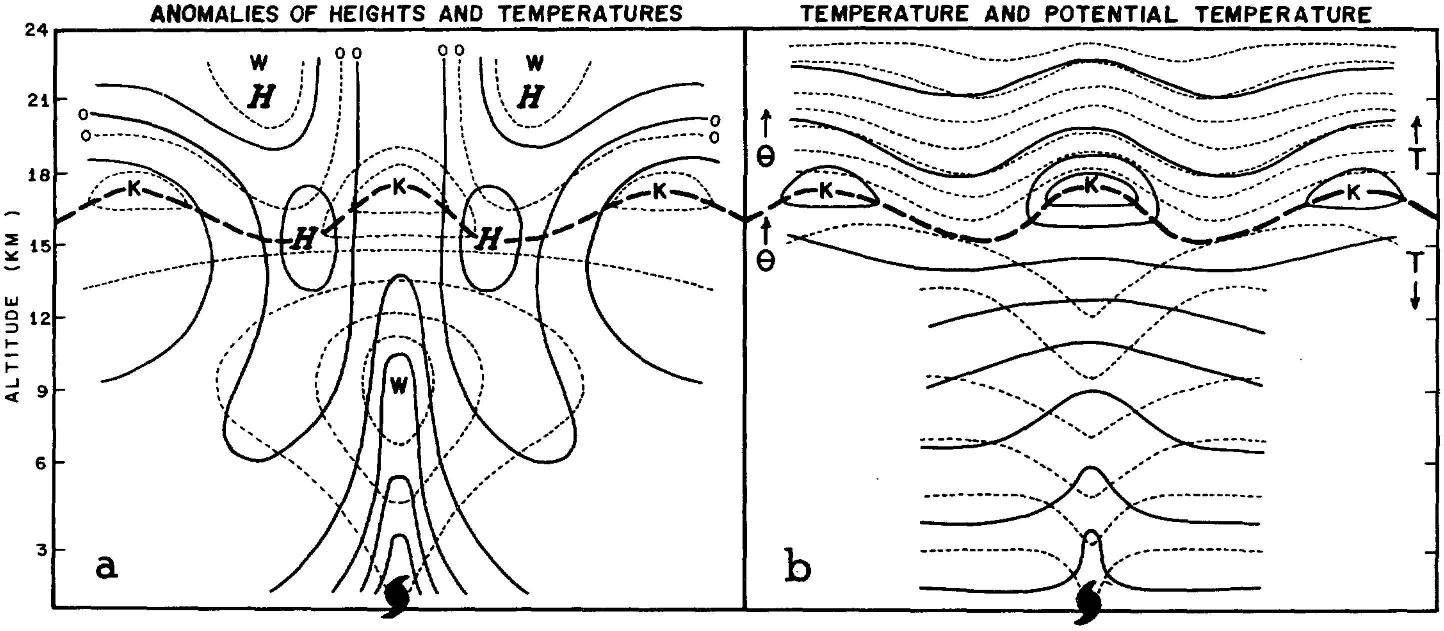

FIGURE 16.—Schematic distribution of specified parameters in an idealized hurricane. (a) Anomalies of heights (solid lines) and temperature (dashed lines), (b) isotherms (solid lines) and isentropes (dashed lines). Tropopause is shown by heavy dashed line.

sphere has revealed that the mature hurricane, before recurvature, seems to have some characteristic features at its upper levels—upper cold core, upper peripheral ridge, and upper peripheral jets. Based on qualitative considerations, it appears that ascending currents near the eye-wall may extend up to the tropopause level and even beyond into the lower stratosphere, and there may be some peripheral descent near the outer rim of the upper peripheral ridge. The mature hurricane, before recurvature, seems to be more extensive laterally and vertically than has been generally believed. In the case of hurricanes which recurve and become embedded in the extratropical westerlies, the above-mentioned upper-level features may sometimes be absent and the hurricane structure may correspond to the classical model.

Detailed observations by aircraft at different levels above 200 mb. would be of great interest not only in determining the nature and intensity of these upper-level features in hurricanes during different stages of development but also in assessing their role in the hurricane mechanism.

ACKNOWLEDGMENTS

The author expresses his sincere appreciation to Dr. R. Cecil Gentry, Director, and Mr. Harry F. Hawkins, Assistant Director, of the National Hurricane Research Laboratory for the facilities and assistance provided for carrying out the research mentioned in this report and for many helpful discussions. Thanks are also due to Professor Homer W. Hiser of the Radar Meteorological Laboratory of the University of Miami for his helpful assistance, Mr. Robert L. Carrodus and Mr. Charles H. True for preparation of diagrams, and Miss Debbie Nejman for typing the article.

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[Received December 23, 1966; revised May 18, 1967]