UDC 551.515.227:551.524.72:551.551.5:551.507.352(764) "1967.09.20" Beulah

TEMPERATURES AND TURBULENCE AT TROPOPAUSE LEVELS OVER HURRICANE BEULAH (1967)

DAVID E. WACO

Lockheed-California Company, Burbank, Calif.

ABSTRACT

Horizontal and vertical temperature variations along with true gust velocity measurements of atmospheric turbulence were obtained above hurricane Beulah (1967) by an instrumented U–2. The U–2 flight was part of the U.S. Air Force High Altitude Clear Air Turbulence program. Pertinent findings include: (1) location of the tropopause just above the cloud tops at 54,000 ft (100 mb) with a temperature of −86°C, 12°C lower than the mean; (2) a vertical temperature rise of 11°C in a few hundred feet just above the tropopause; (3) horizontal temperature changes up to 7°C and smooth flight conditions in the stable layer above the cloud tops; and (4) small temperature fluctuations and generally turbulent conditions at cloud top level.

Aircraft measured winds, although questionable as to their exact directions and speeds, indicated that the flow was weak and anticyclonic near Beulah's top, becoming increasingly anticyclonic above.

1. INTRODUCTION

Stratospheric conditions above hurricane Beulah (1967) were measured in detail during a half-hour period after the storm crossed the south Texas coastline. A special instrumented U–2 aircraft completed two large loops around the hurricane's axis, just above cloud tops, near 54,000 ft (100 mb). Temperature, wind, and air motions recorded 12 times per second are analyzed in this paper together with available radar, rawinsonde, and other information and compared with descriptions of previous hurricanes.

The flight above Beulah was part of the U.S. Air Force High Altitude Clear Air Turbulence (HICAT) program initiated in 1962 to provide fine scale measurements of gust velocity and related atmospheric properties between 40,000 and 70,000 ft. In 4 yr from February 1964 to February 1968, a heavily instrumented USAF U–2 completed 285 flights over and near Australia, New Zealand, Panama, the Caribbean, and the British Isles, as well as several parts of the United States including Alaska and Hawaii. Instrumentation included a digital pulse code modulation (PCM) system, an inertial navigation system, a fixed vane gust probe, and an oscillograph recorder. A Rosemount[1] Engineering Model 102 total temperature probe was mounted in the aircraft nose. Measurements, analysis, and meteorological summaries of the flights have been given by Crooks et al. (1967), Crooks et al. (1968), Ashburn et al. (1968, 1969).

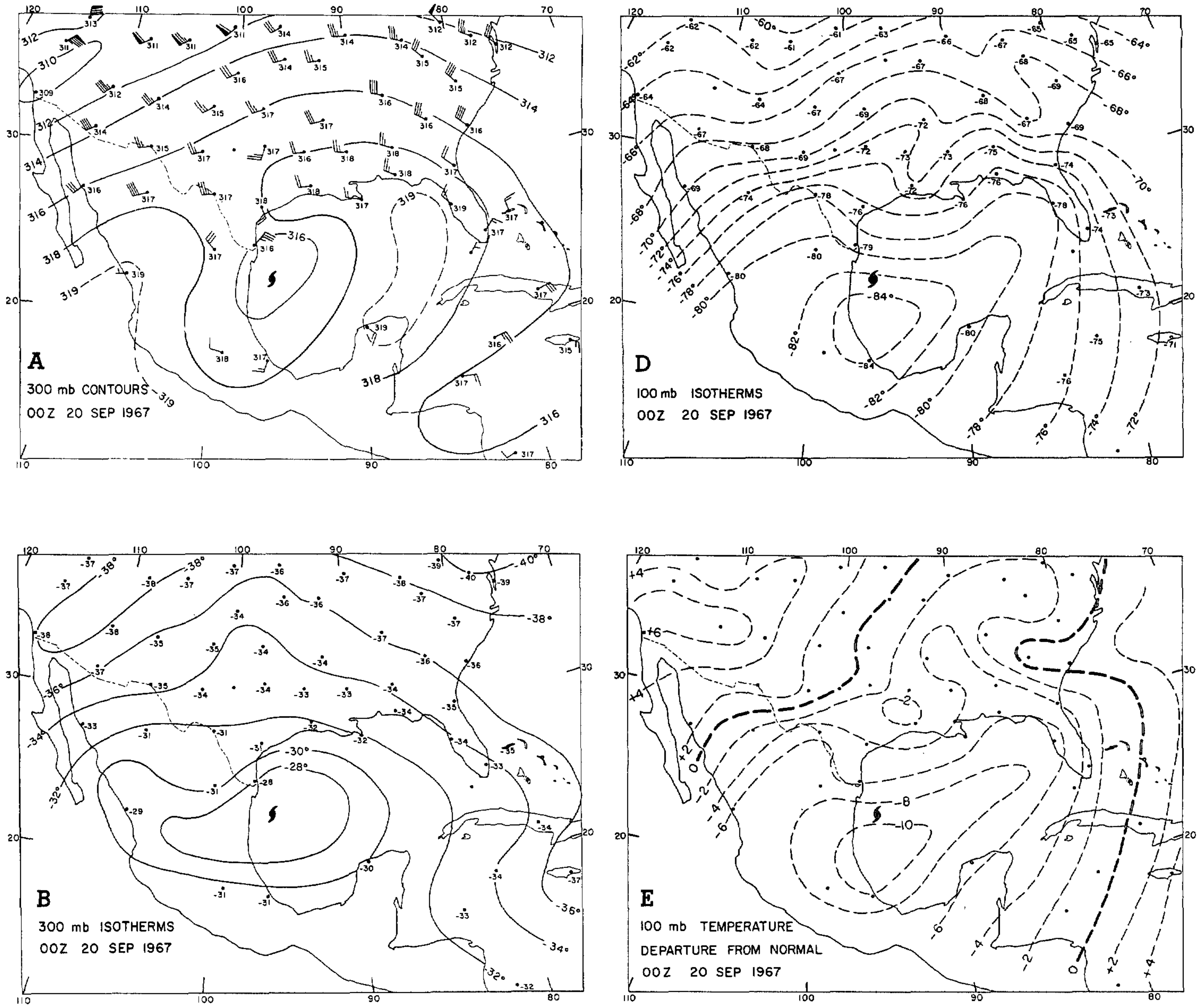
While stationed at Patrick Air Force Base, Fla., during September of 1967 for flights into potential turbulent areas around Florida, the U–2 was dispatched on Flight 247 to Brownsville, Tex., where Beulah was crossing the coastline. Beulah's history has been summarized by Sugg and Pelissier (1968). Only the third September storm of the century to attain hurricane intensity in the eastern Caribbean, Beulah had brushed Hispaniola and Yucatan before landfall on Sept. 20, 1967. The preceding day, a USAF hurricane reconnaissance aircraft found a central pressure of 923 mb, and at 1400 GMT (0800 CST) on the 20th, 2 hr after landfall, pressure at Brownsville was 951 mb; peak gusts of 95 kt were recorded on an anemometer tilted 30° from vertical. Beulah moved about 110 mi north-northwest from Brownsville before turning southwest on the 21st and broke up in the mountains west of Monterrey on the 22d. Beulah was only the fifth of what has been referred to as the "great" hurricanes (Kraft 1966) since 1955 to enter the United States.

2. SYNOPTIC SITUATION

A synoptic description of Beulah was obtained from rawinsonde observations at 0000 GMT on Sept. 20, 1967, the last time at which the observation network was reasonably complete but 12 hr before landfall and 16 hr before the U–2 flight above the storm. At 300 mb, the hurricane had a typical cyclonic wind vortex (fig. 1A) and a rather extensive and quite warm low-pressure core (fig. 1B). Over Brownsville, when Beulah was 160 mi to the southeast, the 300-mb temperature was only −28°C, higher by 5° than the mean September sounding for the Caribbean (Jordan 1958). The −30°C isotherm encircled the hurricane at distances of about 400 mi, within which winds were generally light, only 10 to 25 kt; Brownsville reported 35 kt. The general situation was similar to the pattern around hurricane Cleo (1958) for which LaSeur and Hawkins (1963) found positive temperature anomalies increasing with height, and also quite widespread.

At 100 mb (fig. 1C), flow was anticyclonic for several hundred miles around the hurricane, but weak (4 kt over Brownsville); whether the flow immediately above the core was cyclonic cannot be established for lack of observations. The contours on the 100-mb map are doubly smoothed: first, heights at grid points 200 mi apart were interpolated from charts prepared using the Northern Hemisphere data

[1] Mention of commercial products does not constitute an endorsement.



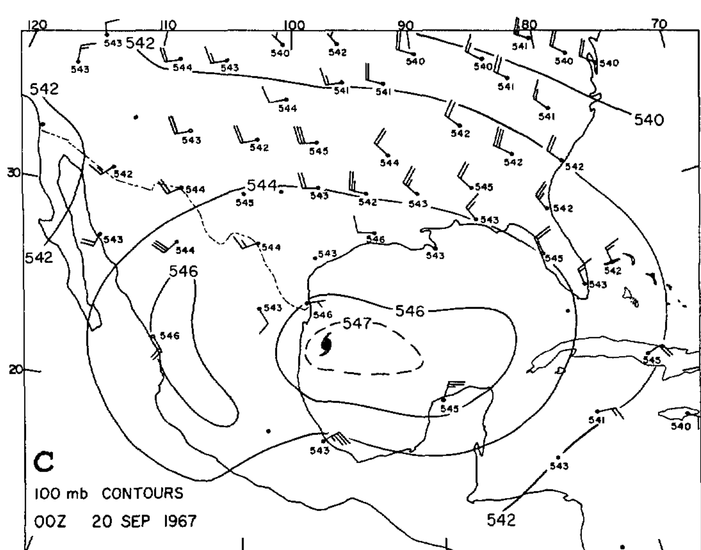


FIGURE 1.—(A) 300-mb contours and winds, (B) 300-mb isotherms, (C) 100-mb contours and winds, (D) 100-mb isotherms, and (E) 100-mb temperature departure from normal, all for 0000 GMT on Sept. 20, 1967. Contours in hundreds of feet; winds in knots; and isotherms and temperatures in degrees Celsius.

tabulations and teletypewriter data, and then values for four grid points were averaged and plotted. Such smoothing is needed to reduce inaccuracies arising from the measurement unreliabilities at this height.

Temperatures at 100 mb were lower than the mean values for September (Muench and Borden 1962) for hundreds of miles in all directions (figs. 1D and 1E), and the core itself was quite cold, as has generally been found in the upper levels of intense hurricanes (Penn 1966; Koteswaram 1967; Miller 1967; and Gentry 1967, 1968). Although at 0000 GMT the cold core appeared to be somewhat south of the surface center, inflight measurements of −86°C at 1600 GMT, when the hurricane had passed its maximum intensity, suggest that the coldest area was directly above the surface center.

3. CLOUDS

The extent of the cirrus deck associated with hurricane Beulah gives some idea as to the massiveness of the storm. The U–2 pilot observed cirrus-type clouds with 46,000-ft (147-mb) tops extending 275 mi northeast of the storm's center and extending south as far as the eye could see. This is of the same order as the cirrus shield over hurricane Daisy, 1958 (Malkus et al. 1961), which had a radius of 230 mi. Cloud tops 50 mi from Beulah's center on the north side were 50,000 ft (121 mb), and an occasional cumulonimbus tower protruded 500 ft above the cirrus.

The height of the cirrus continued to increase radially inward to 53,000 ft (105 mb) 10 to 15 mi from the hurricane's center, then rose abruptly in wall-like fashion to 54,000 ft (100 mb). The cloud structure inward from this "wall" deserves special attention and is discussed in detail in the next few paragraphs.

While flying above the hurricane at 65,000 ft (57 mb), the pilot observed a dark circular band in the cirrus deck with a diameter of about 25 mi. After the descent, it was discovered that the band more or less coincided with the wall described above. The band or wall gave a visual picture of the eye, which was completely obscured by the cirrus shield. The cloud surface inward from the wall was relatively flat instead of dome-shaped as has sometimes been suggested (e.g., Koteswaram 1967).

One cumulonimbus tower protruded above the cirrus in the northwest quadrant of the hurricane. On the western edge of the wall, the 54,000-ft (100-mb) cap extended out over the surrounding area in an unorganized fashion.

It should be noted that, in locating the hurricane's center, a perpendicular eye wall was assumed, an observation noted by Malkus and Riehl (1960) and Miller (1967).

4. AIRCRAFT OBSERVATIONS

The flight track of the U–2 aircraft is shown in figure 2 along with the track of Beulah. The plane approached Beulah's northwestern side at 65,000 ft (57 mb) and flew three counterclockwise loops around the center. For half of the first loop, the aircraft continued at 65,000 ft to a point almost due east of the center. From there, the pilot descended to 55,000 ft (95 mb) on the western side. The next two loops were flown, for the most part, at cloud-top level (approximately 54,000 ft or 100 mb).

The positions of Beulah at 1221, 1840, and 1945 GMT were established from radar fixes at Brownsville. The 1624 GMT location was estimated from the pilot's observation of the circular pattern within the clouds.

HORIZONTAL TEMPERATURE VARIATION

Figure 2 shows time histories of temperature and pressure altitude from eight 3-min runs (segments, each approximately 22 mi) along the U–2's flight path in the immediate vicinity of Beulah. The location of the runs in reference to the hurricane's position is illustrated in the diagram of the flight track. The runs are discussed below.

Run 1—The start of this run was at 55,000 ft (95 mb) along the western edge and about 1,000 ft above the eye cloud area. By the end of the run, the pilot had descended to just above the cloud tops. A sharp drop in temperature of 4.5°C in 7 sec (approximately 1 mi) occurred when the pilot descended to within 700 ft of the cloud tops. The temperature continued to fall to −85°C at cloud-top level. There was a total temperature drop of 10°C in the 750 ft of descent.

Run 2—This run commenced about 10 mi south-southeast of the hurricane's center and was completed 3 mi west-southwest of the center. The altitude was kept fairly constant at 54,300 ft (98 mb). The temperature of −86°C near the beginning of the run equaled the lowest on any part of the flight. A sudden 4°C rise took place after the start of the run, and the rise continued to −77°C about 3 mi before the end; the temperature then dropped sharply to −84°C. The cold portions appear to have coincided with the level of the cloud tops. The pilot observed that the tops were lower in the area of warming. The lowering of the tropopause along with the clouds could explain the higher temperatures. Simpson (1952) noted in the case of typhoon Marge in 1951 that the tropopause lowered as the hurricane approached, then rose to a maximum over the eye. Since the U–2's altitude was kept fairly constant, observations were likely higher above the tropopause where the clouds were lower.

Runs 3 to 5—The temperature fluctuated between −82° and −85°C in the early part of run 3 when the plane was in the vicinity of the hurricane's center heading north. The temperature rose slowly to −81°C on the north side (run 4) and gradually lowered as the plane headed south (run 5). On the north side, the pilot descended while turning to stay near the cloud tops (run 4), which could account for lower temperatures than were recorded on the south side (run 2) where the plane's altitude was kept fairly constant while in the turn.

Run 6—This run was flown in a southern direction along the western side of the eye. During the first half of the run, the pilot flew within the wispy portion of the cirrus. Temperatures were low throughout the run, with

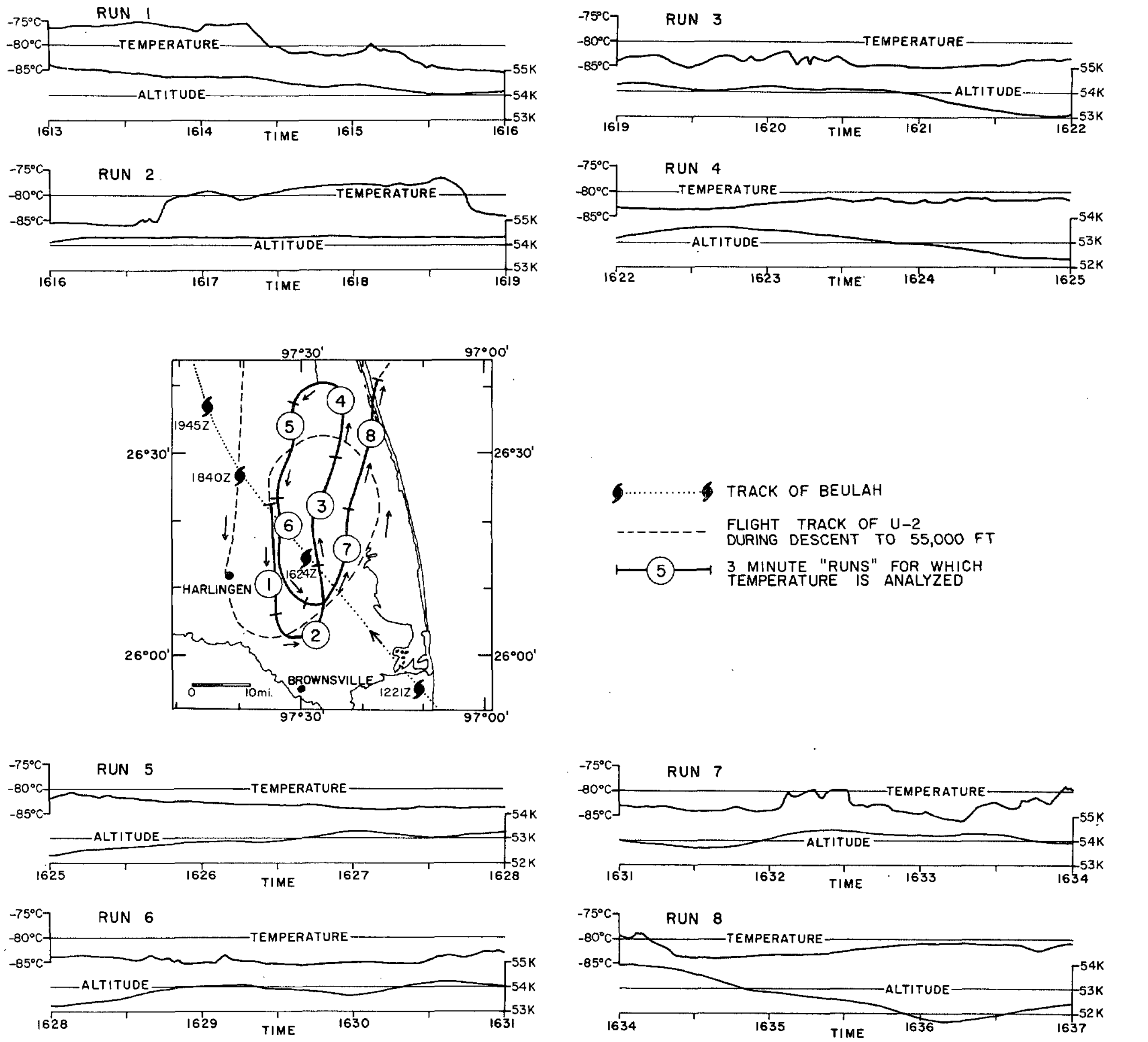


FIGURE 2.—Time histories of temperature (deg Celsius) and pressure altitude (feet) for runs 1 through 8 and the flight track of the U-2 aircraft over hurricane Beulah.

only 2° fluctuations. A slight cooling took place in the middle of the run as the pilot climbed above the cirrus. Run 6 was flown in proximity to run 1, with the exception of being closer to the cloud tops. Hence, the 10°C drop in temperature during run 1 was probably due to the aircraft's descending from the stratosphere into the troposphere. Run 6, on the other hand, was entirely below the tropopause.

Run 7—This leg was on the eastern side of the hurricane, fairly close to the cloud tops. Temperature fluctuations up to 7°C occurred with only a 250-ft altitude change. Temperatures were lowest in the southeast portion of the hurricane near the beginning of the run (−84°C) and in the area about 7 mi east of the eye center (−86°C). There were two zones of warming, again appearing to be above the tropopause. The first was attributed to the plane's ascent above the clouds, the second to the dropping-off of the cloud tops and the accompanying lowering of the tropopause as the pilot directed the aircraft away from the eye center.

Run 8—The temperature was −83°C near the beginning of the run, 12 mi northeast of the hurricane's center. The pilot descended during the run to stay close to the clouds. A gradual temperature rise took place to −80°C. This was most likely due to the increased distance of the aircraft from the hurricane's center and a subsequent lowering of the tropopause.

Summary—The lowest temperatures above Beulah appeared to coincide with the position of the highest clouds, or, more precisely, a few hundred feet above their tops.

Since the cirrus cap was relatively flat above the hurricane, the coldest zone was uniformly distributed over a wide area rather than in one or more particular locations. Warming that took place away from the hurricane's center corresponded to a lowering of the tropopause.

VERTICAL TEMPERATURE STRUCTURE

The change in temperature with height above Beulah revealed interesting features. Temperatures were measured by the U–2 between 1605 and 1639 GMT on September 20. They are 20-sec averages, read every minute on the descent from 66,000 to 55,000 ft and every 30 sec thereafter. The results are presented in figure 3 with the soundings for Monterrey, Mexico, and Victoria, Tex., and the mean September sounding for the West Indies area (Jordan 1958). The Monterrey sounding was taken at 0000 GMT on the 20th when the hurricane was 240 mi to the southeast and Victoria's at 0600 GMT when Beulah was 225 mi south.

A certain amount of caution should be taken in comparing the U–2's measured temperature profile with a true vertical sounding. First, the readings were taken over an area 25 by 40 mi. Second, the plane never actually penetrated the clouds while over the hurricane; hence, all readings below about 53,500 ft (102 mb) were outward from the eye cloud area. Nevertheless, the profile reveals some interesting features, namely:

1. The thick layer cooler than the mean,
2. A tropopause at 54,000 ft (100 mb), about 5,000 ft (27 mb) higher than the mean, with a temperature of − 86°C, 12°C lower than the mean for that level, and
3. An 11°C temperature rise in only a few hundred feet above the tropopause. These observations agree closely with U–2 measurements over hurricane Isbell in 1964 (Gentry 1967) where a tropopause of 102 mb (− 85°C) and a strong inversion and subsequent cooling above the tropopause were observed.

The soundings for Monterrey and Victoria, although taken over 200 mi from the hurricane's center, display some of the features found on the U–2 temperature profile. Evident are the high tropopause and large vertical extent of below-normal temperatures. Also present is the sharp rise in temperature above the tropopause, 10°C in 2,500 ft at Monterrey and 9°C in 1,200 ft at Victoria.

WIND MEASUREMENTS

Despite an oscillograph malfunction that led to some erroneous readings, directions of winds greater than 20 kt and the relative windspeeds are sufficiently trustworthy to support the general conclusions:

1. Both the highest level of measurements, 65,000 ft (57 mb), and lowest level, 54,000 ft (100 mb), had winds anticyclonic outward from the hurricane center, with a curvature similar to that observed in the clouds below.
2. The lower level winds tended to decrease radially inward, becoming very weak near the center (the same trend appearing to a lesser degree at the upper level).

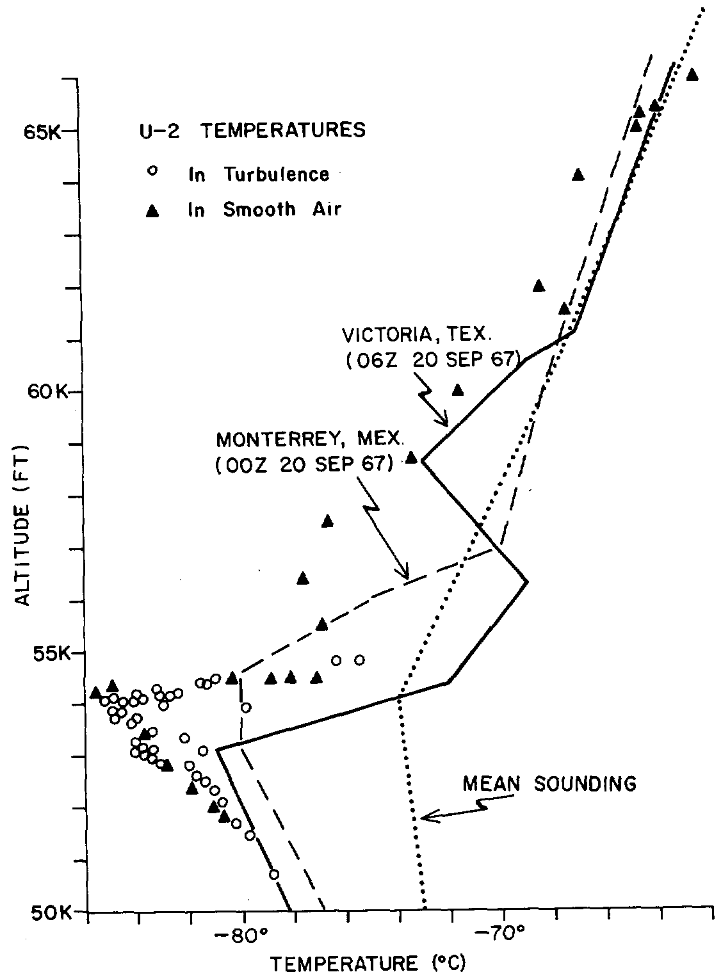


FIGURE 3.—Vertical distribution of temperature from aircraft measurements between 1605 and 1639 GMT on Sept. 20, 1967; temperature soundings for Monterrey, Mexico (0000 GMT on September 20), and Victoria, Tex. (0600 GMT on September 20), and the mean September sounding for the Caribbean are plotted for comparison.

The anticyclonic circulation near the top of Beulah does not support the hypothesis of Simpson (1952) and others that the cyclonic vortex increases in the cold core.

TURBULENCE

Turbulence encountered by the U–2 over Beulah varied from very light to light-moderate. Most of the turbulence occurred near the level of the cloud tops. Smooth conditions prevailed at all altitudes higher than 1,500 ft above the cloud tops, and only very light turbulence was found in the layer from 500 to 1,500 ft above the tops.

After leaving the hurricane area, the pilot experienced moderate turbulence at 51,000 ft (116 mb), 45 mi northeast of the eye. During this portion of the flight, the aircraft's location was 500 ft below the top of the cirrus deck.

The horizontal temperature variation above Beulah, as measured by the U–2, was related both to the the aircraft's proximity to the cloud tops and to the presence or absence of turbulence. Only small horizontal changes occurred during portions of the flight near the cloud tops where most of the turbulence was experienced. The absence of large temperature variations was probably because the flight was entirely below the tropopause in a region where the vertical temperature gradient was small and little mixing took place between the stratospheric and tropospheric air.

The zone in which the U–2 measured the largest horizontal temperature changes, located only a few hundred feet above the cloud tops, had relatively little turbulence. This was likely related to the aircraft's position in respect to the tropopause. Smooth flight conditions might be expected in a stable area, such as existed in the inversion above the vertical overshoot of the cumulonimbus clouds. At the same time, this layer had a rather strong vertical temperature gradient (fig. 3), and large horizontal temperature changes would be likely, especially considering the unevenness of a tropopause surface above cumulonimbus clouds. In actuality, the aircraft was probably sampling alternating tropospheric and stratospheric air while flying in a horizontal path due to the uneven tropopause.

5. SUMMARY

The following meteorological features associated with hurricane Beulah were found in the upper troposphere and lower stratosphere through analysis of radiosonde data and measurements by a U–2 aircraft:

1. A warm core cyclonic circulation encircled by a peripheral ridge at the 300-mb level,

2. Large zones of negative temperature anomalies both in the vertical and horizontal near the 100-mb level,

3. A tropopause just above the cloud tops at 54,000 ft (100 mb) that was 5,000 ft higher than the mean and with a temperature of −86°C, 12°C lower than the mean for the season at this level,

4. An 11°C temperature rise in only a vertical rise of a few hundred feet above the layer where convective motion reached its highest limit (the bottom of this inversion appeared to be located about 400 ft above the cloud tops; this 400-ft layer represented the overshoot of rising air in the cumulonimbus towers, and warming within the inversion layer probably resulted from subsiding air above the level of divergence), and

5. Weak but apparently anticyclonic winds at cloud top level.

Light to moderate turbulence was observed when the aircraft flew near cloud-top level, whereas relatively smooth air prevailed a few hundred feet above this. Within the turbulent zone, ascending motion in the overshoot layer above the clouds prevented the downward penetration of warmer air. Consequently, temperatures were uniformly lower in the turbulent zones. On the other hand, some rather large horizontal temperature changes occurred slightly above the cloud-top level where the U–2 experienced relatively smooth flight conditions. These changes were probably related to the large temperature change in only a few hundred feet above the tropopause and the nonuniformity of the tropopause surface. Under these conditions, a flight track along a horizontal path near the tropopause surface could result in the sampling of air alternately at the bottom and top of the inversion layer. The absence of any moderate turbulence above the cloud-top level may be partially explained by the intense inversion that could have had a dampening effect on vertical mixing.

ACKNOWLEDGMENTS

The author is indebted to Messrs. F. A. Mitchell, J. M. Rapp, and W. M. Crooks of the Lockheed-California Company for their assistance in the reduction and interpolation of the HICAT data and to H. F. Hawkins of the National Hurricane Research Laboratory for supplying pertinent synoptic data. Special acknowledgment is due Dr. Arnold Court of San Fernando Valley State College for the helpful comments stemming from his review of the paper and to Maj. Kenneth J. Mason who piloted the single engine U–2 at near-maximum range and altitude over Beulah when this violent hurricane was near its maximum intensity. Portions of the flight were conducted without benefit of radio communications. Engine failure or flameout over the area of 160-kt winds and extreme turbulence would not have permitted bailing out or gliding the aircraft to safety.

REFERENCES

Ashburn, E. V., Prophet, D. T., and Waco, D. E., "High Altitude Clear Air Turbulence Models for Aircraft Design and Operation," *AFFDL Technical Report* 68–79, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, July **1968**, 120 pp.

Ashburn, E. V., Waco, D. E., and Mitchell, F. A., "Development of High Altitude Clear Air Turbulence Models," *AFFDL Technical Report* 69–70, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, Sept. **1969**, 72 pp.

Crooks, W. M., Hoblit, F. M., and Mitchell, F. A., "High Altitude Clear Air Turbulence Measurements and Meteorological Correlations," *AFFDL Technical Report* 68–127, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, Sept. **1968**, 762 pp.

Crooks, W. M., Hoblit, F. M., and Prophet, D. T., "Project HICAT—An Investigation of High Altitude Clear Air Turbulence," *AFFDL Technical Report* 67–123, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, Nov. **1967**, 1130 pp.

Gentry, R. Cecil, "Structure of the Upper Troposphere and Lower Stratosphere in the Vicinity of Hurricane Isbell, 1964," *Papers in Meteorology and Geophysics*, Vol. 18, No. 4, Meteorological Research Institute, Tokyo, Dec. **1967**, pp. 293–310.

Gentry, R. Cecil, "Research Activities at the National Hurricane Research Laboratory," *Weatherwise*, Vol. 21, No. 4, Aug. **1968**, pp. 144–151.

Jordan, C. L., "Mean Soundings for the West Indies Area," *Journal of Meteorology*, Vol. 15, No. 1, Feb. **1958**, pp. 91–97.

Koteswaram, P., "On the Structure of Hurricanes in the Upper Troposphere and Lower Stratosphere," *Monthly Weather Review*, Vol. 95, No. 8, Aug. **1967**, pp. 541–564.

Kraft, Raymond H., "Great Hurricanes, 1955–1965," *Mariners Weather Log*, Vol. 10, No. 6, Nov. **1966**, pp. 200–202.

LaSuer, N. E., and Hawkins, H. F., "An Analysis of Hurricane Cleo (1958) Based on Data From Research Reconnaissance Aircraft," *Monthly Weather Review*, Vol. 91, Nos. 10–12, Oct.–Dec. **1963**, pp. 694–709.

Malkus, Joanne S., and Riehl, Herbert, "On the Dynamics and Energy Transformations in Steady-State Hurricanes," *Tellus*, Vol. 12, No. 1, Feb. **1960**, pp. 1–20.

Malkus, Joanne S., Ronne, Claude, and Chaffee, Margaret, "Cloud Patterns in Hurricane Daisy, 1958," *Tellus*, Vol. 13, No. 1, Feb. **1961**, pp. 8–30.

Miller, Banner I., "Characteristics of Hurricanes," *Science*, Vol. 157, No. 3795, Sept. 22, **1967**, pp. 1389–1399.

Muench, H. Stuart, and Borden, T. R., Jr., "Atlas of Monthly Mean Stratosphere Charts, *1955–1959*, Part II, July–December," *Air Force Surveys in Geophysics*, No. 141, Air Force Cambridge Research Laboratory, Bedford, Mass., Oct. **1962**, 96 pp.

Penn, Samuel, "Temperature and Ozone Variations Near Tropopause Level Over Hurricane Isbell October 1964," *Journal of Applied Meteorology*, Vol. 5, No. 4, Aug. **1966**, pp. 407–410.

Simpson, Robert H., "Exploring the Eye of Typhoon 'Marge,' 1951," *Bulletin of the American Meteorological Society*, Vol. 33, No. 7, Sept. **1952**, pp. 286–298.

Sugg, Arnold L., and Pelissier, Joseph M., "The Hurricane Season of 1967," *Monthly Weather Review*, Vol. 96, No. 4, Apr. **1968**, pp. 242–250.

[*Received January 23, 1969; revised April 29, 1970*]

CORRECTION NOTICE

Vol. 97, No. 11, Nov. 1969: p. 770, fig. 50 caption, 10^{-3} should precede joules; p. 779, fig. 7A, 1000 joules is to be read instead of 100 joules; p. 788, fig. 27, bottom part, scale of the ordinate is too small by a factor of 10; p. 800, fig. 47, the value of the heat of condensation for the A-model is 0.23 ly/min at 3° latitude; p. 801, footnote 5, add "The poleward transport of various quantities represents the transport across the whole latitude circle in part I (section 5B) and part II, whereas it represents the transport in one model ocean in part III. Therefore, it is necessary to divide the oceanic heat transport in figure 49 of part II by a factor of 3 to compare it with the corresponding transport shown in figure 14 of part III."; p. 802, fig. 51, scale of ordinate, 10^{19} CAL is to be read instead of 10 CAL; p. 810, eq. (17), delete the minus sign; p. 810, eqs. (21) and (22), κ should precede each equation; p. 820, eq. (31) is to be preceded by a^2 and eq. (32) by a.

403–235 O—70——5