NOTES AND CORRESPONDENCE

Dropwindsonde and Radar Observations of the Eye of Hurricane Gloria (1985)

JAMES L. FRANKLIN, STEPHEN J. LORD AND FRANK D. MARKS, JR.

NOAA/ERL/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

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ABSTRACT

Two soundings from the eye of Hurricane Gloria (1985) during a period of rapid deepening are described. The soundings were made by Omega dropwindsondes (ODWs) during research flights of the NOAA Hurricane Research Division on 24–25 September 1985. During the 4.7 hours between the two ODW drops, Gloria's minimum sea-level pressure fell from 932 to 922 mb.

The ODWs indicate substantial warming due to dry-adiabatic descent from 580 to 660 mb. Descent rates are estimated to be about 11 cm s^{-1}. Near 500 mb, ascent is indicated. Approximately 60% of the 10 mb pressure fall is associated with thermodynamic changes below 500 mb.

1. Introduction

On 24 and 25 September 1985, the Hurricane Research Division (HRD) of the NOAA Atlantic Oceanographic and Meteorological Laboratory conducted an experiment to determine the wind and thermodynamic fields within 1000 km of Hurricane Gloria. Omega dropwindsondes (ODWs) were released from the two NOAA Office of Aircraft Operations (OAO) WP-3D research aircraft during the experiment. Two ODW soundings were made of the lower half of the eye, as Gloria's central pressure was falling at ~2.5 mb h^{-1}. One hour after the second HRD sounding, Gloria reached its maximum intensity with a central pressure of 919 mb, which made Gloria the most intense hurricane ever to be observed in the Atlantic Ocean (Case 1986).

The eye soundings, 4.7 h apart and originating near 450 mb, presented a rare opportunity to investigate the changes in eye structure throughout the middle and lower troposphere during a period of rapid deepening of an already intense hurricane. Soundings made by reconnaissance aircraft in intense Pacific typhoons typically begin at 700 mb (e.g., typhoon Nora in 1973; Holliday 1975). Although rawinsonde ascents in hurricane eyes extend to great heights and even have penetrated the tropopause (e.g., Stear 1965), these soundings generally have not described the time evolution of the eye.

In this note we briefly describe the observing platforms used during the Gloria eye penetrations and present data from the two eye soundings, along with radar depictions of the eyewall region. The soundings are used to estimate vertical velocities within the eye during the period of rapid deepening.

Corresponding author address: Mr. James L. Franklin, Meteorologist, HRD, NOAA/ERL/AOML, 4301 Rickenbacker Causeway, Miami, FL 33149.

2. The HRD synoptic flow experiment for Gloria

The HRD conducted a synoptic flow experiment for Hurricane Gloria from 1800 UTC 24 September to 0230 UTC 25 September 1985. The experiment was designed to measure the environmental wind and mass fields surrounding hurricanes, and to provide data for detailed analyses to be used in hurricane track prediction over the normally data-void western Atlantic Ocean (Burpee et al. 1984; Lord and Franklin 1987).

On the basis of previous analyses of the environment of Hurricane Debby (1982), Lord and Franklin (1987) hypothesized that improved resolution of the wind fields within 300 km of the storm center was desirable for a more accurate diagnosis of current storm motion. Therefore, the aircraft flight tracks (Fig. 1) were modified to provide increased ODW coverage within 300 km and Doppler radar coverage within 75 km of the center.

The first NOAA/OAO WP-3D aircraft, without the Doppler radar, made a south-to-north eye penetration at 467 mb through Gloria's inner core from ~1930–2000 UTC and dropped three ODWs within 75 km of the center. About 5 h later, the second WP-3D aircraft executed a "figure 4" pattern around Gloria's center, gathered Doppler wind data, and dropped four ODWs from 446 mb at locations that were complementary to those of the first aircraft. Each aircraft dropped one ODW close to the wind center of the eye.

3. Observing platforms

The data presented here were obtained by Omega dropwindsondes (ODWs) and by the NOAA WP-3D

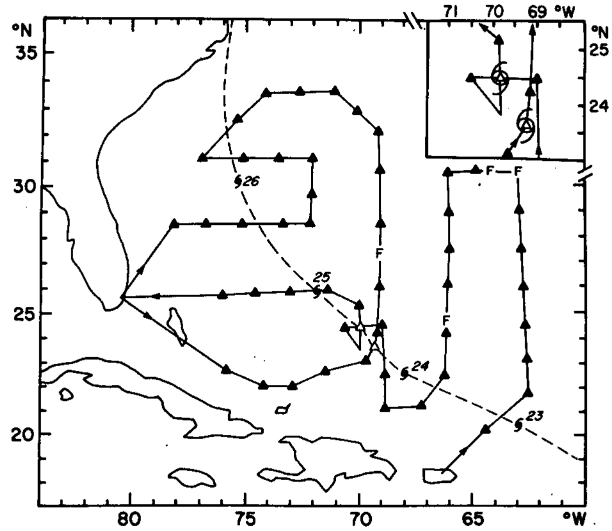


FIG. 1. Flight tracks for the Gloria synoptic flow experiment, 24–25 September 1985. Gloria's track is marked with a dashed line; the hurricane symbols identify the position of the hurricane at 1200 UTC on the dates indicated. ODW locations are marked by solid triangles; ODWs that failed are labeled "F." An expanded view of the seven ODWs in the vicinity of Gloria's center is shown in the insert. The two eye soundings are identified by open triangles.

airborne radars. The ODWs measure vertical profiles of pressure, temperature, humidity, and wind, and can be released over data-sparse oceanic regions. They have been used extensively in many field programs, including the First Global Atmospheric Research Program Alpine Expriment (ALPEX), the Genesis of Atlantic Lows Experiment (GALE), and the Equatorial Mesoscale Experiment (EMEX).

Sonde instrumentation includes an aneroid cell for pressure, bead thermistor for temperature, and carbon hygristor for humidity; nominal accuracies (for temperatures above freezing) are 2 mb, 0.5°C, and 5%, respectively (Cole et al. 1973). To measure winds, ODWs use a network of eight very low frequency (VLF) transmitters, each of which broadcasts an approximately 1 s pulse of energy every 10 s. Relative position of an ODW within a 22 km wide lane can be calculated by measuring the signal phase of that station's transmission. As the sonde descends on a parachute, it moves with the wind, and Omega signals retransmitted from the sonde to the aircraft provide instantaneous estimates of the sonde's horizontal location. Successive position estimates are then used to estimate the wind. Smoothing of the measured Omega signals is required to remove noise, so that ODW winds typically represent 50–75 mb layer means. The accuracy of ODW wind estimates depends upon many factors (Franklin and Julian 1985); for the Gloria eye soundings, wind errors are expected to be 2–3 m s^{-1}.

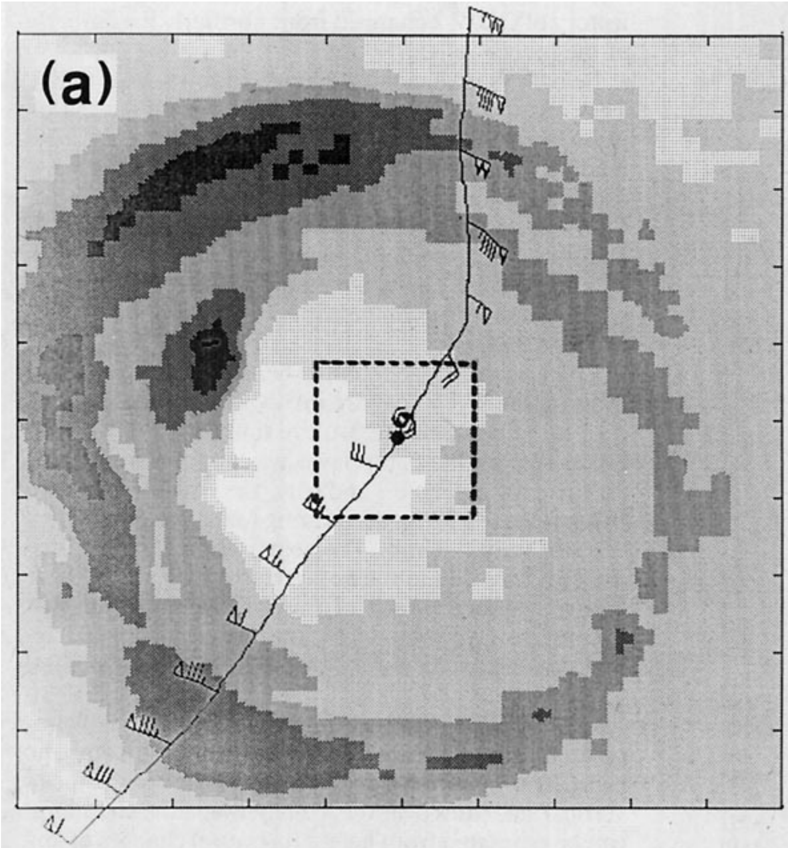
The lower fuselage (LF) radars on both NOAA WP-3D aircraft are used to map the horizontal distribution of precipitation. The LF radar characteristics may be found in Jorgensen (1984). Details of the horizontal reflectivity structure of the eyewall are determined from the LF radar data, which are mapped onto a 1 km resolution Cartesian grid centered on the moving wind center of the storm. The time compositing technique employed is described by Marks (1985). Flight-level data from the Doppler aircraft were used to determine the storm track objectively (Willoughby and Chelmow 1982). The composite reflectivity distribution is most representative of the precipitation intensity at flight level, which, for the ODW flights, was 6–7 km.

4. The ODW observations in the eye of Gloria

Figure 2a is a radar composite of the eye of Gloria at the time of the first ODW sounding (1942 UTC 24 September). At this time Gloria was moving to the north-northwest at 5–6 m s^{-1}. The eye was closed and well defined, with a diameter of 40 km. The interior of the eye was substantially filled with radar echo (equivalent rainfall of about 0.5 mm h^{-1}). The reflectivity pattern was asymmetric, with the most intense reflectivity (34–39 d*BZ*) west-northwest of the storm center, or ahead of and slightly to the left of the track. The mean reflectivity in this portion of the storm was 33 d*BZ*.

Figure 2b shows the trajectory of the ODW as it descended from a flight level of 467 mb. This storm-relative trajectory was determined from the ODW wind profile, and the objective storm motion estimate that was determined from flight-level data from the Doppler aircraft. The ODW is seen to remain well within the radar eyewall at all times. Initially, the ODW executes a cyclonic semicircle, then abruptly changes direction and moves off again with a slight cyclonic curvature to the northwest.

Figure 3 is a skew *T*–log*P* thermodynamic diagram of the data from the 1942 UTC ODW (ODW 1); tabulated data are given in Table 1. The sounding is saturated and largely moist adiabatic from 665 mb to the surface (932 mb). At the top of this cloud layer the ODW trajectory (Fig. 2b) changes from northerly to southerly. The three-dimensional radar structure (not shown) confirms that the inversion at 665 mb represents the top of a cloud layer, rather than motion of the ODW into a tilted eyewall. Above the inversion, the sounding is unsaturated, with a 500 mb temperature of 6.1°C and a relative humidity of 50%. This is slightly warmer than the 500 mb mean temperature for "intense" Atlantic hurricanes determined by Jordan (1957). The low-level moisture should not be surprising; Jordan's mean eye sounding for intense hurricanes shows relative humidities > 80% at all levels below 700 mb. Low-level moist or saturated layers within the eyes of deep storms have been reported by numerous investigators (e.g., Jordan 1952, 1961; Simpson 1952). It is unlikely, however, that saturated conditions extend



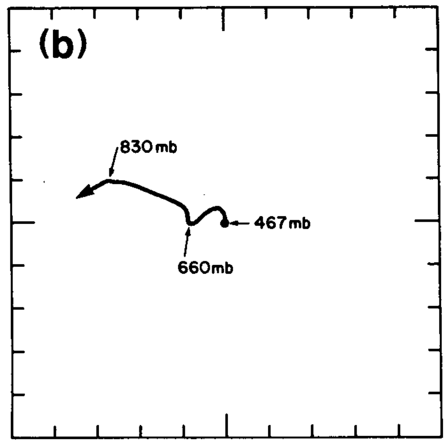


FIG. 2. (a) Time composite of the horizontal reflectivity distribution (at 6.4 km) in Hurricane Gloria from the 5.5 cm lower fuselage radar on the WP-3D for 1906–2006 UTC 24 September 1985. Reflectivity contours are at 21, 23, 27, 30, 34 and 38 dBZ and are indicated by increasing shades of gray. The dot at the center of diagram indicates the ODW launch location; and the hurricane symbol indicates the estimated center of circulation. Flight level winds at 30 s intervals are plotted in the standard fashion (full barb equals 5 m s^{-1}, flag equals 25 m s^{-1}). The tick marks indicate a distance of 5 km. The dashed box delineates the region covered in (b), which shows the storm-relative trajectory of the 1942 UTC ODW. Tick marks in (b) represent a 1 km distance.

completely to the surface, in light of the nearly dry adiabatic lapse rate in the lowest 25 mb; ODW humidity measurements are typically too high beneath cloud layers (Franklin 1987).

Figure 4 shows the history of Gloria's minimum central pressure, as determined by Air Force and NOAA reconnaissance (Clark and Case 1986). Between 1200 UTC 24 September and 0000 UTC 25 September, Gloria's pressure dropped 30 mb, a deepening rate of 2.5 mb h^{-1}. Holliday and Thompson (1979) have defined a rapidly deepening typhoon as one with a 24 h pressure fall of at least 42 mb (1.74 mb h^{-1}). Gloria met this criterion for the 24 h ending at 1800 UTC 24 September. On HRD flights, ODW surface pressures are normally estimated by a hydrostatic integration of ODW thermodynamic data downward from flight level. On this flight, however, a problem with the aircraft static pressure instrument precluded such a hydrostatic calculation. The raw ODW splash pressure is thus the only surface estimate available for this sounding. Included in Fig. 4 is the splash pressure indicated by ODW 1 (935 mb), which appears to be 2–3 mb high, compared with pressures from Air Force reconnaissance dropsondes. Examination of flight-level data (not shown) suggests that this difference is probably not due to horizontal pressure gradients within the eye. Since the discrepancy is smaller than the 5 mb rms error associated with ODW splash pressures (Franklin 1987), the pressure profile of ODW 1 was adjusted to give a surface value of 932 mb, to agree with the Air Force reconnaissance values. Geopotential heights for this ODW were then computed upward using the adjusted pressure profile.

Figure 5a is a radar composite of the eyewall at the time of the second ODW sounding (0024 UTC 25 September). The ODW trajectory shown in Fig. 5b indicates that this sonde also remained well inside the radar eye. The eye diameter, as depicted by the radar, contracted from 40–32 km over the preceding 4.7 h. The low levels of reflectivity present at the earlier time have dropped below the minimum detectable signal. The asymmetry in the eyewall reflectivity distribution is

TABLE 1. Sounding data from Gloria eye ODWs.

P (mb)	T (°C)	RH (%)	Height (m)
ODW 1: 1942 UTC 24 September 1985			
500	6.1	50	5305
525	8.8	49	4902
550	8.5	64	4517
575	10.4	62	4147
600	11.2	86	3791
625	13.0	87	3447
650	13.9	88	3115
675	13.3	100	2796
700	14.0	100	2488
725	15.5	100	2189
750	16.9	100	1899
775	18.2	100	1617
800	19.5	100	1343
825	21.0	100	1076
850	22.7	100	815
875	24.3	100	559
900	25.2	100	310
925	26.6	100	67
932	27.0	100	0
ODW 2: 0024 UTC 25 September 1985			
450	1.3	55	6121
475	1.8	81	5685
500	4.6	70	5268
525	6.1	62	4868
550	8.6	59	4485
575	11.4	52	4115
600	14.3	46	3757
625	17.1	43	3410
650	19.7	40	3073
675	22.3	36	2746
700	24.8	33	2429
725	27.7	31	2119
750	28.2	36	1818
775	21.3	83	1530
800	M	100	M
825	M	100	M
850	M	100	M
875	M	100	M
900	M	100	M
922	M	100	0

more pronounced, with the most intense reflectivity west of the center, or to the left of the storm track. However, the mean reflectivity in the western portion of the eyewall (34 dBZ) increased only slightly over the earlier time.

A skew *T* thermodynamic diagram of the 0024 UTC 25 September ODW (ODW 2) is shown in Fig. 6; tabulated data appear in Table 1. Dramatic changes occurred in the 4.7 h between ODWs 1 and 2: the 700 mb temperature rose from 14.0° to 24.8°C and the relative humidity fell from 100% to 33%. The reading of 24.8° is only 5° cooler than the record of 30° observed in Typhoons Nora, Ida, and Vera (Holliday 1975). Above 550 mb, ODW 2 was cooler and more moist than ODW 1. The temperature inversion at cloud top significantly strengthened, and fell from 660 to 780 mb (1500 m). As was the case with ODW 1, the trajectory of ODW 2 changed from northerly to southerly at the inversion (at 780 mb).

Below the inversion, the temperature sensor failed. This was most likely due to a short circuit caused by water droplets connecting the thermistor leads. The relative humidity below the inversion was 100%. A hydrostatic surface pressure calculation was possible for ODW 2, with the assumption of saturated moist adiabatic conditions where the thermistor failed. This calculation gave a surface pressure of 922 mb, a value which fits in well with the Air Force dropsondes shown in Fig. 4.

Changes in the geopotential heights of pressure levels indicate the layers that are involved in Gloria's 10 mb deepening between the two eye soundings. In Gloria's eye at sea level, a 1 mb layer was about 9.5 m thick. As the data in Table 1 indicate, the height of the 500 mb surface fell 37 m, accounting for a surface pressure drop of only 3.9 mb. The remaining 6.1 mb of fall (61%) is thus due to the net warming between 500 mb and the surface. Much of this fall occurs from 680–780 mb, a layer whose thickness increases by 37 m, and thus alone accounts for a surface pressure fall of 3.9 mb.

One would expect that the dramatic changes of temperature and moisture are due largely to dry adiabatic vertical motions in the eye. With this assumption, mean vertical velocities over the 4.7 h between the soundings can be estimated from height (pressure) changes of levels of constant potential temperature. Vertical velocities may also be calculated from pressure changes of levels of constant mixing ratio. Comparison of these two es-

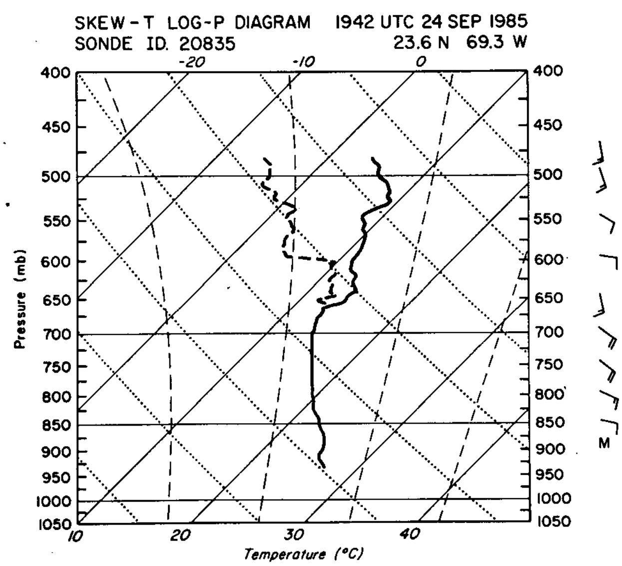


FIG. 3. Skew *T*–log*P* thermodynamic diagram for ODW 1. Temperature is indicated by the thick solid line; dew point temperature by the thick dashed line. Isotherms are indicated by the sloping, thin solid lines. Dry and moist adiabats are indicated by the thin dashed and dotted lines, respectively. ODW wind estimates are plotted at 50 mb intervals in the standard fashion.

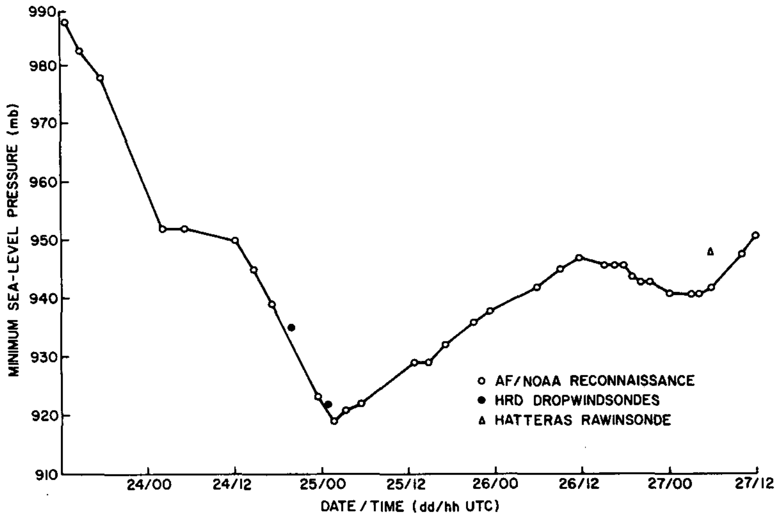


FIG. 4. Reconnaissance (open circles) and HRD dropwindsonde (closed circles) observations of Gloria's minimum sea-level pressure.

timates (Fig. 7) should provide a posteriori confirmation of the assumption. Where the two estimates of vertical velocity agree, dry adiabatic ascent or descent is the likely cause of the thermodynamic changes. Where the two estimates differ, other processes must be involved.

Based upon Fig. 7, it appears that eye air that was initially between 580 mb and the inversion (660 mb)

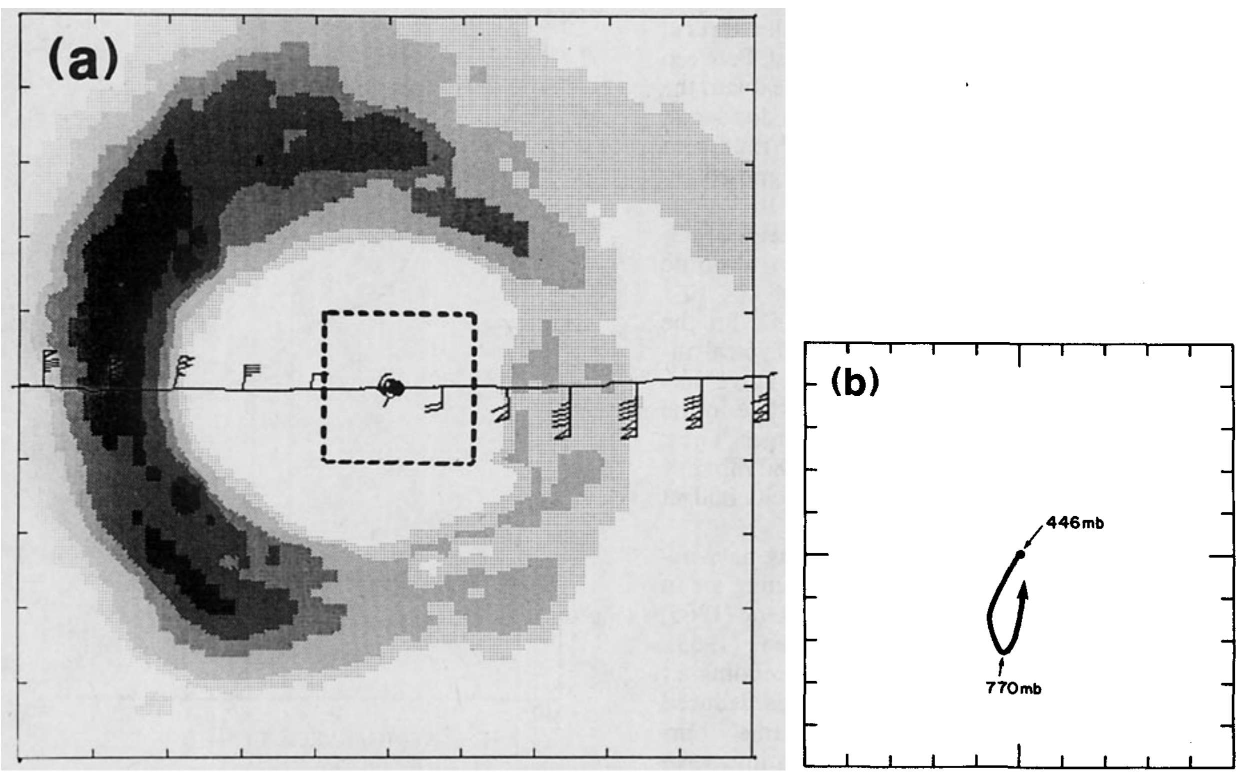


FIG. 5. (a) Time composite of the horizontal reflectivity distribution at 6.7 km in Hurricane Gloria from the 5.5 cm lower fuselage radar on the WP-3D for 0012–0042 UTC 25 September 1985, as described for Fig. 2. The dashed box delineates the region covered in (b), which shows the storm-relative trajectory of the 0024 UTC ODW. Tick marks in (b) represent a 1 km distance.

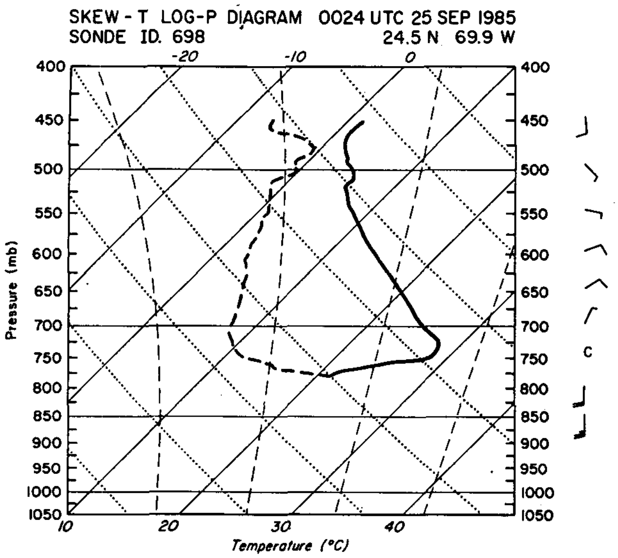


FIG. 6. Skew T–log$P$ thermodynamic diagram for ODW 2. Diagram in Fig. 3.

descended adiabatically at rates up to ~30 mb h^{-1}, or about 11 cm s^{-1}. These values agree with both observational (Riehl 1947) and theoretical (Malkus 1958; Smith 1980) estimates of eye descent rates. Near 500 mb, there is evidence of about 10 mb h^{-1} of ascent. Since the fall of the 500 mb surface suggests net descent and warming in the upper troposphere, the vertical extent of the rising motion is probably modest. Between 530 and 580 mb, adiabatic motions do not explain the thermodynamic changes, although the data do suggest that vertical motions are probably small. With ascent diagnosed above this layer, and descent diagnosed below, a convergence of approximately 1×10^{-4} s^{-1} is necessary to satisfy mass continuity. Estimates of relative vorticity in the eye of Gloria from airborne Doppler wind analyses are on the order of 1×10^{-2} s^{-1}. This gives a magnitude of 1×10^{-6} s^{-2} for the divergence term in the vorticity equation. Typical analyzed values of horizontal advection of relative vorticity in the eye are also ~1×10^{-6} s^{-2}, while in the eyewall they are an order of magnitude larger. Thus, the implied convergence between 530 and 580 mb may make a significant contribution to the vorticity budget in this layer.

Simpson (1952) suggests that ascent may have accounted for a layer of cooling and moistening air in the eye of Typhoon Marge (1951), and Stear (1965) offers evidence of ascent in Hurricane Arlene (1963). In the former case, the layer of possible ascending air was 600–700 mb; in the latter, ascent was deduced above 400 mb. Arlene was a recurving 44 m s^{-1} hurricane over Bermuda when the eye observations were taken, while Marge was a mature typhoon with a central pressure of 895 mb. Simpson does not indicate, however, whether Marge was strengthening at the time of his dropsonde observations. As far as the authors are aware, the Gloria data are the first to indicate any midtropospheric ascent in the eye of a rapidly intensifying tropical cyclone. Many physical processes, including entrainment into or detrainment from eyewall convection or gravity waves inside the eyewall, could be involved in the diagnosed vertical velocity distribution shown here. Investigation of these possibilities, however, is beyond the scope of this note.

5. Observations during the weakening stage

The WP-3D aircraft made additional observations of Gloria as it passed over Cape Hatteras at 0538 UTC 27 September—53 h after the time of Fig. 5a. The minimum sea-level pressure estimated from the flight level of 700 mb was 942 mb. Figure 8 shows the radar structure of the hurricane at that time. There is no longer a closed eyewall; the wind center appears to be tucked up against the western end of an inner rainband.

The Hatteras rawinsonde site made a sounding in the eye as Gloria moved by. The balloon was released at 0525 UTC 27 September—13 minutes before the

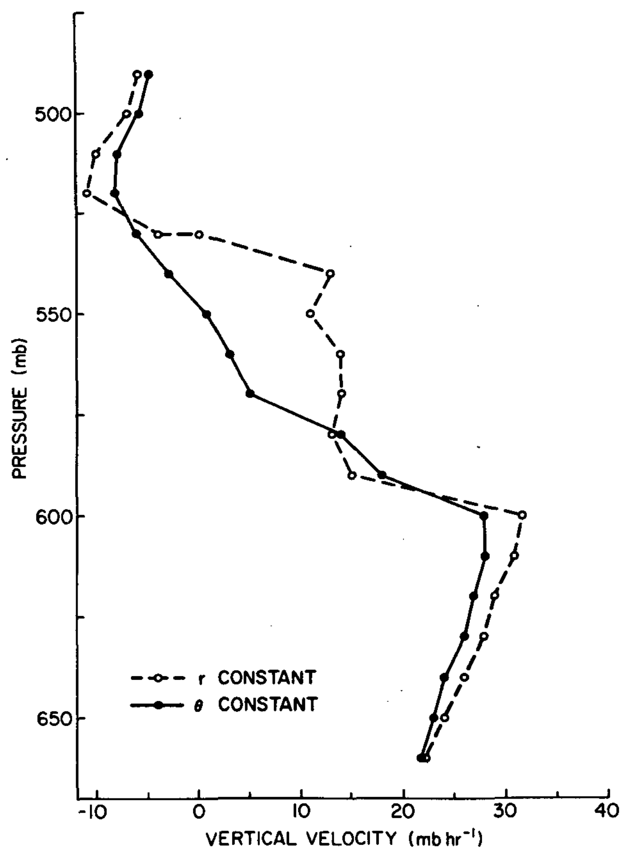


FIG. 7. Calculated mean vertical velocities for air parcels at indicated pressure levels at 1942 UTC 25 September (ODW 1). Solid line indicates velocities calculated assuming constant potential temperature; dashed line, velocities assuming constant mixing ratio.

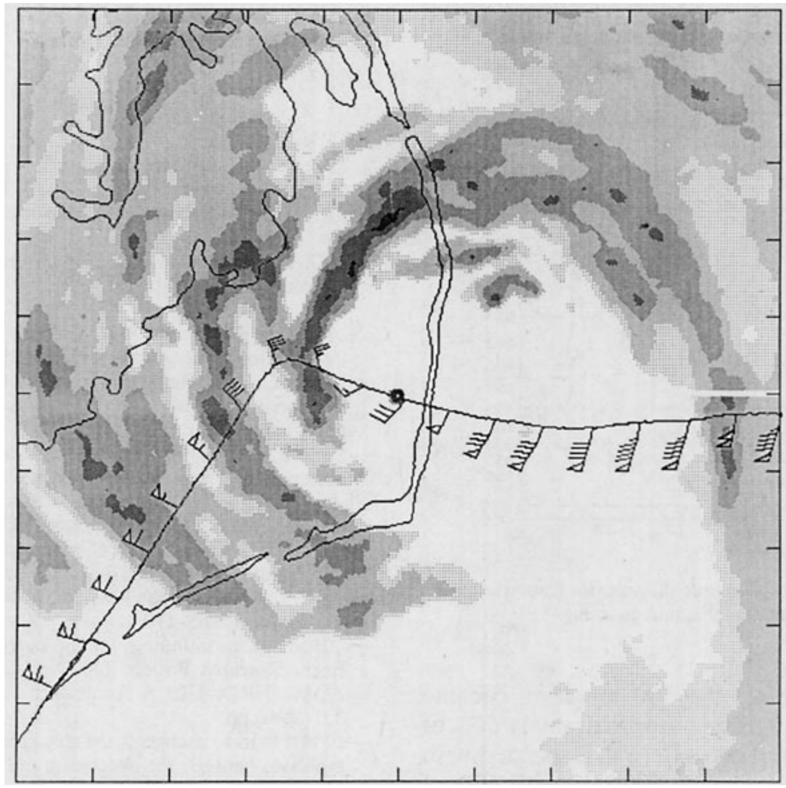


FIG. 8. Single sweep of horizontal reflectivity distribution (at 2.7 km) in Hurricane Gloria from 5.5 cm lower fuselage radar for 0538 UTC 26 September 1985, as the eye passed over Cape Hatteras, NC. Reflectivity contours are as in Fig. 2. The center of the diagram is at 35.40°N, 75.54°W. Flight-level winds at 1 min intervals are plotted as described for Fig. 2. The tick marks indicate a distance of 12 km.

radar picture in Fig. 8. This ascent (Fig. 9) indicates considerable cooling since the HRD ODW 2 sounding. The precise amount of cooling is unclear, as there are some discrepancies between the Hatteras sounding and WP-3D flight data. The rawinsonde reports saturation from the surface to 570 mb. This observation conflicts with 700 mb flight-level data from the WP-3D, which indicated relative humidities of 80–90% in the eye. The peak 700 mb temperatures observed by the aircraft were 16°–17°C, about 3° higher than indicated by the rawinsonde. The surface pressure reported by Hatteras at the time of the ascent was 948 mb, 6 mb higher than the extrapolation by the aircraft, although part of this discrepancy may have been due to the assumed temperatures used in the extrapolation. Nonetheless, these discrepancies, the time of the ascent, and the aircraft radar data all suggest that the rawinsonde was launched very close to the northern eyewall and did not stray far from the innermost spiral band until it climbed above 600 mb. Above 400 mb the sounding dried out and winds increased to 37 m s^{-1}, presumably as the balloon exited the eye from the east side.

Due to this possible trajectory of the balloon, one should be careful in comparing geopotential heights from the rawinsonde with those from the ODWs. Recalculating the geopotential heights of the rawinsonde with an assumed surface pressure of 945 mb (obtained by averaging the estimates from Hatteras and the WP-3D aircraft) gives a 500 mb height of 5380 m. Allowing for a slight underestimate of the minimum 500 mb to surface thickness due to the apparent horizontal temperature gradient, we can estimate that the true minimum 500 mb height may have been ~5410 m. This is a rise of 140 m from the value calculated from ODW 2, and corresponds to a surface pressure rise of about 15 mb. Since the surface pressure rose by about 23 mb during this time, we can crudely estimate that two-thirds of the pressure rise was associated with thermodynamic changes above 500 mb.

6. Summary and conclusions

Two ODW soundings in the eye of Hurricane Gloria showed dramatic thermodynamic changes as the hurricane deepened from 932 to 922 mb over 4.7 h. Both soundings indicated saturated conditions beneath a well-defined inversion, which fell from 660 to 780 mb. As the inversion passed through the 700 mb level, the 700 mb temperature rose from 14.0° to 24.8°C, and the relative humidity fell from 100% to 33%. During

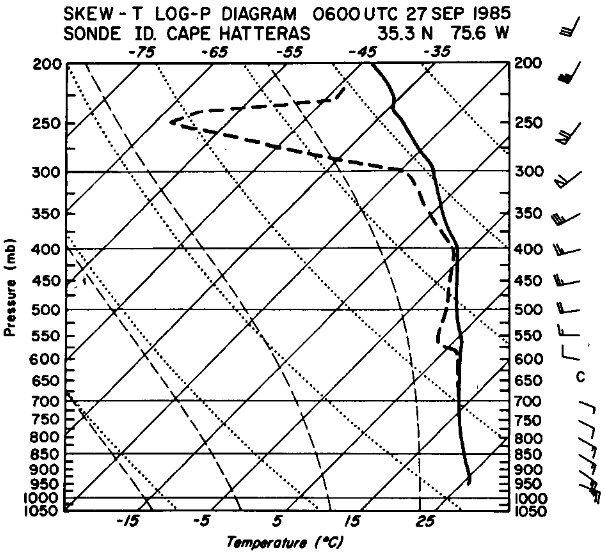


FIG. 9. Skew T–log$P$ thermodynamic diagram for Cape Hatteras Gloria eye sounding. Diagram as in Fig. 3.

this period of deepening, the 500 mb level became somewhat cooler and moister. Approximately 60% of the 10 mb fall in central pressure was associated with thermodynamic changes below 500 mb, with 40% of the total associated with the 100 mb layer initially based at 780 mb.

Vertical velocities computed from the soundings indicated peak descent rates of 30 mb h^{-1} just above the lowering temperature inversion. The fall of the 500 mb surface indicated net descent and warming above this level. Near 500 mb, however, ascent of 10 mb h^{-1} was diagnosed. As far as the authors are aware, this is the first evidence of midtropospheric ascent in the eye of a rapidly deepening tropical cyclone.

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