Warm-Core Formation in Tropical Storm Humberto (2001)

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ABSTRACT

At 0600 UTC 22 September 2001, Humberto was a tropical depression with a minimum central pressure of 1010 hPa. Twelve hours later, when the first global positioning system dropwindsondes (GPS sondes) were jettisoned, Humberto’s minimum central pressure was 1000 hPa and it had attained tropical storm strength. Thirty GPS sondes, radar from the WP-3D, and in situ aircraft measurements are utilized to observe thermodynamic structures in Humberto and their relationship to stratiform and convective elements during the early stage of the formation of an eye.

The analysis of Tropical Storm Humberto offers a new view of the pre-wind-induced surface heat exchange (pre-WISHE) stage of tropical cyclone evolution. Humberto contained a mesoscale convective vortex (MCV) similar to observations of other developing tropical systems. The MCV advects the exhaust from deep convection in the form of an anvil cyclonically over the low-level circulation center. On the trailing edge of the anvil an area of mesoscale descent induces dry adiabatic warming in the lower troposphere. The nascent warm core at low levels causes the initial drop in pressure at the surface and acts to cap the boundary layer (BL). As BL air flows into the nascent eye, the energy content increases until the energy is released from under the cap on the down shear side of the warm core in the form of vigorous cumulonimbi, which become the nascent eyewall. This series of events show one possible path in which a mesoscale convective system may evolve into a warm-cored structure and intensify into a hurricane.

1. Introduction

Wind-induced surface heat exchange (WISHE) is one of the leading theories explaining the intensification of a strong tropical depression to a full-fledged hurricane (Emanuel 1986; Rotunno and Emanuel 1987). In this theory the boundary layer (BL) air acquires heat and water vapor from the sea, which in turn is transported upward in the eyewall resulting in a maximum temperature anomaly in the upper troposphere. This warming hydrostatically reduces the surface pressure in the core of the tropical cyclone (TC), and the enhanced pressure gradient between the core and the environment produces the destructive winds associated with a hurricane. The acceptance of the WISHE theory for mature TCs is widespread among the scientific community, essentially formalizing the importance of sea to air energy transfer recognized earlier as vital for tropical cyclone development (Byers 1944; Riehl 1948; Kleinschmidt 1951; Malkus and Riehl 1960; Ooyama 1964). Some have proposed that the intensification process should be split, with a pre-WISHE phase, in which some other mechanism spins up a vortex to a critical point at which the WISHE theory can then take over (Montgomery and Farrell 1993; Bister and Emanuel 1997; Ritchie and Holland 1997; Montgomery and Enagonio 1998; Davis and Bosart 2001; Hendricks et al. 2004; Molinari et al. 2004).

Theories about the pre-WISHE phase have recently been framed as either being top down or bottom up. Both of these approaches assume that the inner core of the cyclone evolves from a mesoscale convective system (MCS). Some MCSs develop a mesoscale convective vortex (MCV) in the stratiform region, which trails the leading edge of convection (Gamache and Houze 1982; Leary and Rappaport 1987; Brandes 1990; Chen and Frank 1993). Others have hypothesized that if an MCS moves into an area favorable for genesis to occur, the stratiform rain region might play a role in tropical cyclogenesis (Bosart and Sanders 1981; Velasco and Fritsch 1987; Menard and Fritsch 1989; Frank and Chen 1991; Chen and Frank 1993; Simpson et al. 1997; Rodgers and Fritsch 2001).

Top-down theories propose that the MCV migrates to the surface at which point WISHE takes over. Simpson
et al. (1997) emphasize the importance of MCV mergers during the formation of TC Oliver during the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE). The mergers increase the vertical extent of the resulting vortex so a surface connection can be established. The vorticity-rich MCV environment reduces the Rossby radius of deformation, which allows for the more efficient warming of the troposphere. Harr et al. (1996) used Omega dropwinds sondes (ODWs) to investigate the formation of Typhoon Ofelia (1993) that formed from one persistent MCS. Although Ofelia’s formation is viewed as a top down, Harr et al. (1996) found warm, dry midlevel air near the circulation center and argues that subsidence induced on the concave side of the main convective band might have played a role in warming the troposphere and in the formation of an eye.

In the Tropical Experiment in Mexico (TEXMEX), Bister and Emanuel (1997) suggested that after an MCS has formed with a cold core in the lower atmosphere and a cyclonic circulation in the midtroposphere, the troposphere becomes nearly saturated in the core of the vortex. This prevents the evaporation of rain and inhibits downdrafts that bring cool dry air to the BL. Enhanced surface fluxes associated with increased surface winds near the core will increase the BL moist static energy. After convection occurs, the temperature of the vortex core will increase, and the WISHE mechanism can then act as a positive feedback to the warm-core cyclone.

Bottom-up theories suggest that a low-level vorticity-rich environment in concert with deep convection can initiate tropical cyclogenesis. Montgomery and Kallenbach (1997), Molinari et al. (2004), and Reasor et al. (2005) have hypothesized that the axisymmetrization of vorticity centers is important in spinning up a TC. Here vorticity is increased in localized areas by vortical hot towers (cumulonimbi with high vorticity) embedded in a well-organized, but weak low-level cyclonic circulation. Axisymmetrization and the stretching of these vorticity centers intensify the initial surface vortex to a critical point at which time WISHE becomes dominant.

To examine the formation of TC Diana (1984), Hendricks et al. (2004) used a model with a 3-km horizontal grid that is near–cloud resolving. The simulation shows the presence of vortical hot towers (VHTs), Cbs with high vertical vorticity. They develop from the buoyancy-induced stretching of the local absolute vertical vorticity. At this grid spacing, VHTs are the preferred mode of convection. VHTs produce diabatically generated low-level PV anomalies that axisymmetrize and merge, which is a step in the intensification of the newly formed vortex (Montgomery and Lu 1997; Montgomery and Enagonio 1998; Montgomery and Franklin 1998; Enagonio and Montgomery 2001; Hendricks et al. 2004; Montgomery et al. 2006). Recently, VHTs have been hypothesized to be part of the marsupial pouch paradigm (Wang et al. 2010a,b). In this scenario, an area of quasi-closed Lagrangian circulation (the cat’s eye) is moistened by convection and mostly protected from dry air intrusion. The parent wave is maintained and amplified by convection within the cat’s eye, defined as the intersection of the wave critical latitude and the trough axis.

Stossmeister and Barnes (1992) documented the development of a new second vortex that became the circulation center for Isabel (1985). This new vortex formed beneath the downwind anvil of intense convection in a rainband. They hypothesized that subsidence warming beneath the anvil, similar to the mesolows found at the trailing edge of MCSs, could lower the pressure and serve as the initial perturbation for a TC. Heymsfield et al. (2006) investigated Tropical Storm Chantal in a highly sheared environment. Although Chantal failed to intensify into a hurricane, detailed analysis of the storm provides clues to warm-core formation. The low-level circulation center (LLCC) is observed 80 km west-southwest of the deep convection in a rain-free region. Two broad regions of warming are found, one of these was argued to be due to subsidence from the interaction of the storm with high wind shear, as suggested earlier by Ritchie and Elsberry (2001). This area had a maximum temperature perturbation at 500 hPa and was located partially over the low-level circulation center. The other area of warming was found to have a maximum at the 700-hPa level. Heymsfield et al. (2006) hypothesized that this area of warming was due to similar mechanisms as observed by Stossmeister and Barnes (1992).

A rare set of observations collected in Tropical Cyclone Humberto (2001) are interpreted to gain insights into how a hurricane may form. The observations provide evidence that WISHE theory, though vital for intensification, may not explain the formation of a tropical cyclone where deep clouds become organized and rotational flow develops. The flights into Tropical Storm Humberto on 22 September provide observations on the pre-WISHE phase of tropical cyclone development. GPS sondes, radar from the WP-3D, and in situ aircraft measurements are utilized to observe thermodynamic and kinematic structures in Humberto and their relationship to stratiform and convective elements. In this study, we examine the following questions:

1) Does the warm core form in deep convection or does it form in the stratiform area of precipitation?
2) Where does the warm core form as a function of height and do the observations verify WISHE theory?
3) Is there an MCV present and what role does it play in the formation of the tropical cyclone?

2. Data and methodology

a. GPS sonde quality control

The global positioning system dropwindsondes (GPS sondes) sample at 2 Hz providing data every 6–7 m in the lower atmosphere. Wind errors from the sondes are 0.5 m s\(^{-1}\) while temperature and pressure errors are 0.2°C and 1.0 hPa, respectively (Hock and Franklin 1999). Relative humidity errors average less than 5%; however, sensor wetting can still be a problem. Bogner et al. (2000) and Barnes (2008) offer schemes to mitigate this issue. The data are initially processed using the Atmospheric Sounding Processing Environment (ASPEN) program. ASPEN, developed at the National Center for Atmospheric Research (NCAR), uses an extensive series of quality control algorithms to systematically identify spurious data and either corrects or removes these from the dataset. Details of these quality control algorithms can be found in the ASPEN user manual (Martin 2007).

b. GPS sonde deployment

Ninety-five percent of the GPS sondes deployed on 22 September recorded data successfully. A few GPS sondes were not used because of their distance from the storms circulation center. The WP-3D dropped 21 GPS sondes from approximately 600 hPa. The ER-2 dropped 2 GPS sondes, sampling from the stratosphere to the surface, while the DC-8 flew at 300 hPa and jettisoned 15 GPS sondes. The horizontal spacing of GPS sondes is about 20 km near the circulation center and about 40 km by 100 km from the center. Twenty-three GPS sondes were used for the analysis of the low-level fields (Fig. 1). These GPS sondes were jettisoned between 1843 and 2131 UTC, resulting in a composite time of 2 h, 48 min. This is approximately one sonde launch every 7–8 min. The upper-level analysis used 10 GPS sondes. They were jettisoned between 1819 and 2236 UTC, a composite time of 3 h, 17 min. This is an average of one sonde launch every 25–26 min. A brief summary of the Convection and Moisture Experiment (CAMEX) and the coordination between the aircraft is presented by Kakar et al. (2006).

c. Aircraft instrumentation

Two research radars are on the WP-3Ds. The lower fuselage (LF) radar operates at a wavelength of 5.5 cm (C band). This radar scans horizontally at all azimuth angles and provides plan views of the TC. The tail radar (X band, 3.2-cm wavelength) scans from 25° ahead to 25° behind the aircraft and rotates in a vertical plane. The WP-3D reflectivity observations from both radars are discussed by Marks (1985). The radar scans determine the convective and stratiform regions and they are used to place the GPS sonde data with respect to the persistent mesoscale features found in the TS. In situ aircraft sensors are described by Jorgensen (1984) and Aberson et al. (2006).

d. Analysis scheme

Determining storm track is the first step of the analysis. The technique of Willoughby and Chelmow (1982) is employed to establish the circulation center based on aircraft fixes. Best-track satellite centers for periods that extend on either side of the flight time are used to supplement the aircraft fixes. A few of the fixes were not used because they would cause unusual accelerations in the storm's motion. On 22 September the fixes fit a linear regression with an \( r^2 = 0.98 \).

After acquiring the storm track, the position of each sonde relative to the circulation center is determined. As the sonde falls its position was corrected for its motion relative to the moving circulation center. These data were then all composited to a central time. Here we are assuming that the evolution of the TS produced negligible variations in structure compared to the spatial
variations inherent to the TS at any given time. Humberto deepened only a few hectopascal (hPa) during the flight resulting in our ability to link our derived vortex-scale wind and state variable fields to the long-lived mesoscale features.

In the third step the storm motion $u$ and $v$ winds were subtracted from the earth-relative $u$ and $v$ winds to obtain the storm relative winds. These were then placed into cylindrical coordinates to obtain relative tangential and radial components. The fourth step is to apply a linear interpolation to fill gaps of 300 m or less and interpolate values to 10-m height intervals.

In the final step a piecewise cubic Hermite interpolation (Fritsch and Carlson 1980) was performed to create a field for any chosen variable for each level. This cubic spline method preserved the monotonicity and the shape of the data and reproduced the observed value at its observed location. The plan view maps constructed with the cubic spline matched well with subjective analyses. A three-dimensional matrix is created by stacking the plan view maps at every 10 m and keeping the grid boundaries the same. Once a three-dimensional matrix is constructed, one may slice through it at any point and in any direction to get a vertical cross section. For some of the meteorological variables this was possible through a large depth of the troposphere because the DC-8 and the ER-2 were dropping GPS sondes at high altitudes. Convective available potential energy (CAPE) is calculated for each vertical column in the matrix. This is likely an underestimate as CAPE in TCs may be calculated on lines of constant angular momentum, which tilt out from the vortex core with height. More details of the analysis scheme can be found in Dolling (2010).

e. Humberto (2001)

Humberto had its origin in a trough that extended southwest from the circulation of Hurricane Gabrielle (Beven et al. 2003). On 18 September, a westward-moving tropical upper-tropospheric trough (TUTT) enhanced the deep convection and a weak low formed in the area. The system became a tropical depression near 1200 UTC 21 September, when deep convection developed near the center of a broad cyclonic circulation. At about 1800 UTC 21 September Humberto’s pressure began to drop while under the east side of the TUTT. Early on 22 September, Humberto was a tropical depression with a minimum central pressure of 1010 hPa. The movement was to the north-northwest at approximately 4 m s$^{-1}$. Humberto would continue moving to the north and eventually recurve to the northeast. The sea surface temperatures (SSTs) ranged from about 28° to 28.5°C and the vertical wind shear was 6–7 m s$^{-1}$, which are within parameters for genesis (Gray 1968, 1979). At the time of the analysis there was still strong divergence aloft associated with the TUTT to the southwest of Humberto, facilitating the deep convection. When the first GPS sondes were jettisoned late on 22 September Humberto’s minimum central pressure was 1000 hPa and it had attained tropical storm strength. Twenty-four hours later, late on 23 September, it would intensify to a category-2 storm.

3. Results

a. GPS sonde analysis and reflectivity structure

The pressure field and streamlines at 20-m altitude (Fig. 2) reveal an area of confluence about 50 km to the north-northeast of the circulation center. The reflectivity field (Fig. 3) exhibits an arc of deep convection, oriented north to east of the low pressure center, located 40–50 km from the nascent circulation center. The arc of deep convection is collocated with the area of confluence in the streamline analysis provided in Fig. 2.

Vertical cross sections of the reflectivity structure (i.e., the RHI), taken from the tail radar of the WP-3D appear in the next two figures. Figure 4a is a north–south vertical cross section along the line marked “a” in Fig. 3. This scan cuts through the arc of convection located to the north of the circulation center. Echo tops reach to 15–16 km, the highest echo tops in the convective arc. Echo tops become progressively lower farther to the east and south in the arc. Another RHI scan (Fig. 4b) runs from northwest to southeast and is shown as a line marked “b” in Fig. 3. To the northwest there is an anvil with its base near 6 km and tops around 10 km. The area of stratiform clouds (anvil) is the exhaust from the
convective arc that lies to the north of the LLCC. The WP-3D in Fig. 4b is located about 10 km northwest of the LLCC at the time of the RHI scan. To the southeast of this scan, the reflectivity rates are about 20–30 dBZ. This is equivalent to a rain rate of about 1–4 mm h$^{-1}$ (Jorgensen and Willis 1982). Notice that the area of light rain is located over the LLCC.

The plan view reflectivity with a streamline analysis at 5 km superimposed on it (Fig. 3) reveals that an MCV is observed with its center located about 50 km north-northeast of the LLCC and just south of the convective arc. The MCV advects the exhaust from the arc of deep convection in a cyclonic direction over the LLCC. This is in contrast to prior work mentioned in the introduction. Bister and Emanuel (1997) hypothesize that the vorticity associated with the MCV migrates to the surface. In Humberto, the center of the MCV and the LLCC are offset by 50 km; the MCV remains at midlevels and advects the anvil over the LLCC where the warm core is observed under the trailing edge of the anvil.

b. The role of the stratiform precipitation in forming the warm core

During the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE), Zipser (1977) and Houze (1977) looked at the structure of strong tropical squall lines. The leading edge of the squall line is composed of a gust front and tilted updrafts followed by an area of heavy precipitation where cool saturated downdrafts are colocated with a mesohigh. In the rear of the squall is an area of lighter stratiform precipitation where a mesolow is maintained. This mesolow is characterized by a specific type of sounding that is nearly saturated and moist adiabatic from the tropopause to around 600 hPa. Between 600 hPa and the top of the BL, the air is warmer than the surrounding environment with high dewpoint depressions and a lapse rate that is nearly dry adiabatic. This structure indicates subsidence; Gamache and Houze (1982) calculated descent rates on the order of $-0.5$ m s$^{-1}$ under the anvil of one of the stronger squall lines that traveled through the GATE array.

Leary (1980) used a one-dimensional, steady-state, hydrostatic model in an attempt to reproduce this area of dry adiabatic descent on the trailing edge of the anvil. The red dashed line (Fig. 5) exhibits a sounding for a mesoscale downdraft originating at 600 hPa with a temperature of $0^\circ$C and relative humidity of 100%. The profiles of temperature and humidity in these soundings are located...
under the trailing edge of a precipitating anvil cloud (Zipser 1977). Leary calculates that with a realistic drop size distribution, the model reproduces soundings that closely resemble the soundings found in the mesoscale area of the tropical squall line. She found that with light rain rates (~1–5 mm h⁻¹) and a preexisting mesoscale downdraft originating at the base of the anvil of ~0.5 m s⁻¹, the model soundings closely resembled the thermodynamic structures found in these mesoscale unsaturated downdrafts.

Near the LLCC of Humberto under the trailing edge of the anvil, from about 600 to about 850 hPa, the temperature profile is close to dry adiabatic (Fig. 6). Dewpoint depressions reach about 13°C at 820 hPa. The base of the inversion is at 940 hPa. Two other GPS sondes were jettisoned near the circulation center and they display similar structures to the GPS sonde in Fig. 6. All three of the soundings look very similar to the soundings discussed by Zipser (1977) and Leary (1980). Bister and Emanuel (1997) suggest that after an MCS and a mid-tropospheric MCV has formed, the troposphere becomes nearly saturated on the mesoscale in the vortex core. Observations in Humberto demonstrate that the core is
not saturated. The high dewpoint depressions indicate a deep dry layer in the lower troposphere.

Figure 7 displays the vertical velocity observed by the WP-3D as it travels under the stratiform area near the circulation center. The WP-3D track is from west-southwest to the east-northeast and the red arrow (Fig. 3) depicts the path of the aircraft as it passed by the LLCC. A downdraft of significant magnitude is present during

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**FIG. 6.** Skew $T$–log$p$ diagram for a GPS sonde jettisoned at 1854 UTC 22 Sep 2001, from the DC-8 near the circulation center. The red horizontal lines are pressure, the blue lines slanted from bottom left to top right indicate temperature, the dark blue lines slanted in opposite direction are dry adiabats, the curved green lines are moist adiabats, the blue dashed lines are water vapor, the thick red line is the sounding temperature, and the thick blue dashed line is the sounding dewpoint (Dolling and Barnes 2012).

**FIG. 7.** Vertical velocity (m s$^{-1}$) as a function of time (UTC) from the WP-3D flying at 4–5 km. The aircraft is near the circulation center from 1852 to 1855 UTC.
the passage near the circulation center. The magnitude of the downdraft is 2–6 m s\(^{-1}\) for about 3 min corresponding to a distance of 25 km. The area of mesoscale descent may be larger as the WP-3D flew adjacent to the LLCC. Equivalent potential temperature \(\theta_e\) on the same transect increases by 2 K as the WP-3D traverses the downdraft. This warmer \(\theta_e\) is likely from the convective arc that has been advected downwind in the anvil and over the LLCC.

Two soundings found near the LLCC are compared with soundings jettisoned at the periphery of the analysis area to determine the impact of the warm dry layer that was apparent from 500 to 1000 hPa on the surface pressure. Calculating the hydrostatic pressure deficit from this warm dry layer reveals that this layer accounts for about 9–11 hPa drop in pressure, depending on which peripheral sounding is used. This accounts for over 90% of the total pressure drop observed at the surface in TS Humberto.

Using all the GPS sondes jettisoned on 22 September, a three-dimensional matrix is constructed and then a vertical cross section of the temperature perturbation is made as described in the data and methodology section. This vertical crosssection is an east–west slice directly through the LLCC. The temperature perturbation cross section (Fig. 8) exhibits a maximum of 6°–7°C located at about 2 km. This low-level positive temperature perturbation is found beneath the anvil with rain rates of approximately 1–4 mm h\(^{-1}\). This suggests that in Tropical Storm Humberto, conditions occur that are similar to those discussed by Zipser (1977) and Leary (1980), except that the downdraft observed just below the anvil is an order of magnitude larger.

Subsidence collocated with the trailing edge of the stratiform precipitation forms a low-level warm core and decreases the surface pressure. In the upper troposphere thermodynamic conditions are similar to the surrounding environment with no evidence of the expected positive temperature perturbation that has been observed in mature hurricanes (e.g., Hawkins and Imbembo 1976). There is only a small positive temperature perturbation of about 1°C in the upper troposphere over the circulation center (Fig. 9). The National Aeronautics and Space Administration (NASA) DC-8, which was flying at 10 km, also observed a 1°C temperature perturbation confirming the GPS sonde data. One might expect some warming to the north and the possibility of a tilted warm core because of the moderate vertical shear of the horizontal wind; however, this is not present. In these early stages of development, the maximum temperature perturbation is not in the upper atmosphere as would be expected from the WISHE theory.

In a related study using the vortex data messages, Vigh (2010) investigates eye formation. He observes that many storms display evidence of subsidence warming and drying in the lower troposphere up to 3 days before the aircraft eye (visible on radar) is observed. The pre-eye warming events become more frequent 30–24 h before eye formation and are present up to the time that the eye has formed.

The schematic in Fig. 10 highlights the difference in warm-core formation for early stage TC development for Humberto and a system if it were to form from a WISHE
perspective. The top two panels reveal how a warm core would appear if WISHE was in action. As Bister and Emanuel (1997) suggest, a nearly saturated core with increased fluxes from the sea surface would cause convection in the core of the system. Having nearly saturated the core of the storm and assuming an undilute updraft, air would rise along a slightly warmer moist adiabat than the environment (Fig. 10a). Since moist adiabats spread with height, the maximum warming would be present in the upper troposphere (Fig. 10b). In the case of Humberto, a mesoscale downdraft on the trailing edge of the anvil causes dry adiabatic descent under the anvil (Fig. 10c). This warms the lower troposphere, decreases the surface pressure, and causes a maximum temperature perturbation at low altitudes (Fig. 10d).

c. Trapping of air below warm core and $\theta_e$ buildup

The area of mesoscale descent (Figs. 6 and 7) located on the trailing edge of the anvil observed from the WP-3D and GPS sondes is performing two functions. It is responsible for the formation of the nascent warm core located in the lower levels of the troposphere (Fig. 8). The area of mesoscale descent is also capping the area beneath it, which allows for a buildup of $\theta_e$ via fluxes from the sea surface. As discussed by Dolling and Barnes (2012), this reservoir of $\theta_e$ is about 750 m deep and is as warm as 365 K (Fig. 11). The reservoir was created over a number of hours as air swirled into the LLCC and acquired heat and moisture from the sea. The high $\theta_e$ air is not located in the high wind area of the storm as is expected from WISHE. Humberto is yet to be driven by the sea to air fluxes that are so important in mature TCs.

The cap (Fig. 12) has values of CIN as strong as $\sim 250$ J kg$^{-1}$ over the LLCC. CAPE near the LLCC is as high as 2500 J kg$^{-1}$ and values of $\sim 2000$ J kg$^{-1}$ are also found in a small area collocated with the deep convective band to the northeast of the circulation center. The large CAPE collocated with the LLCC could contribute to the acceleration of the updraft and spinup via the stretching term of the absolute vorticity equation. This is

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**Fig. 10.** (a) Schematic of skew $T$–log$P$ based on WISHE. The black line is a moist adiabat and represents environmental temperature structure, while the red line represents an undilute eyewall updraft. The red hatched area displays warming. (b) A schematic of the temperature anomaly associated with (a) displays a maximum temperature anomaly in the upper troposphere. (c) As in (a), but for the observations of Humberto. Below 500 hPa, the red line follows a dry adiabat until encountering the inversion and the BL. (d) As in (b), but that the temperature anomaly is associated with the temperature structure of (c) and displays maximum warming in the lower troposphere as observed in Humberto. The values in (b) and (d) are not actual observed values, but simply representative of $T$ structure.
the dominant term in the spinup process given that the environment of a developing TC has low vertical shear of the horizontal wind (Gray 1968; McBride and Zehr 1981) and density variations (solenoidal term) are negligible. The convective cells that feed upon this air would have a higher concentration of vorticity and may be akin to the vortical hot towers discussed by Hendricks et al. (2004), Reasor et al. (2005), and Montgomery et al. (2006).

d. Evolution of reflectivity structures and building an eyewall

Figure 13a is a plan view of the reflectivity structure at 1942 UTC. The WP-3D is flying from north to south at an altitude of 4 km. Comparing Figs. 13a and 3 (1900 UTC), there is a marked change in the reflectivity structure. In contrast to Fig. 3, the structures in Fig. 13a exhibit reflectivity as high as 46 dBZ adjacent to the north side of the capping inversion within about 25 km of the LLCC. The arc of deep convection 50 km to the north of the circulation center looks less organized at this time. As the WP-3D travels north and passes just west of the new convection near the LLCC at 2002 UTC, an RHI scan (Fig. 13b) shows that the anvil to the west is still present as vigorous new convection reaches heights of 15 km.

At 1941 UTC the WP-3D is flying directly through the new convection (Fig. 13a) on the north side of the LLCC. Equivalent potential temperatures as warm as 356 K are recorded by the WP-3D (Fig. 14). Such warm \( \theta_e \) can only have originated in the reservoir found in the nascent eye and under the dry adiabatic layer. As the WP-3D flies south it encounters another area of warm \( \theta_e \) (350 K) at 1942 UTC. The 350-K \( \theta_e \) is advected cyclonically around the nascent eye and mixing out from the strong convection on the north side of the nascent eyewall.

The arc of convection at 2109 UTC (Fig. 15a) wrapping from southeast to north of the LLCC in Fig. 3 has reformed closer to the circulation center. At this time the WP-3D is far enough away from the LLCC that attenuation is a problem when viewing the convection near the storm center. The plan view of the reflectivity at 2123 UTC (Fig. 15b) reveals that the convection near the circulation center has changed from the plan view in Fig. 13a. Instead of two distinct areas of convection, the arc 50 km north and the new cells nearer the center, there is one broad arc of convection. In observing a loop of the radar images, at the time that warm \( \theta_e \) BL air breaks out from under the nascent warm core and initiates convection just north of the circulation center, the arc of convection 50 km to the north breaks apart and new convective cells start to form adjacent to the low-level warm core with the trailing southeast portion of the convective arc remaining as a major rainband.

As the WP-3D first entered Humberto the convective arc was at a distance more than double the radius (20–25 km) of the low-level warm perturbation. As the WP-3D left Humberto, the new unified arc is adjacent to the low-level warm core and has a structure more like a mature TC with a warm core, a nascent eyewall, and a major rainband. Equivalent potential temperatures will increase in the eyewall as convection transports higher \( \theta_e \) up the eyewall column. A ring of higher \( \theta_e \) around the eyewall would eventually create a TC with
a warm core in the upper troposphere, essentially like WISHE theory.

4. Summary and discussion

Plan views and vertical cross sections of kinematic and thermodynamic structures constructed from GPS sondes acquired over 3 h on 22 September 2001 are utilized to examine Tropical Storm Humberto. High-altitude GPS sondes from NASA’s ER-2 and the DC-8 along with GPS sondes from the NOAA WP-3D allows for an investigation of Humberto through the depth of the troposphere. A thorough investigation of every GPS sonde is made to correct the key variables and to omit spurious data. The GPS sonde data are combined with WP-3D flight level data and radar in an effort to document the important aspects of the formation of Tropical Storm Humberto.

The salient observations in Humberto are as follows: (i) the warm core forms away from deep convection under the anvil in the stratiform area of precipitation, (ii) the warm core forms in the lower troposphere contrary to what would be expected if WISHE were acting, and (iii) the MCV is offset from the LLCC and advects the exhaust from the anvil over the LLCC where a mesoscale area of subsidence is observed to warm the lower troposphere. A schematic of the structures that are observed in Humberto appears in Fig. 16. As the WP-3D first enters Humberto on 22 September, when it is a 1000-hPa tropical storm, the reflectivity pattern consists of an arc of convection approximately 50 km north of the low-level circulation center. GPS sonde observations reveal that an MCV is present with its center about 50 km north-northeast of the LLCC. RHI scans clearly show that an anvil created from the convective arc is advected over the LLCC by the midlevel winds associated with the MCV. Under the trailing edge of the anvil and over the LLCC, subsidence is evident from aircraft observations and multiple GPS sondes. The soundings in the vicinity of the LLCC have lapse rates below 5 km that are approximately dry adiabatic with dewpoint depressions of over 12 K. The maximum temperature perturbation over the LLCC is about 7 K at 2 km. The warm dry layer beneath 5 km accounts for 90% of the surface pressure reduction. High-altitude GPS sondes and the NASA DC-8 record only a 1-K temperature perturbation in the upper troposphere. At this point in formation the warm dry layer below 5 km is caused by subsiding air and not warmer $\theta_v$ air moving up the eyewall column. Rain rates over the circulation center are a few millimeters per hour. The thermodynamic and reflectivity structures we observe in Humberto are similar...
to the model results by Leary (1980). An existing mesoscale downdraft with light rain rates allows the air to continue its descent without becoming saturated and causes a deep layer of warm dry air to form. The pressure reduction of 11 hPa at the sea surface is due to this warm dry layer.

If a mesoscale area with such a pressure lowering could be maintained for 12 h, then we may be viewing a critical step in tropical cyclone formation.

Underneath the warm perturbation the boundary layer acquires more heat and moisture, but the warm layer above the BL traps this air, allowing \( \theta_e \) to reach the warmest values seen anywhere in the storm. When this air eventually escapes it has a CAPE of 2500 J kg\(^{-1}\) that feeds the deep vigorous cumulonimbi that later become the nascent eyewall. This high CAPE would tend to concentrate vorticity via the stretching term.

Similar to TS Chantal (Heymsfield et al. 2006) and TS Isabel (Stossmeister and Barnes 1992), Humberto had a LLCC that was displaced tens of kilometers from convection. Both Chantal and Humberto had their highest temperature perturbation in the lower troposphere. The analysis of Isabel also displayed a warm dry layer in the lower troposphere. Another commonality between developing tropical storms is the high \( \theta_e \) reservoir collated with the LLCC in TS Chantal, Humberto, and Danny (Molinari et al. 2004).

Although Humberto forms at a relatively high latitude, the environmental conditions on 22 September are ideal for formation and intensification of a tropical system. A primary theme of many past observational studies has been the transformation of a low-level cold core to a warm core (Riehl 1948; Hubert 1955; Yanai 1961). In Humberto, the observations reveal a warm dry layer in the lower troposphere. The warm dry layer lowers the surface pressure and caps the BL allowing for an increase in \( \theta_e \). It is this warm \( \theta_e \) air that feeds the nascent eyewall convection. Concurrently with the outbreak of eyewall convection, the convective arc 50 km to the north reforms adjacent to the low-level warm core. In this paradigm, the formation of the nascent warm core is the first step in a sequence of events that transform Humberto from a tropical system that resembles an MCS to a system that resembles a TC. More studies on systems in the pre-WISHE phase of development are needed to verify whether this is a common path for formation. Humberto does, however, continue to develop and the minimum central pressure drops by
20 hPa in the next 24 h, close to the threshold for rapid intensification.

Future experiments in developing storms should use both GPS sondes and Doppler radar with the two WP-3Ds and upper-level aircraft. More aircraft will lower the sampling time and allow sampling of a larger area. GPS sondes jettisoned to capture the mesobeta scale near the circulation with a larger spacing farther away from the center is necessary. Doppler analysis together with GPS sondes analysis might reveal the role of both VHTs and the thermodynamics of the inner core. It will also be important to jettison high-altitude GPS sondes to map the MCV/LLCC displacement.

5. Speculation

The prevalence of anvils in nearly all developing TCs suggests that subsidence in a light rain region resulting in a warm core should occur often. What are the critical conditions that make some anvils more potent than others in forming a low-level warm core? The VWS direction and magnitude likely affect the spatial arrangement of the MCV relative to the LLCC. An example may be TS Chantal. The lower-tropospheric warming was observed 80 km southwest of the deep convection; this region was possibly a remnant of warming that occurred when Chantal was in a lower VWS environment. Increasing VWS may have separated the anvil from the LLCC. The rain rate under the anvil cannot be too heavy, otherwise, the temperature will approach a moist adiabatic profile with little warming. The anvil and stratiform rain need to be maintained for many hours. To achieve this, deep convection, which supplies the anvil with much of its condensate, must remain in proximity to the stratiform rain. It is important that the subsidence under the anvil remains in an area with high vorticity and survives long enough that a reservoir of warm \( \theta_e \) can form. The reservoir and the associated convective burst may be critical in the transition of the MCS/TS to a mature TC with its wind maximum adjacent to the warm core.

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