The Evolution of Hurricane Humberto (2001)

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ABSTRACT

In 2001, the National Oceanic and Atmospheric Administration and the National Aeronautical and Space Administration marshaled their resources to sample Hurricane Humberto for 3 successive days during the fourth Convection and Moisture Experiment (CAMEX-4). Humberto developed from a tropical storm into a category-2 hurricane despite the deep-layer vertical shear of the environmental horizontal wind (VWS) increasing markedly on the second and third days of sampling. As exhibited in earlier studies, the eyewall convection developed an azimuthal wavenumber-1 ($n=1$) asymmetry as the VWS increased. Horizontal divergence and vertical stability within 100 km of the eye exhibited persistent relationships to the VWS vector.

The warm core evolved in an unexpected way. The warm anomaly was initially located in the lower troposphere and built upward as the storm intensified. The maximum temperature anomaly remained in the lower troposphere on all 3 days while the development of the upper-tropospheric warm anomaly appeared to be inhibited by the increasing VWS and the entrainment of dry environmental air into the core at midlevels.

The warm core of this higher-latitude (33°N) storm displayed large differences when compared to most numerical simulations, wind-induced surface heat exchange theory, and observations of tropical cyclones in the deep tropics acquired nearly 50 years ago. The results were similar to some recent numerical simulations.

1. Introduction

The cause of intensity change of tropical cyclones (TCs) has remained a major challenge for the meteorological community (Marks et al. 1998; American Meteorological Society 2000; National Advisory Board 2007). A contributing factor to our lack of understanding about intensity variations is the inadequate sampling of a TC, especially the warm core, throughout its life cycle. In 2001, the fourth Convection and Moisture Experiment (CAMEX-4) provided an opportunity to examine Humberto as it evolved from a tropical storm (TS) to a Saffir–Simpson category-2 (Simpson and Riehl 1981) and finally to a category-1 hurricane over 3 consecutive days (Beven et al. 2003). Rarely do we get a view of TC evolution with multiple aircraft, the deployment of over 200 global positioning system dropwindsondes (GPS sondes), and airborne expendable bathythermographs (AXBTs). Using methods pioneered by Frank (1977), GPS sondes jettisoned over 3–4 h are composited for each day of the experiment. The observations provide an opportunity to examine Humberto (2001) as it forms, intensifies, and weakens at higher latitudes in strengthening vertical shear of the horizontal wind (VWS). A comparison of the structures in Humberto with observations of more intense low-latitude hurricanes that developed in a more homogeneous environment reveals important structural differences between these two types of TCs. We shall emphasize the warm core, which is responsible for the reduction of surface pressure in the center of the TC.

Shapiro and Willoughby (1982), Schubert and Hack (1982), Holland and Merrill (1984), and Pendergrass and Willoughy (2009) examined the response of a hurricane-like vortex to imposed heat and momentum sources via the balanced Sawyer–Eliassen equation. A heat source placed in an area of high inertial stability—a crude approximation of an eyewall—had two effects. One was to increase the secondary circulation of the TC; another was to cause dry adiabatic descent on the inner edge of the eyewall. Shapiro and Willoughby (1982) showed that this descent can cause a pressure drop along both the inner
edge of the eyewall and in the eye, which caused the eyewall to contract; both changes would favor increasing intensity. These analytic explorations do not address the importance of the energy exchange at the sea surface and its role in affecting warm-core creation and magnitude.

The intensification of a TC due to wind-induced surface heat exchange (WISHE; Emanuel 1986) depends on higher equivalent potential temperatures $\theta_e$ in the eyewall column. The higher values are the result of greater fluxes at the air–sea interface. Higher-$\theta_e$ air ascends along warmer moist adiabats, resulting in the largest temperature differences in the upper troposphere between the eyewall and the environment. The observations in Hurricane Hilda (1964) (Hawkins and Rubsam 1968) and Hurricane Inez (1966) (Hawkins and Imbembo 1976) are considered to be some of the best views of the warm core and are often interpreted as a verification of the WISHE concept with their maximum temperature anomaly in the upper troposphere. However, both of these views show the warmest air in the eye, not the eyewall, which would necessitate radial advection and perhaps subsidence to produce the observed field. Hurricane Inez (1966) displayed a secondary positive temperature maximum below 500 hPa on both days that it was sampled, which hints that the WISHE concept may not be the only process involved with warming the eye–eyewall of a TC.

Simulations of Hurricane Wilma (2005) by Chen and Zhang (2013) show that convective-scale updrafts in the eyewall induce sinking in the eye from the stratosphere, which also could account for the maximum warming in the upper troposphere. Stern and Nolan (2012) applied the Weather Research and Forecasting model (WRF) to show a possibility that the warm core is centered in the midtroposphere. Stern and Zhang (2013), using the same model, presented evidence of radial advection from the eyewall to the eye and subsidence. Warming occurred alternately in the upper and lower troposphere as the simulation proceeded, revealing an intensification process far more complex than WISHE.

The aforementioned Sawyer–Eliassen models are idealized, but a number of observed variables would affect either heat or momentum sources. Higher amounts of midlevel moisture, eye-to-eyewall mixing, warmer sea surface temperatures (SSTs), and cooler outflow temperatures would affect convection and thus heat sources (Malkus and Riehl 1960; Emanuel 1986; Molinari and Vollaro 1989; Bosart et al. 2000; Eastin et al. 2005; Schubert et al. 2007). Upper-level outflow jets, VWS, changes in the radius of maximum wind (RMW), low-level momentum surges, and vortex Rossby waves (VRWs) may be viewed as momentum sources (Sadler 1978; Holland and Merrill 1984; Molinari et al. 1995). Through conservation of angular momentum, these factors would alter intensity.

The effects of VWS on a TC are known to be detrimental (DeMaria 1996), although the mechanism by which VWS impedes TC intensity is not fully understood and may differ depending on the conditions of the TC and the environment. Vertical shear of the horizontal wind is one of the best predictors of intensity change based on dynamic and statistical models (DeMaria et al. 2005; DeMaria 2009). Frank and Ritchie (2001) studied the phenomena with a three-dimensional numerical model and observed a weakening from the top down due to radially outward eddy fluxes of entropy at upper levels. In contrast to this view is the idea that VWS may reduce the moist entropy to the eyewall. Here, enhanced convection on the downshear side of the TC produces downdrafts that transport low-$\theta_e$ air into the boundary layer that is eventually ingested by the eyewall (Riemer et al. 2010; Riemer and Montgomery 2011). These arguments are similar to those of Barnes et al. (1983) and Powell (1990), who observed downdrafts and low-$\theta_e$ air from convective rainbands diminishing the moist entropy that reached the eyewall. Cram et al. (2007) and Tang and Emanuel (2010) view the inhibition of TC intensity by VWS through the ventilation of the TC at midlevels with low-$\theta_e$ air. Other theories include the stabilization of the vortex from midlevel warming (DeMaria 1996) and eyewall asymmetries that interact with the mean vortex through eddy momentum fluxes that diminish the mean radial and tangential winds (Wu and Braun 2004).

The Humberto dataset provides an opportunity to address a series of questions about how the inner 200 km of the vortex causes or responds to intensity change:

1) How does the warm core evolve over the 3 days? Is the warm core primarily located in the upper troposphere as we find in mature TCs in the deep tropics?
2) Are the observations of the warm core consistent with WISHE?
3) How does increasing VWS affect the vertical structure of the warm core?

2. Data and methodology

Our prior papers on Humberto (e.g., Dolling and Barnes 2012a,b) provide a detailed discussion of sonde quality control, sonde deployment, aircraft instrumentation, and analysis scheme. A total of 228 GPS sondes were deployed over the 3 days within approximately 250 km of the TC center. Every sounding was processed using the Atmospheric Sounding Processing Environment (ASPEN) program (Martin 2007). Further state-variable corrections were made following advice offered by Bogner et al. (2000) and Barnes (2008). The aircraft
observations were corrected for sensor wetting following techniques described by Zipser et al. (1981) and Eastin et al. (2002). Airborne radar interpretation follows from guidance offered by Marks (1985) and Gamache et al. (1995). Figures in the earlier papers (Dolling and Barnes 2012b, their Fig. 3; Barnes and Dolling 2013, their Fig. 2) revealed the sonde deployment. The GPS sonde deployment pattern was star-shaped with six radials emanating from the center. The analysis scheme produced storm-relative fields, corrected for sonde and TC motion, with 10-m vertical grid spacing and variable horizontal GPS sonde spacing of about 20 km near the circulation center and about 40 km by 100 km from the circulation center. When calculating the temperature perturbation, the soundings considered to be indicative of the environment were approximately 4° from the low-level circulation center.

Details on the formation of Humberto were described by Dolling and Barnes (2012b). Humberto’s early development from a cloud cluster to TS was enhanced as a tropical upper-tropospheric trough (TUTT) moved over the system and caused persistent deep convection. The system became a tropical depression near 1200 UTC 21 September and was named at 1000 UTC 22 September. The storm was located in the Atlantic basin near 29°N, 66°W and the movement was initially to the north-northwest at approximately 4 m s⁻¹. On 22 September, as GPS sondes were first jettisoned, Humberto’s minimum central pressure was 1000 hPa. Humberto continued moving to the north at 6 m s⁻¹ on 23 September as the TC intensified to 983 hPa during the second period of sampling. On the third day of sampling, late on 24 September, Humberto filled to 992 hPa as it maintained its speed during recurvature (Fig. 1).

3. Results

a. Evolution of the large-scale environment

Environmental values of relative humidity (RH), evaluated in a 200–800-km ring around the vortex, from the Statistical Hurricane Intensity Prediction Scheme (SHIPS) model (DeMaria and Kaplan 1994; DeMaria and Kaplan 1999; DeMaria et al. 2005) exhibited that Humberto evolved in a dry environment. Environmental RH in the 850–700-hPa layer for the 3 days of the experiment had values of 60%–65%. In the 700–500-hPa layer, environmental RH stayed at 45%–50% and in the 500–300-hPa layer, lower values of approximately 40%–50% were present throughout the sampling.

SSTs changed considerably from 22 to 23 September. As Humberto transitioned from a depression to a TS on 22 September, SSTs near the circulation center were approximately 28.3°C. From 22 to 23 September, there was a large north-to-south gradient and temperatures near the circulation center dropped from 28.3°C to 26.3°C. From 23 to 24 September, SSTs dropped from 26.3°C to 25.8°C.

As Humberto became a TS on 22 September, the vertical wind shear (expressed as the vector difference from 850 to 200 hPa from the SHIPS model) was 5–7 m s⁻¹ (Fig. 2) and directed toward approximately 70° (with 0° oriented toward the north). From 22 to 23 September, the VWS increased to 11 m s⁻¹ and was
toward 45°. Despite the increasing VWS, Humberto continued to intensify and the minimum central pressure dropped by 20 hPa from 22 to 23 September. On 24 September, Humberto weakened to 992 hPa while under similar VWS magnitude to 23 September, but with the vector now directed toward approximately 90°. Besides the TUTT that retrograded farther west on 22 September, the low-level and upper-level large-scale fields showed no evidence of any synoptic disturbances in the vicinity of Humberto. No changes in intensity were expected from the large-scale height fields or upper-level momentum sources.

**b. Evolution of reflectivity fields**

The mesoscale reflectivity structure of the storm is shown first in the context of the environmental shear vector. The plan views of reflectivity in Fig. 3 are centered in the vicinity of the eyewall. The three images chosen for each day represent the approximate beginning, middle, and end of the sampling period.

Figures 3a–c display the evolution of the reflectivity at 1900, 1938, and 2116 UTC 22 September. In Fig. 3a, the major feature was an arc-shaped convective band about 50 km north of the circulation center. By 1938 UTC, new
convection had developed just north of the circulation center, forming the nascent eyewall. At 2116 UTC, the nascent eyewall and the arc of convection had reformed into a large wedge shape.

On 23 September, the eyewall was crescent-shaped (Figs. 3d–f). As shown in other studies (Jones 1995; Bender 1997; Drury and Evans 1998; Frank 1998; Black et al. 2002; Eastin et al. 2005; Frank and Ritchie 1999, 2001), the convection was downshear left of the shear vector. As the shear vector turned toward the east throughout the day, the crescent also followed, keeping the maximum reflectivity to the left of the vector. Of all 3 days, the eyewall reflectivity on 23 September varied the least in shape and size.

On 24 September, as the aircraft first entered the weakened TC, the eyewall appeared as two arc-shaped wedges left of the shear vector but disconnected from each other to the northeast and northwest of the circulation center (Fig. 3g). At approximately the midpoint of the sampling period, the shape of the eyewall reflectivity changed dramatically. There appeared to be almost a 90° angle formed from two lines of convection with one covering the northern sector of the eyewall and one covering the eastern sector—the latter directly downshear (Fig. 3h). Near the end of the sampling, the reflectivity in the eyewall had become more circular and formed a large arc from the northwest to the southeast of the circulation center (Fig. 3i). The eyewall was going through a period of major restructuring on 24 September, but the convection continued to be located downshear and left of the shear vector.

The range–height indicator (RHI) views in Figs. 4a–f show the vertical structure of the reflectivity field near the circulation center. Figure 4a is a RHI scan from north to south at 1853 UTC 22 September. The scan runs through the arc of convection 50 km to the north of the low-level circulation center. The highest reflectivity in the arc was 45 dBZ and cloud tops reached to 16 km. At this time, light stratiform precipitation was occurring close to the circulation center. Reflectivity of about 45 dBZ was 25 km north of the circulation center in an east-to-west cross section of the nascent eyewall (Fig. 4b). The highest echo tops reached 14 km with returns of 37 dBZ reaching about 6.5 km. The stratiform exhaust from the convective arc 50 km to the north was still clearly visible to the west.

At 2326 UTC 23 September, a north-to-south RHI scan through some of the highest reflectivity in the north-central convective arc of the evolving eyewall revealed 40–51 dBZ located from the surface to approximately 6-km altitude (Fig. 4c). On the same day, the RHI scan (Fig. 4d) was from south-southeast to north-northwest through the mature eyewall in the northwest sector of the convective arc when Humberto was at peak intensity. Minimum detectable signal reached 16 km with maximum reflectivity of 44 dBZ near the sea surface and 37 dBZ extended to about 8 km. Similar to Black et al. (2002), the tallest echo tops were located in the downshear-left quadrant.

Figures 4e and 4f, at 2128 and 2428 UTC 24 September, respectively, show the eyewall of Humberto after a period of weakening. At 2128 UTC, the RHI scan runs from west to east through the two wedges of convection.
shown in Fig. 3g. Echo tops reached 14 km; however, the highest returns of 37 dBZ reached only about 4 km. At 2428 UTC, the RHI scan runs from south-southeast to north-northwest. The echo tops, associated with a period in which the eyewall had a more circular shape and seemed to be better organized, reached about 14 km. Scattered higher returns of 33 dBZ reached to 4 km.

The maximum echo tops were 14, 16, and 14 km while the 37-dBZ contour reached to 6.5, 8, and 4 km for the 3 days, respectively. The highest tops and greatest vertical extent of 37 dBZ coincided with the most intense period of the TC.

c. **CAPE and CIN in the vicinity of the eyewall**

Observational (Black et al. 2002; Eastin et al. 2005) and modeling (Frank and Ritchie 2001) studies offer evidence that in moderate to high shear, eyewall convection has a quasi-stationary wavenumber-1 asymmetry in vertical velocity and reflectivity. Strongest updrafts are located downshear with convective-scale reflectivity maxima located left of the downshear vector.

On 22 September, the convective available potential energy (CAPE) exceeded 2000 J kg\(^{-1}\) with convective inhibition (CIN) from \(-150\) to \(-250\) J kg\(^{-1}\) in the nascent eye; details are covered by Dolling and Barnes (2012a,b). On 23 September, CAPE of 700–800 J kg\(^{-1}\) was collocated with the downshear right quadrant of the eyewall (Fig. 5a) with small to no CAPE collocated with the upshear quadrant of the eyewall. High CIN (Fig. 5b; \(-350\) J kg\(^{-1}\)) was collocated with the eye and the upshear quadrant of the eyewall, which suppressed convection in those locations. Similar to 22 September, the cap weakened on the downshear side of the eyewall. This area was also collocated with the initiation of convection (Figs. 3d–f).

On 24 September, after a day of weakening, Humberto exhibited CAPE of 600–800 J kg\(^{-1}\) in the downshear quadrant of the eyewall with decreased values present on the upshear side. High CIN was located over the eye and the upshear quadrants of the eyewall (Fig. 6b) and had the effect of suppressing convection in those areas. Similar to 23 September, there was an absence of CIN southeast and north of the circulation center, where there was convection in the downshear quadrants.

The overall patterns of CAPE around the eyewall on 23 and 24 September support the observations and theories that locate convection and buoyant updrafts on the downshear side of the TC. CIN acted to suppress convection on the upshear side of the eyewall.

d. **Divergence in the lowest 200 m**

To calculate the horizontal divergence, the eyewall was divided into eight sections. The outer edge of each octant was determined by identifying the outer edge of the maximum reflectivity in the eyewall. For 22 September, the nascent eyewall convection was used as the outer edge and was about 25 km from the low-level circulation center (LLCC). On 23 September, the eyewall was 25 km from the LLCC and on 24 September, it was at approximately 50 km from the LLCC. Divergence was calculated from the outer edge to the LLCC. Therefore, the area of each octant was approximately 246, 246, and 982 km\(^2\), respectively.

On 22 September, convergence was located in the northern half of the eyewall and divergence in the southern half (Fig. 7a). The convergence in the lowest 200 m was located to the left of the VWS vector with divergence to the right of the vector. On 23 September, this layer was convergent upward of the nascent eyewall convection (Figs. 7b and 3d–f). Convergence was to the
right and left of the shear vector with divergence located directly upshear in two octants. The convergence increased its annular extent from the prior day and originated in the upshear-right quadrant, increasing to its highest magnitude in the downshear-left quadrant. On 24 September (Fig. 7c), the convergence lessened slightly in its annular extent and originated in the downshear-right quadrant of the storm. Similar to 22 and 23 September, following the cyclonic trajectory of the winds, convergence began upwind of the reflectivity features in Figs. 3g–i.

On all 3 days, horizontal convergence originated cyclonically upwind of the reflectivity. Convergence covered more area around the eyewall as the storm intensified and had a persistent orientation with the VWS and motion vector.

e. Warm core and clues to intensification

The warm anomaly was estimated by comparing the temperature in the eye minus the temperature along the periphery of the TC as observed with the GPS sondes. Dolling and Barnes (2012b) have noted that on 22 September, the warm anomaly was collocated with light stratiform rain and a downdraft of 6 m s\(^{-1}\) (Fig. 8a). On 23 September, as Humberto reached its peak intensity for the experiment (983 hPa), maximum warming was 7–9 K between 1500 and 5700 m (Fig. 8b). The warming in the upper troposphere was 4–5.5 K. On 24 September, after Humberto weakened to 992 hPa, maximum temperature anomalies of 6–7 K were located between 2300 and 4500 m (Fig. 8c). In the upper troposphere, temperature anomalies of approximately 4 K were present. The maximum temperature perturbation in the lower troposphere is unlike mature TCs in the deep tropics (Hawkins and Rubsam 1968; Hawkins and Imbembo 1976).

As noted by Dolling and Barnes (2012b), 90% of the pressure drop on 22 September was caused by warming from the surface to 5 km (Fig. 9a). On 23 September, warming in the 2–3-km layer led to a maximum pressure perturbation of over 5 hPa (Fig. 9b). The contribution to the surface pressure perturbation declined at a steady rate toward the top of the troposphere. Below 6 km, over 70% of the pressure is accounted for. On 24 September, the layers below 5 km had the largest warming and thus produced the greatest pressure perturbations in the vicinity of 3–5 hPa (Fig. 9c). Similar to 23 September, over 70% of the pressure decrease was due to warming below 6 km.
The warm-core maximum and hence the largest contribution to the pressure fall at the surface was occurring in the lower troposphere on each of the 3 days. This hints that the resilience of the storm in the fairly hostile VWS conditions was likely due to processes occurring in the lower troposphere.

f. The complexity of Humberto: Contrasts to WISHE and axisymmetry

One can estimate the maximum warming possible from WISHE by first determining an environmental temperature profile from the periphery of the GPS sonde field. This profile is compared to an eyewall sounding that is assumed to be the result of an undilute moist adiabat that corresponds to the warmest saturated \( \theta_e \) from observations in the eyewall from the WP-3D aircraft. The difference between these two reveals the expected WISHE temperature anomaly through the depth of the troposphere. We interpret any warming beyond the WISHE profile as due to subsidence barring any other sources of warmer \( \theta_e \).

On 22 September, the WP-3D observed the first convective outbreak of the eyewall, which contained the highest \( \theta_e \) measured for the entire day. On 23 and 24 September, there were 12 eyewall passes by the two low-flying WP-3Ds on each day, sampling the entire eyewall annulus. On 22 September, the WISHE temperature perturbation and the Humberto temperature perturbation showed large contrasts (Fig. 10a). The expected warming in the upper troposphere from WISHE did not contribute much to the overall warming; most of the warming was due to subsidence below 5 km. On this day the low-level warm core was capping the atmosphere, allowing for an increase in \( \theta_e \) under the nascent warm core. High \( \theta_e \) of about 360 K formed a dome-shaped structure under the cap (Dolling and Barnes 2012a). The 7–8 h needed to build up the high-\( \theta_e \) reservoir, which caused CAPE to reach 2500 J kg\(^{-1}\) in the core, leads us to argue that the low-level warm core likely existed in some form since the tropical depression stage.

The temperature perturbation on 23 September exhibited increased warming in the lower troposphere and decreased warming above approximately 6 km when compared to WISHE (Fig. 10b). The highest \( \theta_e \) (356 K at 2 km) used for the WISHE estimate was located in the northern eyewall, coincident with the reflectivity maximum. The highest \( \theta_e \) observed in the southern eyewall
was 347 K at 2 km. These values are confirmed from both aircraft and GPS sonde measurements in the eyewall. Therefore, dry adiabatic descent was also dominating the southern portion of the RMW annulus where there was an absence of convection and decreased $u_e$.

Observations of intensifying storms often displayed a peak value of $u_e$ in the eyewall and a minimum in the eye (Kossin and Eastin 2001). This was the distribution of $u_e$ on 23 September when Humberto reached its peak intensity. Soon after TCs started to fill, they observed a monotonic $u_e$ distribution. Kossin and Eastin (2001) related this to asymmetric horizontal mixing between the eye and eyewall as described by Schubert et al. (1999). A similar monotonic distribution of $u_e$ was observed in the eye and eyewall as Humberto had weakened by 24 September.

On 24 September, the highest $u_e$ from the eyewall (348 K) was used to estimate the warm anomaly from WISHE. Higher $u_e$ (350–352 K) was observed in the eye above 500 m. The red dashed line in Fig. 10c displays the temperature anomaly based on WISHE if the eye $u_e$ (352 K) were used. Even if this higher eye $u_e$ were used, there was still a considerable layer of warming due to subsidence.

Although higher $u_e$ was one cause of the warming in and around the eyewall column, subsidence in the lower eye was having a large impact on the hydrostatic pressure falls and the structure of the eye–eyewall column. These arguments do not discount that increased fluxes from the sea surface with increased wind speeds were not an important component of Humberto’s development. Equivalent potential temperatures in the subcloud and lower cloud layers (not shown) on 23 and 24 September increased, moving cyclonically from the upshear quadrant of the storm to the downshear quadrant, and were collocated with high CIN.

g. Evolution of the warm core

The evolution of the warm core (Fig. 11) exhibited unexpected results. The warm core developed in the lower troposphere and built upward from 22 to 23 September as the TC’s central pressure dropped 17 hPa. Figure 12a shows the difference in the warm-core anomaly between 23rd and 22 September. Notice that the temperature anomaly increased by 6 K at 5 km; dry adiabatic descent was causing much of the increased warming as it built upward from 22 to 23 September. This is in contrast to past theories (Malkus and Riehl 1960; Emanuel 1986) and observations (Hawkins and Rubsam 1968; Hawkins and Imbembo 1976), where the highest temperature perturbation was located in the upper troposphere owing to increased fluxes from the sea surface. The secondary circulation in the eye displayed by Shapiro and Willoughby (1982) and Holland and Merrill (1984) may have played a large role in the evolution of the warming of Humberto’s core. A heat source was apparent on 23 and 24 September, although asymmetric, based on the distribution of the eyewall convection. The heat source seemed to be effective at causing dry adiabatic descent in the eye, not through the entire troposphere, but building upward as the area of
subsidence increased in vertical extent from 22 through 23 September in the lower and midtroposphere.

Above the area of subsidence, on 23 September, convection was warming the upper troposphere but with less efficiency than in the lower troposphere. Equivalent potential temperatures at 10 km on 23 September reached values of 349 K (Fig. 13a). The difference from the 356-K $\theta_e$ at 2 and 5 km, measured by the WP-3Ds, to 349 K at 10 km indicates that cooler $\theta_e$ was mixing into the eyewall as the air ascended up the eyewall column. It is likely that the VWS had already inhibited upper-level warm-core formation on 23 September.

The schematic of the difference in the temperature perturbation in the core of Humberto from 23 to 24 September (Fig. 12b) displayed the largest cooling of 4 K between 4 and 6 km. Above 6 km, there was only slight cooling of about 1 K. On 24 September, $\theta_e$ remained fairly steady from a high of 348 K in the eyewall at 2 km to 347 K at 10 km (Fig. 13b), although if one considers the higher $\theta_e$ in the eye (352 K), there was cooler $\theta_e$ mixing into the eye column. From 23 to 24 September, there was only a 2-K differential in the upper-tropospheric $\theta_e$. This hints that the ventilation and inhibition of the upper-level warm core had already occurred by 23 September with only minor cooling from 23 to 24 September, when the magnitude of the VWS was invariant.

FIG. 10. Comparison of Humberto temperature anomaly (green) with WISHE temperature anomaly (red) on (a) 22, (b) 23, and (c) 24 Sep 2001. Red dashed line in (c) is the WISHE temperature anomaly if the eye $\theta_e$ is used instead of the eyewall.

FIG. 11. The evolution of the warm core as a function of height and day from 22 to 24 Sep. Contours are of the warm-core anomaly every 1 K.

FIG. 12. Schematic of the warm-core temperature perturbation difference calculated by (a) subtracting 23 Sep from 22 Sep 2001 and (b) subtracting 24 Sep from 23 Sep 2001. The contour interval is 1 K.
h. Effects of vertical wind shear on the warm-core structure

The cross section of relative humidity on 23 September (Fig. 14) revealed that in the eye, the layer from 1500 to 6500 m had a lower relative humidity of 40%–60% compared with the areas above and below this layer. The dry layer in the eye was associated with lapse rates that were close to dry adiabatic. Comparing Figs. 10b and 14 revealed two regimes: The warm dry vortex (WDV), located in the lower to midtroposphere, was caused by subsiding air. The second regime, the warm moist vortex (WMV), was caused by the moist air advected from convection throughout the vortex at upper levels.

Extremely dry air with relative humidity of 10%–20% was encroaching into the southern eyewall at approximately 6 km on 23 September. The effect of dry-air intrusion into an updraft would tend to cool the updraft to its wet bulb temperature and shift the parcel path to a cooler moist adiabat above this level. Below this level the subsidence in the WDV was causing much of the warming.

On 23 September, there was a steady decrease in warming above 6 km (Figs. 8 and 12a) collocated with the intrusion of dry air into the eyewall. The WP-3D flights at 2 and 5 km show a persistent updraft with $\theta_e$ of 355–356 K (not shown) ascending up the northern eyewall column. There were no flights between 5 and 10 km, so high-altitude GPS sondes jettisoned at upper levels were used to estimate $\theta_e$. Equivalent potential temperatures of approximately 349 K were located at 10 km (Fig. 13a). This is a 6–7-K drop in $\theta_e$ from the convective updrafts at 2 and 5 km. This hints that the WMV on 23 September already had been cooled owing to the entrainment of dry air.

On 24 September, there was a layer of air with relative humidity of 40%–55% that was nearly dry adiabatic from 2500 to 4500 m in the eye of Humberto (Fig. 15). This area constituted the WDV on 24 September. The vertical extent of the WDV had decreased from 23 September in both the middle troposphere and the lower troposphere. Notice also that the level of dry-air entrainment (RH ~ 50%) intruding into the southern eyewall had lowered from 6 km on 23 September to 4 km on 24 September.

The schematic of the difference in the temperature perturbation in the core of Humberto from 23 to 24 September (Fig. 12b) displayed the largest cooling between 4 and 6 km of 4 K as Humberto persisted under high-VWS conditions. This coincided with the lowering of the dry-air intrusion from 6 km on 23 September to 4 km on 24 September. This corresponded with a decrease in height of the WDV from about 6 km on 23 September to approximately 4 km on 24 September.
The cooling of about 3 K at 2 km on 24 September was due to a rise in the inversion layer. Intensifying TCs typically have warm dry eyes above a marked inversion that tends to descend during intensification while, during periods of filling, the inversion level tends to ascend and the eye soundings are moister (Jordan 1961; Franklin et al. 1988; Willoughby 1998, Barnes and Fuentes 2010).

The cross sections of the warm-core differences and relative humidity offer compelling evidence that the changes in the warm core from 23 to 24 September were due to the advection of dry air into the eyewall and the penetration of this air to lower levels from 23 to 24 September as Humberto weakened. There was evidence that the differential advection caused by the VWS produced additional cooling from 23 to 24 September above 6 km. Above 6 km, about 19% of the hydrostatic pressure filling was due to the ventilation of the upper warm core. The remaining 81% of the pressure change from 23 to 24 September was due to processes occurring in the lower troposphere. Most of the pressure change was correlated with the decrease in the magnitude and vertical extent of the WDV.

The RHI scans offer additional evidence that the updraft was affected by the entrainment of dry air into the eyewall convection. On 23 September, in the northern eyewall (Fig. 4d), the highest reflectivity of 40–51 dBZ abruptly stopped at 6 km—the level of dry-air entrainment on 23 September. On 24 September, the highest reflectivity in the eyewall (Fig. 4e) of 37 dBZ ceased at 4 km, with a drastic decrease in reflectivity above this level. These observations are supporting evidence that the eyewall updrafts were losing some of their buoyancy owing to dry-air entrainment.

Overall, the largest warming or cooling in the warm core was occurring because of the variations in the vertical extent of the WDV. As Humberto intensified from a tropical storm to a category-2 TC on 23 September, the WMV in the upper troposphere warmed between 1 and 4 K. However, the largest warming of 6 K occurred in the midtroposphere as the extent of the WDV increased. From 23 to 24 September, as the WVS remained at 11 m s$^{-1}$, the WMV in the upper troposphere exhibited moderate decreases in its temperature anomaly, while most of the cooling occurred between 2 and 6 km as the WDV decreased in magnitude and in its vertical extent.

i. Vertical structure of Humberto in high VWS

Figure 16 displays the relative humidity and streamlines at different levels on 23 and 24 September. At 3 km on 23 and 24 September (Figs. 16a,d), the vortex was vertically aligned with the low-level vortex. The core of the Humberto was surrounded by moist air, although there was dry air on the far western side of the TC. On 23 September, the vortex remained vertically aligned up to an altitude just below 6 km, where the vortex started to tilt to the north (Fig. 16b). This level coincided with the layer of dry-air intrusion (Fig. 14). As the vortex tilted left of the shear vector, dry air on the upshear side of the TC was advected into the eyewall (Figs. 16b and 14).

Similar vortex structures were apparent on 24 September. At 3 km (Fig. 16d), the vortex was vertically aligned with the low-level vortex. At 4.5 km, the vortex was tilted to the north-northwest and dry air from the upshear side of the TC intruded into the core, which was likely ingested by the updraft (Figs. 16e and 15). North-to-south vertical cross sections of the radial winds (not shown) displayed little to no inflow at these levels on 23rd or 24 September. It seems that the tilt of the vortex allowed dry environmental air to intrude into the eyewall and disrupt the updraft at these levels.

At 8 km on 23 and 24 September (Figs. 16c,f), the vortex center had moved left of the VWS vector. This has similarities to model simulations (Braun et al. 2006; Riemer et al. 2010) and observations (Reasor and Eastin 2012; Nguyen and Molinari 2012). The upper-level warm core had shifted to the north, which was to the left of the VWS vector (Fig. 17). This north–south vertical cross section shows the marked asymmetries of the warm core with strong temperature gradients on the northern side of the TC below 6 km on the downshear side and weaker gradients on the upshear side. Above 6 km where dry air was entraining into the updraft, the reverse was true.
Weaker temperature gradients were present on the downshear side and stronger temperature gradients were located on the upshear side.

4. Discussion

One can imagine various scenarios for warm-core evolution. In the top panel of Fig. 18, the warm core intensifies because of WISHE with no VWS. The warm-core anomaly is highest aloft at all times and increases at upper levels as the TC intensifies. The middle panel has a warm core intensifying because of WISHE but with the addition of stronger VWS on days 2 and 3. The prevailing theory of a dissipating warm core in the upper troposphere due to ventilation occurs from days 2 to 3 in the absence of a WDV. The bottom panel exhibits Humberto’s evolution. The warm core forms on day 1 (22 September) owing to subsidence under an anvil in the lower troposphere collocated with light stratiform precipitation. On day 2, the WDV increases its vertical extent in the lower and midtroposphere, with slight warming aloft because of the inhibiting influence of the high VWS. On day 3, the WDV decreases in thickness owing to entrainment in the midtroposphere and a rising
of the inversion base. Maximum cooling is in the mid-
and lower troposphere during this weakening.

The difference between what was seen in Humberto
and what one expects from WISHE as depicted in an
ideal environment are caused by two factors: 1) sub-
sidence that produced the warm dry portion of the vortex
and 2) increasing VWS that truncated the warming in
the upper troposphere. The lack of warming aloft ap-
pears to be due to the entrainment of dry environmental
air in the midtroposphere that diluted the updrafts of the
eyewall.

5. Summary

CAMEX-4 has resulted in our ability to explore as-
pects of the evolution of Humberto (2001) over 3 days.
Despite the decreasing SST and increasing VWS,
Humberto intensified from the first day to the second
day with the central core warming and expanding upward
from the lower troposphere. The lower-tropospheric
temperature anomaly, here labeled the warm dry vortex,
was unsaturated and initially found beneath the stratiform
rain portion of the convective system. Within 100 km of
the eye, there was low-level convergence, high CAPE,
and low CIN in the downshear quadrants and low-level
divergence, low CAPE, and high CIN in the upshear
quadrants, confirming and extending prior studies (e.g.,
Frank and Ritchie 2001; Black et al. 2002; Eastin et al.
2005). Reflectivity in the eyewall was observed in areas
with higher CAPE and an absence of CIN, and located
cyclonically downwind of the low-level convergence. As
the VWS increased from the second day to the third day,
there was entrainment of dry air into the midlevels of the
eyewall and eye. This entrained air reduced the equiva-
 lent potential temperature of the eyewall updrafts and
ultimately led to a reduction of the warm moist vortex
located in the upper troposphere. The temperature
anomaly of the WDV in the middle and lower tropo-
sphere also weakened during this period. In this sheared
environment, the dilution of the warm core via the dif-
ferential advection of dry air appeared to have a greater
effect on intensity change than did the tilting of the
warm core by the VWS.

We speculate that we are seeing a pre-WISHE con-
dition on the first day with the maximum temperature
perturbation in the lower troposphere, followed by the
shear inhibiting the full development of the warm core
normally seen in mature hurricanes (e.g., Hawkins and
Imbembo 1976) and often interpreted as WISHE-induced
warming.

The subsidence warming in the WDV, collocated with
the eye, has similarities to what might be expected based
on the idealized models of Shapiro and Willoughby
(1982), Schubert and Hack (1982), Holland and Merrill
(1984), and Pendergrass and Willoughby (2009). We
note that the warming in the midlevels of Humberto has
parallels to the idealized TC WRF simulations con-
ducted by Stern and Nolan (2012) and Stern and Zhang

FIG. 17. North-to-south vertical cross section of the warm-core anomaly (K) of Humberto on
(2013). Future sampling of the warm core at greater temporal and spatial resolution with the Global Hawk and manned aircraft is viewed as a fruitful path to unravel the causes of TC intensity changes.

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