



## Rapid intensification, eyewall contraction, and breakdown of Hurricane Charley (2004) near landfall

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Received 21 August 2006; revised 2 October 2006; accepted 1 December 2006; published 16 January 2007.

[1] The rapid intensification and decay in Hurricane Charley (2004) was sampled by the WSR-88Ds in Key West and Tampa. Charley's axisymmetric wind fields, vertical vorticity, perturbation pressure, and reflectivity were derived from the ground-based velocity track display (GBVTD) technique. Charley's rapid intensification was accompanied by a contracting eyewall. The central pressure dropped  $\sim 33$  hPa in three hours. The vortex was unstable (possessed a ring vorticity profile) during the eyewall contraction while the vortex became stable (monopole vorticity profile) after Charley reached its peak intensity. Charley's eyewall broke down during the decaying stage after the land fall. This study demonstrates the powerful combination of the GBVTD technique and coastal WSR-88D data in monitoring landfalling tropical cyclones. **Citation:** Lee, W.-C., and M. M. Bell (2007), Rapid intensification, eyewall contraction, and breakdown of Hurricane Charley (2004) near landfall, *Geophys. Res. Lett.*, 34, L02802, doi:10.1029/2006GL027889.

### 1. Introduction

[2] Tropical cyclones (TCs) that rapidly intensified before landfall, such as Hurricanes Andrew (1992), Opal (1995), and Charley (2004), have caused tremendous damage to coastal regions in the United States [e.g., *Pielke and Landsea*, 1998; *Franklin et al.*, 2006]. For example, Hurricane Andrew caused 62 deaths and estimated \$24 billion [*Mayfield et al.*, 1994] and Hurricane Charley caused 10 deaths and estimated \$15 billion [*Franklin et al.*, 2006] in the United States. Hurricane Andrew's minimum central pressure dropped 19 hPa in five hours [*Willoughby and Black*, 1996] while Opal's central pressure dropped 49 hPa in 14 hours [*Shay et al.*, 2000] before landfall. The rapid intensification processes in both hurricanes were accompanied by eyewall contraction detected by either infrequent eye penetrations by reconnaissance aircraft and/or the intensity inferred from IR satellite images (e.g., Dvorak technique [*Dvorak*, 1975, 1984]). However, airborne in situ, dropsonde, and/or remote sensing instruments have seldom observed rapid intensification of landfalling TCs with enough spatial and temporal coverage and resolution to effectively identify rapid intensification prior to landfall [e.g., *Franklin et al.*, 2006]. Although the coastal weather surveillance radar 1988 Doppler (WSR-88D) network has provided high temporal ( $<6$  minutes) and spatial ( $\sim 1$  km) resolution observations on many landfalling TCs

in the United States (e.g., Danny (1997), Bret (1999), Georges (1998), Isabel (2003), and others), previously rapid intensification of TCs near landfall (e.g., Andrew and Opal) has never been observed by these coastal Doppler radars.

[3] Hurricane Charley moved northward across Cuba towards the Florida peninsula on the morning of 13 August 2004 (Figure 1a). It strengthened rapidly from Category 2 to Category 4, on the Saffir-Simpson Hurricane scale, within several hours before it made landfall in southwestern Florida near Cayo Costa, as a Category 4 storm. Based on the dropsondes released by the 53rd Weather Reconnaissance Squadron of the Air Force Reserve Command (AFRC) on 13 August 2004, Charley's central pressure dropped from 964 hPa at 1522 UTC to 941 hPa at 1957 UTC (prior to landfall), a deepening rate of  $5 \text{ hPa hr}^{-1}$ . Charley was the most intense hurricane landfall in the United States since Hurricane Andrew (1992). It decayed rapidly after landfall while moving northeastward across Florida but produced serious damage well inland over the Florida peninsula, making Charley the second costliest hurricane in U. S. history through the 2004 season, behind only Andrew of 1992 [*Franklin et al.*, 2006].

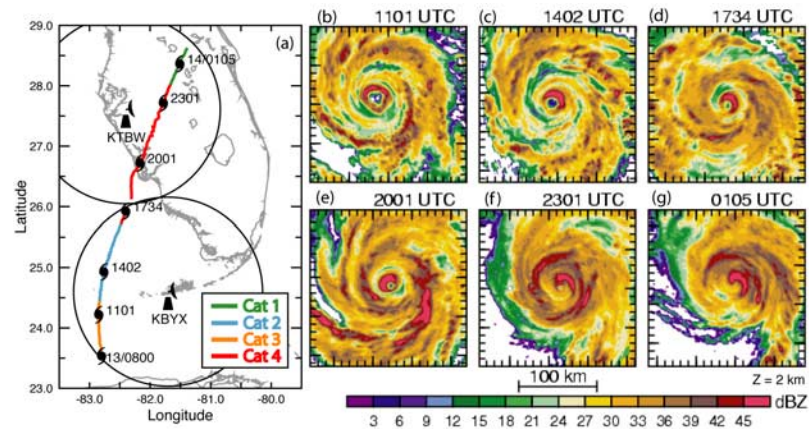
[4] Charley was continuously monitored by the Key West (KBYX) and Tampa (KTBW) WSR-88Ds during an 18-hour period (08 UTC 13 to 02 UTC 14 August 2004) with unprecedented 6-minute volume resolution as shown in Figure 1a. KBYX captured the rapid intensification of Charley while KTBW captured landfall and decaying stages of Charley. Hence, Charley's radar data present the first opportunity to examine kinematic and dynamic structures of a hurricane during its rapid intensification phase by coastal WSR-88Ds.

[5] Single Doppler radar is only capable of measuring the radial component of the wind towards or away from a radar, therefore the detailed structure of a 3-D TC wind field cannot be obtained without observations from a second Doppler radar or from a single Doppler wind retrieval technique involving additional physical assumptions. The distance between KBYX and KTBW and the effective Doppler ranges prevented the dual-Doppler analysis on Charley (Figure 1). A well documented technique to obtain the three-dimensional kinematic structure of a hurricane from the single Doppler radar observations is the ground-based velocity track display technique (GBVTD [*Lee et al.*, 1999]). This paper presents preliminary analyses of Charley's rapid intensification and decaying process at five time periods using quantities derived from the WSR-88D data and GBVTD technique.

### 2. Methodology

[6] The primary circulation of a TC can be deduced by the GBVTD technique through a Fourier decomposition of

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**Figure 1.** (a) Track and radar coverage of Hurricane Charley from 0800 UTC 13 August to 0105 UTC 14 August 2004. Range rings indicate maximum Doppler coverage (174 km) for Key West (KBYX) and Tampa (KTBW) WSR-88D radars. Colors indicate NHC best track Saffir-Simpson scale intensity. (b) – (g) Constant altitude PPI reflectivity at 2 km at six different analysis times.

Doppler velocities in a TC centered cylindrical coordinate system [Lee *et al.*, 1999]. The TC center is defined as a point that yields the maximum circulation enclosed by the radius of maximum wind deduced from the GBVTD-simplex algorithm [Lee and Marks, 2000]. Since Doppler velocities are azimuthally periodic on rings around this TC center, a Fourier analysis can decompose the structure of the radar winds at each radius via a circular wind model. The three-dimensional TC circulation can be deduced from the Fourier coefficients to provide the along beam (in the direction of the radar and TC center) component of the mean environmental wind, axisymmetric (azimuthal mean) tangential and radial winds, and asymmetric tangential winds. Unresolved asymmetric radial winds, which may be large in a landfall situation due to an enhanced surface roughness gradient, and the cross-beam (normal to radar-TC center direction) component of the mean wind are aliased into the resolved quantities. In particular, the unresolved azimuthal wave number two radial wind may bias the retrieved symmetric primary (tangential) and secondary (transverse) circulations (details are discussed in Lee *et al.* [1999]). Harasti *et al.* [2004] demonstrated application of the GBVTD-derived wind fields to nowcasting of land-falling TCs. Evolution and structures of intense landfalling TCs in the Indian Ocean (e.g., TC Dina) and northwestern Pacific (e.g., Typhoon Nari) have been deduced from GBVTD [Roux *et al.*, 2004] and EGBVTD [Liou *et al.*, 2006], respectively. The grid spacing for the GBVTD analyses of Charley is 1 km in both radial and vertical directions, adequate to resolve the axisymmetric kinematic structures. Dynamic quantities, such as the vertical velocities, vorticity, angular momentum and pressure deficits, can be computed from the GBVTD-derived axisymmetric circulations [Lee *et al.*, 2000].

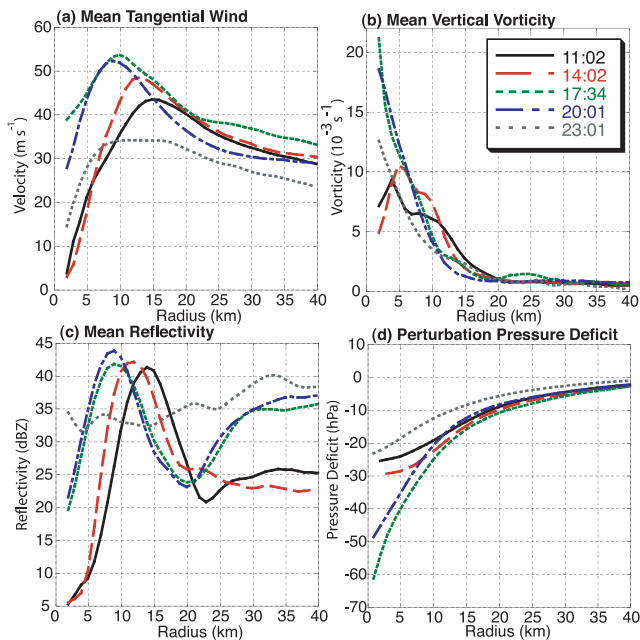
### 3. Results

[7] The low-level reflectivity structures (dBZ, 2 km constant altitude PPI) of Charley at six time periods (from 1100 UTC 13 August 2004 to 0000 UTC 14 August 2004) are illustrated in Figures 1b–1g. Charley possessed a distinct eyewall accompanied by several rainbands spiraling out

from the eyewall at 1100 UTC (Figure 1b). The reflectivity of the rainbands weakened at 1400 UTC (Figure 1c) but re-intensified at 1700 UTC to form a double eyewall (Figure 1d). The size of the eye continued to contract until Charley made landfall at 2000 UTC (Figure 1e). The eye filled with precipitation as Charley moved inland and gradually lost its organization (Figures 1f and 1g).

[8] The evolution of Charley is illustrated using the GBVTD-derived radial profiles of the axisymmetric tangential winds at  $z = 3$  km at five times; 1100, 1400, 1700, 2000, and 2300 UTC (Figure 2). Charley's intensity inferred from the axisymmetric tangential winds peaked around 1700 UTC with a magnitude of  $\sim 53 \text{ m s}^{-1}$  and maintained its intensity until its landfall around 2000 UTC. After landfall, the axisymmetric tangential wind speed decreased rapidly to  $\sim 35 \text{ m s}^{-1}$  at 2300 UTC. During the intensifying phase, Charley's radius of maximum wind fell from  $\sim 13$  km to  $\sim 8$  km between 1400 and 2000 UTC; Charley's inner core then expanded into a broad and flat pattern at 2300 UTC. From the distribution of the axisymmetric tangential wind profile (Figure 2a), the integrated kinetic energy of Charley (proportional to the area beneath each curve) peaked around 1700 UTC.

[9] The vertical vorticity patterns outside the eyewall are quite similar among all five analyses with a magnitude  $\sim 0.001 \text{ s}^{-1}$ . However, an intriguing evolution of vertical vorticity in the core region is apparent. A ring vorticity profile (vertical vorticity peaked near the radius of maximum wind so that the radial vorticity gradient changes sign), which satisfies the necessary condition for a combined barotropic-baroclinic instability [Montgomery and Shapiro, 1995], existed at 1100 UTC and intensified until 1400 UTC with a peak vorticity of  $0.011 \text{ s}^{-1}$  at  $R = 5$  km. The ring vorticity profile of Charley evolved into a monopole pattern (vertical vorticity peaked at the TC center) at 1700 UTC with a peak vorticity exceeding  $0.02 \text{ s}^{-1}$  at  $R = 3$  km, the inner most radius of the analyses. Previous studies using theoretical arguments and barotropic numerical models [Schubert *et al.*, 1999], laboratory tank experiments [Montgomery *et al.*, 2002] and composite aircraft in situ data [Mallen *et al.*, 2005], have all emphasized the importance of the axisymmetric vorticity profile on hurricane



**Figure 2.** Radial profiles at  $z = 3$  km from five analysis times (1102, 1402, 1734, 2001, and 2301 UTC). Different line styles/colors represent analysis times; (a) mean tangential wind ( $\text{m s}^{-1}$ ), (b) mean vertical vorticity ( $10^{-3} \text{ s}^{-1}$ ), (c) mean reflectivity (dBZ), and (d) perturbation pressure deficit (hPa) assuming zero at 60 km radius. Analysis domain extends to 60 km radius, but results out to 40 km are shown for clarity. Hurricane eyewall is area of high reflectivity and wind speed near 10 km radius.

evolution and intensity. The high temporal and spatial resolution of this analysis provides the first observational evidence of the transition of the axisymmetric vorticity profile from an unstable ring to a more stable monopole configuration after the vortex reached peak intensity, which has been previously suggested from composite aircraft in situ data [Kossin and Eastin, 2001]. In this case, a forecaster may have been able to use knowledge of the vorticity profile transition to nowcast that Charley might have reached its peak intensity and further deepening was unlikely.

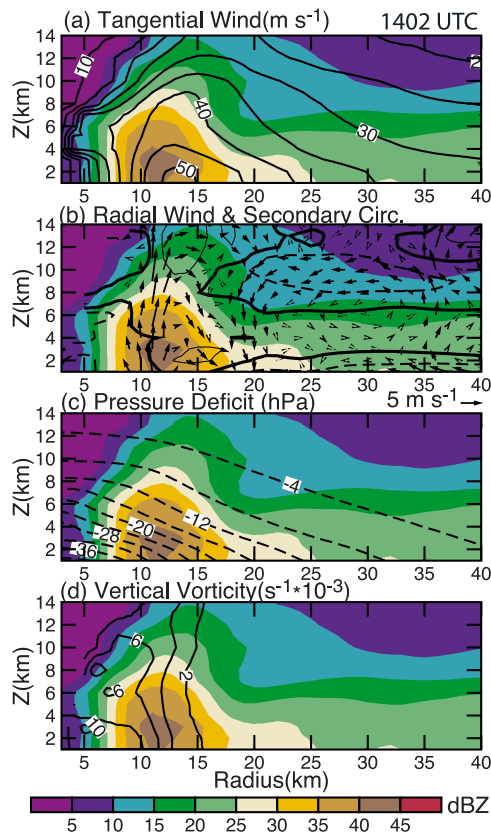
[10] The shrinking of the radius of maximum wind was concurrent with the contraction of the eyewall. The observed weak reflectivity and deduced downdraft on both sides of the eyewall were consistent with a forced response of a balanced vortex to the latent heat release associated with eyewall convection [Eliassen, 1952; Shapiro and Willoughby, 1982]. Although the eyewall reflectivity slightly increased between 1400 and 2000 UTC, the dramatic increase of the mean reflectivity by  $\sim 15$  dBZ beyond  $R = 20$  km was striking. This indicates the formation of a secondary eyewall (Figures 1c and 1d), but there was no secondary wind maximum typically associated with an outer eyewall or concentric rainbands in Charley. We speculate there may be an asymmetric secondary wind maximum and/or a potential lag between the reflectivity and velocity fields during the eyewall replacement cycle. This process might have been disrupted by landfall, preventing the completion of the secondary eyewall formation,

although it is notable that the outer reflectivity maximum was enhanced over land, possibly due to increased surface friction and convergence. After Charley's landfall, the inner eyewall collapsed and the peak reflectivity shifted to  $R = 32$  km accompanied by a broad radial rainfall distribution.

[11] Rapid intensification of Charley can be further illustrated using the perturbation pressure deficits in these five time periods (Figure 2d). Since the radar does not directly measure pressure, the symmetric radial momentum equation was integrated inward using the GBVTD derived winds, assuming the total pressure at  $R = 60$  km remained steady. Charley's central pressure dropped  $\sim 33$  hPa from 1400 to 1700 UTC, filled  $\sim 13$  hPa between 1700 and 2000 UTC, then filled another 25 hPa after its landfall at 2300 UTC. The  $\sim 11 \text{ hPa hr}^{-1}$  pressure drop between 1400 to 1700 UTC in Charley exceeded the  $9.9 \text{ hPa hr}^{-1}$  in Hurricane Wilma (2005), the most intense Atlantic hurricane on record [Pasch et al., 2006]. Note that the two dropsondes released at 1522 and 1957 UTC [Franklin et al., 2006] completely missed the deepening of central pressure from 1400 to 1700 UTC and the filling of central pressure from 1700 to 2000 UTC based on the radar analysis. With the Doppler radar data, the pressure changes can be monitored at a much higher frequency than those can be provided by the aircraft reconnaissance and dropsonde observations.

[12] Vertical cross sections of the axisymmetric structure of Charley are illustrated in Figure 3 at 1400 UTC. In Figure 3a the tangential wind speed (solid lines) and reflectivity (color scale) indicate that the radii of the maximum reflectivity and tangential wind are 11 km and 13 km, respectively, indicating a tight vortex. Both the eyewall reflectivity and axisymmetric tangential wind field were upright below 6 km and tilted outward above. The maximum axisymmetric tangential wind at  $z = 1$  km exceeded  $50 \text{ m s}^{-1}$  and the wind speeds decreased with height. Vertical velocity was calculated from the radial divergence field using the kinematic method [Armijo, 1969], and the derived secondary, or meridional, circulation (vectors, Figure 3b) shows an inflow layer below 3 km that turned into updraft beneath the eyewall [Marks et al., 1992; Lee et al., 1994; Lee et al., 2000]. Eyewall updrafts reached 13 km altitude (Figure 3b). The eyewall reflectivity structure suggests that the updraft and outflow continue above 14 km altitude, beyond the analysis domain. The secondary circulation in Figure 3b shows an inflow layer beneath the anvil outflow, centered at  $z = 10$  km outside the eyewall, converged with the outflow from the eyewall and turned into a downdraft. This is consistent with the downward and inward kink evident in the reflectivity (e.g.,  $R = 20$  km and  $z = 8$  km). The inflow layer below the anvil has been deduced in Hurricane Gloria (1985) [Lee et al., 1994] and numerical simulations [e.g., Rotunno and Emanuel, 1987]. However, the significance of this feature has yet to be explored. A weaker updraft located at  $R = 35$  km appears to precede the enhancement of reflectivity at this radius later in the storm's evolution (see Figure 2c). Since the secondary circulation was derived independently from the reflectivity, the good correlations between them suggest that the secondary circulation is physically plausible.

[13] The pressure deficits (Figure 3c) exhibited a dome-shaped pattern with the horizontal pressure gradient



**Figure 3.** Radius-height cross-section of the azimuthal mean structure at 1402 UTC. Color represents reflectivity in dBZ; contours are (a) mean tangential wind ( $\text{m s}^{-1}$ ), (b) mean radial wind ( $\text{m s}^{-1}$ ), (c) perturbation pressure deficit (hPa) assuming zero at 60 km radius, and (d) mean vertical velocity ( $\text{s}^{-1} \cdot 10^{-3}$ ). Vectors in Figure 3b indicate mean secondary circulation. Analysis domain extends to 60 km radius, but results out to 40 km are shown for clarity.

decreasing with height, in agreement with other tropical cyclone observations and modeling studies [e.g., Lee *et al.*, 2000; Rotunno and Emanuel, 1987]. The central pressure deficit at  $z = 1$  km was 41 hPa from 60 km radius. The axisymmetric vorticity (Figure 2d) shows a maximum of  $0.01 \text{ s}^{-1}$  located at  $R = 5$  km, which is inside the radius of maximum wind of  $\sim 13$  km, indicating a mature storm satisfying the condition for barotropic instability as mentioned previously. The vorticity gradient is concentrated inside the eyewall where the radial gradient of the tangential wind is maximized.

#### 4. Summary and Future Work

[14] This study presents a preliminary analysis of Hurricane Charley's kinematic and dynamic structures before and after its Florida landfall using the coastal WSR-88D data and the GBVTD technique. The GBVTD-derived tangential wind, vorticity and perturbation pressure deficit reveal rapid intensification of Charley before its landfall. The rapid intensification of Charley was accompanied by an eyewall contraction. The WSR-88D data documented the  $11 \text{ hPa hr}^{-1}$  drop of central pressure over a three-hour

period that ranks Charley among the most rapidly intensifying hurricanes in the Atlantic basin. Charley's radial vorticity profile evolved from unstable to stable after it reached its peak intensity.

[15] As a logical next step, we propose to (1) analyze WSR-88D data to document the evolution of Hurricane Charley in six-minute intervals over the 18 hour period, (2) deduce the asymmetric structure of Charley, (3) compare the pressure derived from the Doppler radar data to those measured by dropsondes released by reconnaissance aircraft, and (4) compare results with high resolution numerical models.

[16] **Acknowledgments.** We would like to thank Paul Harasti for his comments on the analysis. Internal reviews provided by D. Parsons, T. Weckwerth, and S. Ellis greatly improved this manuscript. We appreciate the comments and suggestions provided by two anonymous reviewers that significantly improve the content and clarity of this manuscript. We would also like to acknowledge the National Weather Service and National Climatic Data Center for collecting and archiving the NEXRAD Level II data used in this study. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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