Single Doppler radar observation of the concentric eyewall in Typhoon Saomai, 2006, near landfall

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Received 27 November 2007; revised 30 January 2008; accepted 25 February 2008; published 3 April 2008.

Landfalling Typhoon Saomai (2006) was observed by the CINRAD WSR-98D radar on the southeast coast of China. This study documents the formation and evolution of a concentric eyewall episode using the axisymmetric circulation derived from the ground-based velocity track display technique. Saomai’s outer eyewall formed after reaching its peak intensity, ~5 hours before landfall. Updraft, tangential wind maximum and shallow low-level inflow coincided with the high reflectivity and vorticity ring in both inner and outer eyewalls, surrounding a moat region characterized by weak downward motion and lower reflectivity. The subsidence and rain-free moat region between the two eyewalls was filled with rain and upward reflectivity. The subsidence and rain-free moat region between the two eyewalls was filled with rain and upward reflectivity. Meanwhile, the outer vorticity maximum flattened and the central pressure dropped 9 hPa. The eyewall replacement cycle didn’t complete probably due to the landfall. Citation: Zhao, K., W.-C. Lee, and B. J.-D. Jou (2008), Single Doppler radar observation of the concentric eyewall in Typhoon Saomai, 2006, near landfall, Geophys. Res. Lett., 35, L07807, doi:10.1029/2007GL032773.

1. Introduction

Intense, highly symmetric tropical cyclones (TCs) sometimes exhibit concentric eyewall radar reflectivity patterns [Willoughby et al., 1982; Willoughby, 1990; Willoughby and Black, 1996]. Only a very limited number of TCs with concentric eyewalls have been documented by in situ aircraft observations [e.g., Jorgensen, 1984; Willoughby et al., 1982; Willoughby, 1990; Willoughby and Black, 1996]. Airborne pseudo-Doppler radar analyses have revealed detail three-dimensional kinematic structures of concentric eyewalls in hurricane Gilbert (1988) and Rita (2005) [Dodge et al., 1999; Houze et al., 2007]. Deep convection within the inner eyewall is surrounded by a near echo-free moat, which in turn is surrounded by an outer ring of convection. Both convective regions typically are accompanied by well-defined local tangential wind maxima and updraft. The maximum vorticity usually resides inside the inner eyewall, while the outer wind maximum is usually associated with a locally enhanced vorticity field embedded in the outer ring. In contrast, the moat region is characterized by downward air motion and lower vorticity [e.g., Houze et al., 2007]. The eyewall replacement cycle is often occurred in intense TCs (Cat 3 and above). TCs with concentric eyewalls often undergo a replacement cycle in which the inner eyewall is replaced by the outer eyewall, coinciding with a temporary decrease in storm intensity. The TCs eventually intensify should the eyewall replacement cycle be completed.

The aforementioned airborne datasets were limited in spatial and especially in temporal resolutions, typically with only several snap shots. In recent years, the coastal Doppler weather radar network in the United States, China, Taiwan, Korea and Japan have provided a growing number of high temporal (~6 minutes) and spatial (~1 km) resolution observations of double eyewalls in landfalling TCs (e.g., Danny (1997), Bilis (2000), Lekima (2001), Dujuan (2003), Maemi (2003), Haitang (2005), Saomai (2006)). Blackwell [2000] documented the concentric eyewall structure of Danny at landfall near Mobile, Alabama, using reflectivity and Doppler velocity data. Hong and Chang [2005] documented the double eyewall structure of Dujuan by using reflectivity and Doppler velocity but the double eyewall in Dujuan was not concentric (where the trajectory of the inner eyewall possessed a helical pattern). Therefore, the ground-based velocity track display (GBVTD) derived 3-D structures in typhoon Saomai is the first study to document the evolution and structure of a concentric eyewall in a landfalling TC.

The Super Typhoon Saomai, the eighth typhoon to hit China in 2006 formed over the Western Pacific Ocean on 6 August 2006 and then moved northwestward toward southeastern China. While Saomai entered the East China Sea north of Taiwan, it strengthened rapidly to a Catagory 5 storm, reaching its peak intensity with a central pressure of 898 hPa at 1200 UTC 9 August. The storm began to decay steadily after 0000 UTC 10 August, about 9 hours prior to its landfall on Zhejiang, China at 0925 UTC 10 August. During this 9-hour period, Saomai possessed a concentric eyewall. The intensity of Saomai decayed rapidly after landfall while moving northwestward across Zhejiang. Floods, mudslides and landslides occurred along Saomai’s path in a total of seven provinces, including Zhejiang and Fujian. Saomai was the strongest typhoon made landfall in China since 1949.

As Saomai approached landfall, it was continuously monitored by China’s next radar 1998 weather surveillance Doppler (CINRAD WSR-98D) located at Wenzhou (WZRD) during an 12-hour period (00 to 12 UTC, 10 August 2006) with unprecedented 6-minute volume resolution (Figure 1a) to document the formation and evolution of Saomai’s con-
centric eyewall. It was also the first concentric eyewall TC captured by a CINRAD WSR-98D. This preliminary study examines the kinematic and dynamic structures of Saomai’s concentric eyewall at five time periods using the GBVTD technique [Lee et al., 1999] to derive axisymmetric kinematic and dynamic structures from the WZRD CINRAD WSR-98D data.

2. Radar Analysis

[6] The domain of the GBVTD analyses extends from the center of the TC to 70 km radius and from 1 km to 12 km in the vertical. Grid spacing in both the radial and vertical directions is 1 km, consistent with the radar sampling resolution. The TC center is first determined at each altitude as a point that yields the maximum circulation enclosed by the radius of maximum wind (RMW) using the GBVTD-simplex algorithm [Lee and Marks, 2000]. Then, the quantities, including the along-beam (connecting the radar and TC center) component of the mean wind, axisymmetric tangential and radial winds, and the asymmetric tangential winds, are deduced by the GBVTD analysis. Once the azimuthal mean tangential and radial winds are obtained at each radius and height, dynamic quantities, such as the vertical velocity, vorticity, angular momentum and pressure deficit, are computed from the GBVTD-derived axisymmetric circulations [Lee et al., 2000; Lee and Bell, 2007]. The vertical velocity was calculated from the radial convergence field using the kinematic method [Armijo, 1969].

[7] The low-level reflectivity structures, illustrated using 2 km constant altitude PPI (CAPPI), of Saomai at six time periods (from 0231 UTC to 1033 UTC 10 August 2006) are portrayed in Figures 1b–1g. At 0231 UTC (Figure 1b), the eyewall reflectivity exhibited distinct asymmetric structure accompanied by several spiral rainbands outside the eyewall. Between 0355–0537 UTC (Figures 1c and 1d), the inner eyewall weakened, but became nearly symmetric. In contrast, the outer rainbands intensified and formed an outer eyewall, creating a moat region. The outer eyewall intensified at 0655 UTC (Figure 1e) with high reflectivity (> 40 dBZ) and began to contract. The concentric eyewall structure broke down at 0850 UTC (Figure 1f), about 0.5 hour prior to the landfall while the inner eyewall became increasingly asymmetric with an enhanced convection on its southeast side. Saomai’s eye could still be identified one hour after it made landfall at 1033 UTC (Figures 1g) while the moat region was filled with precipitation (> 40 dBZ).

[8] The evolution of Saomai is illustrated using GBVTD-derived radial profiles of the axisymmetric tangential winds at z = 2 km at five different times; 0355, 0537, 0655, 0850, and 1033 UTC (Figure 2). At 0355 UTC, the most intense mean reflectivity was in the eyewall (R = 20 km) associated with a maximum mean tangential wind of ~53 m s⁻¹. Beyond R = 38 km, there was an outer ring of high reflectivity, but no accompanying secondary wind maximum. At 0537 UTC, the maximum wind increased to 55 m s⁻¹ and 50 m s⁻¹ respectively, accompanied with a slightly decrease of mean reflectivity in the inner eyewall. Between 0655–0850 UTC, the RMW of outer eyewall contracted rapidly from R = 45 km to R = 34 km (Figure 2a) concurrent with the radius of maximum reflectivity contracting to 42 km and the tangential wind maximum increasing to 58 m s⁻¹. In contrast, the maximum wind in the inner eyewall increased slightly to 60 m s⁻¹ with the change of RMW less than 1 km. It was noted that the tangential wind profile near the outer eyewall flattened so that no clear secondary maximum tangential wind was observed at 0850 UTC. As suggested
The short distance between outer eyewall and inner eyewall might flatten the tangential wind near the outer eyewall. The reflectivity profile shows the moat region was filled with hydrometeors (> 40 dBZ), which implies the collapse of the moat region. After landfall, the maximum axisymmetric tangential wind speed decreased rapidly to 45 m s\(^{-1}\) at 1033 UTC, but the maximum tangential wind evolved into a more uniform profile, consistent with a near uniform reflectivity field (Figure 2c). The usual eyewall replacement cycle [Willoughby, 1990] was probably disrupted by Saomai’s landfall.

The radial vorticity patterns are very similar to those observed in classic concentric eyewalls with the large vorticity just inside the inner eyewall and an enhanced vorticity in the outer eyewall at 0537, 0655 and 0850 UTC [Kossin et al., 2000]. The vorticity ring in the inner eyewall, which satisfies the necessary condition for combined barotropic-baroclinic instability [Schubert et al., 1999] existed in 0537 UTC with a peak vorticity of 0.01 s\(^{-1}\) at R = 12 km. Subsequently, it rapidly evolved into a near monotonous pattern at 0655 UTC with a peak vorticity of 0.009 s\(^{-1}\) at R = 7 km, and re-evolved into a ring pattern near landfall at 0850 UTC. Although the lack of scatterers within the eye prohibits us from obtaining the complete symmetric vorticity profile in Saomai’s inner core using Doppler data alone, the barotropic instability mechanism [Schubert et al., 1999] may be responsible for the breakdown of the inner eyewall between 0537~0655 UTC, where the ring vorticity pattern evolved into a monotonic pattern. In contrast, the vorticity ring in the outer eyewall initially was broader and weaker before 0655 UTC. It steadily intensified and became narrower until 0850 UTC with a peak vorticity of 0.002 s\(^{-1}\) at R = 31 km, then became broader and weaker after landfall at 1033 UTC. The evolution of the radial profiles of the axisymmetric tangential wind (Figure 2a) and vorticity (Figure 2b) between 0655 and 1033 UTC is similar to the numerical simulations presented by Kossin et al. [2000], who suggested that the nonlinear mixing from instability across the moat will perturb the vortex and weaken the vorticity of outer ring, when the radial extent of the moat is sufficiently narrow. Through this case, a forecaster may have been able to monitor the vorticity profile changes with the high temporal Doppler radar data, and nowcast the evolution of hurricane structure and intensity.

The evolution of Saomai’s intensity was illustrated by central pressure deficit, which was estimated from GBVTD-derived winds (The symmetric radial gradient wind equation was integrated inward, assuming the total pressure deficit).
at R = 70 km remained steady.) [Lee et al., 2000; Lee and Bell, 2007]. Saomai’s center pressure deficit changed slightly from 0355 to 0537 UTC, then rapidly dropped about 9 hPa between 0537 ~ 0850 UTC. The rapid intensification near or at landfall was also observed during the landfall typhoon Herb (1996) by Taiwan Doppler radar [Chang, 2000]. Such a sudden intensification of the storm during its landfall period posed challenges for the local forecasters to forecast very short-term typhoon intensity changes before landfall. After Saomai’s landfall at 1033 UTC, it rapidly weakened and its central pressure filled 12 hPa in one hour.

Figure 3 shows the vertical cross sections of Saomai’s axisymmetric structure at 0537 UTC and 0850 UTC. At 0537 UTC, the tangential wind speed (solid lines) and reflectivity (in color) indicate that the maximum axisymmetric tangential wind at the inner and outer eyewalls exceeded ~52 m s\(^{-1}\) and 48 m s\(^{-1}\), respectively at z = 1 km, and the wind speeds decreased with height (Figure 3a). The inner wind maximum tilted about 20° from zenith in the vertical and the outer wind maximum tilted about 60° from the zenith. This result is consistent with the azimuthal averages of reflectivity field, i.e., smaller vertical tilt in the inner eyewall and larger tilt in the outer eyewall. The derived secondary circulation (vectors, Figure 3b) shows an inflow beyond R = 50 km below 2-km height, which turned into an updraft beneath the outer eyewall and sloped outward with height. It is worth to point out that this inflow could be a proxy for the lower inflow pattern, since the strongest low-level inflow can’t be directly observed by a radar at far distance. Two gyres located near the updraft in the outer eyewall with the clockwise (counter-clockwise) gyre outside (inside) of the updraft, which enhanced the low-level outflow inside and the low-level inflow outside of the outer eyewall. These two gyres with the sloping updraft have been deduced in theoretical models [Eliassen, 1952; Shapiro and Willoughby, 1982]. In the inner eyewall, the primary updraft located just inside the reflectivity maximum. Part of this updraft entered the eye, and the rest flowed outward at mid- and high-levels turning into a downdraft. It was also noted that the low-level inflow outside of the inner eyewall, which was almost confined below 1-km height except for a narrow region at R = 30 km, was much weaker and shallower than that outside of outer eyewall. This weak inflow indicates that the high-energy air from the large-scale environment was impeded by the outer eyewall. Between R = 28 km and 38 km, there was a moat region, characterized by low reflectivity (<35 dBZ) and a weak downward air motion. This downward motion (Figure 3b) was partly induced by the secondary circulation associated with the outer eyewall, in agreement with other concentric eyewall TCs observations and modeling studies [e.g., Houze et al., 2007; Wang, 2008].

3. Concluding Remarks

[13] In this study, the kinematic and dynamic structures of the concentric eyewall in Super Typhoon Saomai during...
landfall were examined at five different times by the GBVTD analysis using the coastal CINRAD WSR-98D data in China. The GBVTD-derived tangential wind, vorticity and perturbation pressure deficit reveal that Saomai formed an outer eyewall about 5 hours prior to landfall when the strong updraft and shallow inflow collaborated with the high reflectivity in both inner and outer eyewalls, while the most region between the two eyewalls was characterized by a weak downward motion and a lower reflectivity. The outer eyewall then strengthened and contracted, while the inner eyewall broke down and weakened. The rain-free moat region was filled with high reflectivity (>40 dBZ) and weak updraft prior to landfall. Meanwhile, a broad region of high reflectivity and a flat tangential wind profile formed outside the inner eyewall, accompanied with steadily enhanced tangential wind, low-level radial inflow, and a 9 hPa drop of the center pressure. It was noted that the eyewall replacement cycle didn’t complete due to the landfall.

In future study, we propose to (1) analyze the evolution and three-dimensional structures of Saomai’s concentric eyewall in six-minute intervals over a six-hour period during landfall, (2) deduce the asymmetric structure of Saomai, and (3) investigate the effect of landfall on the eyewall structure by analyzing the symmetric tangential wind and high-resolution numerical model simulations. This data set can be used for testing the assimilation of Doppler radar data in hurricane models like HWRF.

Acknowledgments. We would like to thank F. Zhang for his comments on the analysis. Internal reviews provided by Y. Wang and M. Bell greatly improved this manuscript. We appreciate the comments and suggestions provided by two anonymous reviewers that significantly improved the content and clarity of this manuscript. We would also like to acknowledge the China Meteorological Administration for collecting and archiving the radar data used in this study. This study is supported in whole or in part by the National Natural Science Foundation of China (grants 40505004, 40405012, and 40333025), the National Grand Fundamental Research 973 Program of China (973; 2004CB413031), and the NMC-TIGGE Program GYHY (QX) 2007-232 6-1. The first author would like to thank NTU for a postdoctorship in 2005 and 2006.

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