Structure and Formation of An Annular Hurricane Simulated in A

Fully Compressible, Nonhydrostatic Model–TCM4

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ABSTRACT

The structure and formation of an annular hurricane simulated in a fully compressible, nonhydrostatic tropical cyclone model – TCM4 are analyzed. The model is initialized with an axisymmetric vortex on an $f$-plane in a quiescent environment and thus the transition from the non-annular hurricane to the annular hurricane is attributed to the internal dynamics. The simulated annular hurricane has all characteristics of those recently documented by Knaff et al. from satellite observations: quasi-axisymmetric structure, large eye and wide eyewall, high intensity, and suppressed major spiral rainbands. A striking feature of the simulated annular hurricane is its large outward tilt of the wide eyewall, which is critical to the quasi-steady high intensity and is responsible for the maintenance of the large size of the eye and eyewall of the storm. Although the annular hurricane has a quasi-axisymmetric structure, marked low-wave number asymmetries exist in the eyewall region.

The formation of the simulated annular hurricane is found to be closely related to the interaction between the inner spiral rainbands and the eyewall convection. As the inner rainbands spiral cyclonically inward, they experience axisymmetrization due to strong shear deformation and filamentation outside the eyewall and evolve into a quasi-symmetric convective ring, which intensifies as it contracts while the eyewall breaks down and weakens. Eventually, the convective ring replaces the original eyewall. The new eyewall formed in such a way is wider and tilts more outward with height than the original eyewall. Several such eyewall cycles in our simulation produce an annular hurricane with large eyewall slope, large eye and wide eyewall. The response of low-level winds to the tilted convective heating in the eyewall is an increase outside and a decrease inside the radius of maximum wind, prohibiting a further contraction of the new eyewall. Strong convective massflux in the eyewall updraft corresponds to strong convective overturning subsidence outside the eyewall, greatly suppressing the development of any major rainbands outside the eyewall. Although the eyewall cycle documented in this study contributes to the formation of annular hurricanes, it could be a general process causing the increase in eye size of real tropical cyclones as well.
1. Introduction

Knaff et al. (2003) introduced and examined a new symmetric category of tropical cyclones, which they called annular hurricanes, based on infrared satellite images and aircraft reconnaissance data. The associated symmetric structure is called the “annular structure” to distinguish it from the non-annular hurricane structure. Compared with the general population of tropical cyclones, the annular hurricanes appear distinctly symmetric about their center and have large circular eye features surrounded by a wide eyewall with a nearly uniform ring of deep convection with no distinct spiral rainbands outside the eyewall. Knaff et al. found that the annular hurricanes have systematic formation characteristics, strong and steady intensities, and existence in only specific environmental conditions. Once they formed, the annular hurricanes can maintain their annular structure and intensity for several days if specific environmental conditions are maintained. Knaff et al. also reported that the averaged intensity forecast errors for annular hurricanes are generally 10-40% larger than for the typical hurricanes in the Atlantic and eastern Pacific during 1995-2001. Therefore, annular hurricanes pose a challenge to tropical cyclone structure and intensity forecast.

Based on infrared satellite images, Knaff et al. (2003) showed that the formation of annular hurricanes mainly results from asymmetric mixing of the eyewall air into the eye or vice versa involving one or two mesovortices, culminating in the formation of axisymmetric storms with large eyes. They also found that the typical annular hurricanes form in very specific environmental conditions, characterized by the combination of 1) weak easterly or southeasterly vertical wind shear, 2) easterly flow and relatively cold temperatures at 200 hPa, 3) a specific range (25.4° – 28.4°C) of sea surface temperatures that are nearly constant, and 4) a lack of 200 hPa relative eddy flux divergence due to environmental interactions. To explain the symmetric nature of annular hurricanes, Knaff et al. speculated that the weak southeasterly
shear can offset the opposite directional shear due to the \( \beta \)-effect on a baroclinic hurricane vortex (e.g., Wang and Holland 1996a,b), prohibiting the development of convective asymmetries that may result from the \( \beta \)-effect (Wang and Holland 1996b; Bender 1997). They also raised two questions yet to be addressed: 1) why is there a relative reduction of outer spiral rainbands? and 2) why do the annular storms display slower weakening rates than other hurricanes?

Although Knaff et al. (2003) examined several aspects of the annular hurricanes, satellite and aircraft reconnaissance data did not allow them to provide either the three-dimensional dynamical and thermodynamic structure of the annular hurricanes or the detailed formation process and the maintenance dynamics of the annular hurricanes. Understanding the formation mechanisms and the evolution of the distinct big-eyed annular hurricane can help improve the prediction of hurricane structure and intensity changes. This is also scientifically interesting as it involves basic dynamics and thermodynamics associated with rapidly rotating geophysical vortices.

Recently, a fully compressible, nonhydrostatic, multiply nested, movable mesh tropical cyclone model (TCM4) has been developed by the author (Wang 2007a) at the International Pacific Research Center, University of Hawaii. The model has been shown to be a very useful tool for studying many aspects of tropical cyclones, including the eye and eyewall structure, spiral rainbands, concentric eyewall, and also the annular hurricane structure, at nearly cloud resolving resolutions.

Wang (2007b) recently examined the rapid filamentation zone in a tropical cyclone simulated in TCM4 and found that the rapid filamentation plays important roles in organizing fine-scale, inner spiral rainbands, and in damping high azimuthal wavenumber asymmetries in the inner core region of the simulated tropical cyclone. He also showed that the model storm
developed a large eye and wide eyewall structure at later stage of simulation and indicated that the storm at the large eye stage is very similar to the annular hurricane as identified by Knaff et al. (2003). However, because the focus in Wang (2007b) was on the rapid filamentation zone in the simulated hurricane, he didn’t analyze either the structure or the formation mechanism of the simulated annular hurricane.

In this paper, we will focus on the analyses of the annular phase of the simulated hurricane in TCM4 under idealized conditions. To examine the long-term behavior of the annular hurricane in the simulation, we extend the integration of the experiment in Wang (2007b) from 240 h to 360 h. The main objectives here are twofold: 1) to provide the three-dimensional dynamical and thermodynamic structure of the simulated annular hurricane; 2) to examine the formation and maintenance mechanisms of such an annular storm simulated in the model.

The rest of the paper is organized as follows. The next section describes the numerical model and the experimental design. Section 3 discusses the overall structure of the simulated annular hurricane and compares it with the storm in its non-annular phase. The formation and maintenance mechanisms of the simulated annular hurricane are examined in section 4. The main findings are summarized in the last section.

2. Model and Experiment

The model used in this study is the fully compressible, nonhydrostatic, primitive equation model – TCM4 recently developed by the author at the International Pacific Research Center, University of Hawaii. TCM4 is an upgrade of its hydrostatic counterpart TCM3 (Wang 2001, 2002a) with the hydrostatic dynamical core replaced by a fully compressible, nonhydrostatic dynamical core. The model has been shown to be capable of simulating the
inner-core structure and intensity change of a tropical cyclone at nearly cloud resolving resolutions (Wang 2007a, b). A full description of the model can be found in Wang (2007a) together with an analysis of the development of asymmetries in the inner core of a tropical cyclone simulated in the model. Wang (2007b) recently applied the model to examine the rapid filamentation zone in tropical cyclones conceptualized by Rozoff et al. (2006). Here only the major features of the model are briefed below.

TCM4 shares the state-of-the-art model physics, the two-way interactive multiple nesting, and automatic mesh movement with its hydrostatic counterpart TCM3 (Wang 2001, 2002a). The model equations are formulated in the Cartesian coordinates in the horizontal and mass coordinate in the vertical and are solved numerically with an efficient forward-in-time, explicit time splitting scheme, similar to the one described by Wicker and Skamarock (2002). A fifth-order (second-order) upwind scheme, which takes into account the effect of spatial variation of the advective flow (Wang 1996), is used to calculate the time tendency due to horizontal (vertical) advection. The model has a flat lower boundary at the surface with an unperturbed surface pressure of 1010 hPa. The model top is set at about 38 km and a sponge upper boundary condition similar to that used in Durran and Klemp (1983) is used to absorb the upward propagating sound and gravity waves. The model uses the state-of-the-art physical parameterizations, including an E-ε turbulence closure scheme for subgrid scale vertical turbulent mixing (Langland and Liou 1996); a modified Monin-Obukhov scheme for the surface flux calculation (Fairall et al. 2003); explicit treatment of mixed-phase cloud microphysics (Wang 2001); a nonlinear fourth-order horizontal diffusion scheme for all prognostic variables except for that related to the mass conservation equation; a simple Newtonian cooling term, which is added to the potential temperature equation to mimic the
radiative cooling in the model (Rotunno and Emanuel 1987); and the dissipative heating due to molecular friction.

The model domain is quadruply nested with two-way interactive nesting and with the inner meshes automatically moving to follow the model storm as used in TCM3 (Wang 2001). The model has 26 levels in the vertical with horizontal resolutions of 67.5, 22.5, 7.5, and 2.5 km and mesh sizes of $201 \times 181$, $109 \times 109$, $127 \times 127$, and $163 \times 163$ grid points for the four meshes, respectively. Note that the model has relatively high resolution both in the lower troposphere and near the tropopause where the tropical cyclone outflow layer is located. Therefore the model results discussed in this study are expected not to be sensitive to the total vertical levels (Zhang and Wang 2003; Kimball and Dougherty 2006). As in Wang (2001, 2007a, b), the same model physics are used in all meshes. Since no large-scale environmental flow is included in this study, convection is mainly active in the inner core region and in the spiral rainbands that are within about a radius of 200 km from the cyclone center and thus are covered by the finest innermost domain. Therefore, cumulus parameterization is not considered even in the two outermost coarse meshes in this study.

The experimental design follows Wang (2007a). The model is initialized with an axisymmetric cyclonic vortex on an $f$-plane of $18^\circ$N in a quiescent environment over the ocean with a constant sea surface temperature of $29^\circ$C. The initial thermodynamic structure of the unperturbed model atmosphere is defined as the western Pacific clear-sky environment given by Gray et al. (1975). Given the tangential wind field for the initial cyclonic vortex, which has a maximum wind speed of $25$ m $s^{-1}$ at a radius of $80$ km at the surface and decreases with height, the mass and thermodynamic fields are obtained by solving the nonlinear balance equation as described in the Appendix of Wang (2001). All the settings for the numerical experiment are identical to that described in Wang (2007a, b).
As mentioned in Wang (2007b), in a 240 simulation, the model tropical cyclone developed an annular hurricane structure after about 228 h of integration. To study the long-term behavior of the annular hurricane in the simulation, we extend the integration of the experiment in Wang (2007b) for another 120 h, namely, from 240 h to 360 h. To identify the distinct features of the simulated annular hurricane, we will compare the storm structure in the annular phase with that in the non-annular phase in the next section. The phase transition will be examined in section 4.

3. Structure of the Simulated Annular Hurricane

Figure 1 shows the maximum azimuthal mean wind (dashed) and its radius (solid) at the lowest model level (35.6 m above the sea surface) of the simulated hurricane. Note that we use the azimuthal mean wind instead of the total wind used in many other studies (e.g., Wang 2007a, b) to avoid the effect of mesoscale and small-scale asymmetries on the estimations of storm intensity and the radius of maximum wind (RMW). As already discussed in Wang (2007b), the storm intensified rapidly after an initial 9 h adjustment and spin-up of the boundary layer and moist processes and reached its quasi-steady evolution after about 60 h of simulation.

The RMW decreased rapidly during the rapid intensification of the storm and reached its lifetime smallest value of 17.5 km after 60 h of simulation. Except for a small change between 72 h and 84 h, the RMW maintained small until 144 h of simulation, which was followed by an overall increase from 144 h to 240 h. The RMW was almost doubled from 144 h to 240 h and remained a nearly constant value between 32.5 km and 35 km throughout the end of model integration (Fig. 1). Accompanied with the increase in the RMW was an overall weakening in the maximum azimuthal mean wind from 132 h to 228 h of simulation. Shortly after that the
storm reached its maximum intensity of 68 m s\(^{-1}\) in the maximum azimuthal mean wind and followed by a very slow weakening throughout the end of model simulation.

Our purposes are to understand the processes and mechanisms that are responsible for the size increase in the storm eye and the RMW and to examine the structure difference between the small eye phase and the large eye phase of the simulated storm. Since the large eye storm is very similar to the annular hurricane identified by Knaff et al. (2003), we thus refer to the large eye phase as the annular hurricane phase and the small eye phase as the non-annular hurricane phase to avoid any ambiguity. We will discuss the structure difference between the non-annular and annular phases of the simulated storm in the rest of this section and leave the discussion for the phase transition to section 4.

Figure 2 shows the snapshot plan views of surface rainrate, vertical velocity at 3 km height, and potential vorticity (PV) at 1 km height for the non-annular hurricane after 120 h (left) and the annular hurricane after 288 h (right) of simulation, respectively. In the non-annular hurricane phase, the storm has a very small eye surrounded by a narrow, quasi-axisymmetric eyewall with strong convection. The asymmetric structure of the storm is characterized by both active inner and outer spiral rainbands as seen in both surface rainrate and vertical motion fields (Figs. 2a and b). The inner spiral rainbands are well organized and have fine-scale structure in the radial direction and elongated structure in the azimuthal direction. This distinct feature is attributed to the rapid filamentation due to strain-dominated flow immediately outside the RMW by Wang (2007b). Convection in the major outer spiral rainbands, on the contrary, is loosely organized in a cyclonically inward spiral band with embedded mesoscale/small-scale convective cells (Figs. 2a and b). PV exhibits a hollow structure with low PV in the eye region and high PV just inside the RMW (about 17.5 km from the storm center at the given time, Fig. 2c). There are cyclonic PV anomalies in both inner and
outer spiral rainbands mainly due to convective heating.

In the annular hurricane phase, both the eye size and the width of the eyewall of the storm (Figs. 2d and e) are more than doubled compared to that in its non-annular phase (Figs. 2a and b). The storm is quasi-axisymmetric in both the annular and non-annular phases but it is more symmetric in the annular phase than in the non-annular phase. In contrast to the non-annular phase, the storm in the annular phase has much less distinct inner spiral rainbands and has suppressed major outer spiral rainbands (Figs. 2d and e). There is a similar size increase in elevated PV (Fig. 2f) just inside the RMW, consistent with the overall size increase in the inner core of the storm. Note that the eyewall updrafts and precipitation in the annular phase are much wider and somewhat stronger in magnitude than those in the small eyed non-annular phase (Figs. 2a and 2d). The convection outside the core is largely suppressed by subsidence (Fig. 2e), giving an overall annular hurricane structure as identified by Knaff et al. (2003).

Figures 3 and 4 show the west-east vertical cross-sections along the storm center for radar reflectivity (calculated by the same algorithm as in Liu et al. 1997), vertical velocity, condensational heating, PV, and equivalent potential temperature at the same model times as in Fig. 2, respectively, for the storm in the non-annular and annular phases. Comparing Figs. 3 and 4, we can see several distinct differences in the vertical structure of the storm between the non-annular and annular phases. First, the 20 dBZ contour in radar reflectivity at the top of the storm is horizontally much more uniform and extends to larger radii in the annular phase (Fig. 4a) than in the non-annular phase (Fig. 3a). We can see from Figs. 4a and b that, the cloud top of the annular storm features the cirrus canopy, especially in the stratiform precipitation region outside the convective eyewall with updraft cores rooted in the lower troposphere. This is consistent with the annular hurricanes documented by Knaff et al. (2003), who found that the annular hurricanes have quite uniform brightness temperature at the cloud top in the infrared
satellite images. Second, the eyewall updrafts have a much larger radial scale and a much larger outward slope (tilt) with height in the annular phase (Fig. 4b) than in the non-annular phase (Fig. 3b). Third, the subsidence both in the eye and outside the outward tilted eyewall is larger in the annular phase (Fig. 4b) than in the non-annular phase (Fig. 3b). This is a feature required to maintain the large eye and the suppression of deep convection outside the convective eyewall in the annular hurricane.

The vertical PV structure of the annular storm is also quite different from that of the non-annular storm (Figs. 4d and 3d). PV is large just inside the eyewall updraft with little vertical tilt in the non-annular phase (Fig. 3d). In the annular phase, however, PV shows large outward tilt (Fig. 4d) as seen in the eyewall updrafts (Fig. 4b). Consistent with the bigger eye and larger outward tilted eyewall, cyclonic PV anomalies in the storm extend outward to much larger radii in the annular phase (Fig. 4d) than in the non-annular phase (Fig. 3d). A distinct feature in the annular phase is the generation of cyclonic PV anomalies in the middle troposphere due to the vertical gradients of condensational heating outside the eyewall in the stratiform precipitation region (Fig. 4c). The equivalent potential temperature is high and quite uniform throughout the troposphere in the core region in both the non-annular and annular phases except that the larger eye and wider eyewall correspond to larger areas of high equivalent potential temperature in the annular phase.

Although we have discussed the different structures in the non-annular and annular phases based on a given time, the features discussed above can also be seen in the time mean of the axisymmetric structure of the storm, as shown in Fig. 5 for the non-annular phase averaged between 96 h and 144 h of simulation and in Fig. 6 for the annular phase averaged between 240 h and 288 h of simulation, respectively. In addition to the larger eye and wider and larger outward tilted eyewall, the updraft in the eyewall in the annular phase is much stronger than in
the non-annular phase, especially in the mid-lower troposphere (Figs. 5c and 6c). As a result, the mass flux in the eyewall is much larger and the secondary transverse circulation is much stronger in the annular phase than in the non-annular phase as seen from the radial wind shown in Figs. 5b and 6b. Indeed, the maximum inflow and outflow are more than doubled in the annular phase than in the non-annular phase. The warm core in the upper troposphere is at slightly higher level and extends to larger radii in the annular phase than in the non-annular phase (Figs. 5d and 6d), indicating a slightly more stable stratification in the mid-upper troposphere in the annular phase.

The azimuthal mean PV has an off-center maximum structure throughout the troposphere in both phases but the absolute PV maximum is much smaller due to the larger RMW in the annular phase than in the non-annular phase (Figs. 5e and 6e). As mentioned already, the PV maximum in the mid-troposphere outside the eyewall in the annular storm is a manifestation of the eyewall tilt and the presence of extensive stratiform clouds in the annular phase (Fig. 4). Consistent with the large outward eyewall tilt with height, the angular momentum (defined as $r v_{\theta}$, where $r$ is the radius and $v_{\theta}$ the azimuthal mean tangential wind) surface in the vertical-radial plan also shows large slope both near and outside the eyewall updraft in the annular phase.

Figure 7 shows the radial distributions of various azimuthal mean variables of the simulated storm in the non-annular (averaged between 96 h and 144 h of simulation) and annular (averaged between 240 h and 288 h of simulation) phases, respectively. The maximum wind at 10-m height is only about 2 m s$^{-1}$ stronger but the winds outside the RMW are much stronger in the annular phase than in the non-annular phase (Fig. 7a). The vertical velocity at 3 km height in the eyewall is about 60% larger with the 0.5 m s$^{-1}$ contour more than doubled in radial extent in the annular phase than in the non-annular phase (Fig. 7b). Although the
maximum rainrate is only about 18% larger in the eyewall, the rainrate outside the eyewall is much larger in the annular storm (Fig. 7c). Peak PV in the core is smaller and PV in the eyewall shows a proportional reduction in the annular phase (Fig. 7d). The boundary layer is about 1 K warmer with higher equivalent potential temperature in the annular phase than in the non-annular phase (Figs. 7e and f). This is mainly due to the lack of significant downdrafts associated with spiral rainbands together with the large subsidence outside the eyewall in the annular phase. Note that the lack of both major outer spiral rainbands and strong downdrafts could be important for the annular hurricanes to weaken at much slower rates than the non-annular hurricanes in nature as documented in Knaff et al. (2003) since both diabatic heating released in the outer spiral rainbands and downdrafts are considered negative to hurricane intensity (Bister 2001; Powell 1990a,b).

In addition to the difference in the axisymmetric structure, the asymmetric structure in the simulated storm is also quite different between the non-annular phase and the annular phase. In both phases, the storm developed considerable asymmetries near the eyewall region and in the outflow layer in the upper troposphere, as seen from the azimuthal mean eddy kinetic energy (EKE)\(^1\) shown in Figs. 8 and 9. The total asymmetries seem to be larger and in a deeper layer in the lower troposphere in the large eyed annular phase than in the small eyed non-annular phase. The asymmetries are dominated by azimuthal wavenumber-2 component in both phases (Figs. 8c and 9c). As shown in Wang (2007a), the low-wavenumber asymmetries in the eyewall are mostly associated with vortex Rossby waves in the mid-lower troposphere (see also Chen and Yau 2001; Wang 2001, 2002b). Asymmetries with azimuthal wavenumber > 4 are suppressed greatly in the inner core region in both phases (Figs. 8f and 9f). This has been

\(^1\) Eddy kinetic energy is defined as \(\left(u'^2 + v'^2\right)/2\), where \(u'\) and \(v'\) are deviations of radial and tangential winds from their corresponding azimuthal mean. Different azimuthal wavenumber component of EKE is defined as the EKE corresponding to the associated wavenumber component of \(u'\) and \(v'\).
attributed to the rapid filamentation and axisymmetrization due to the strong shear deformation just outside the eyewall by Wang (2007b). Two distinct differences in the asymmetric structure can be identified between the non-annular and annular phases. First, the storm in the non-annular phase shows much stronger wavenumber-one and high-wavenumber (with wavenumber > 4) asymmetries in the upper troposphere than in the annular phase (Figs. 8b, f and 9b, f). This is related to the activities of outer spiral rainbands in the non-annular storm. Second, the high wavenumber asymmetries in the annular storm are generally weak and occur predominantly between radii of 60 and 120 km (Fig. 9f) and mainly under the tilted eyewall (Fig. 6c), indicating the asymmetric motion associated with the stratiform precipitation just outside the eyewall and a lack of active outer spiral rainbands.

The large outward tilt of the eyewall with height is dynamically important to the maintenance of the large eye and wide eyewall of the simulated annular hurricane. Since the simulated storm is nearly in hydrostatic and gradient wind balance, the theory for the balanced vortices can be applied. Here, we are not going to perform the calculation but cite the results of Shapiro and Willoughby (1982) and Willoughby (1982). According to Shapiro and Willoughby (1982), the main mechanism for eyewall contraction of a developing balanced vortex is the heating in the eyewall. The response of the storm to heating near the RMW is a maximum positive tendency of the low-level tangential wind just inside the RMW. It is this tendency that causes the inward contraction of the RMW, and thus the decrease in the eye size of the storm. However, when the heating source is outside the RMW, the response of low-level tangential wind to a heat source depends strongly on both the radial tangential wind profile of the vortex itself and the height of the heat source (Shapiro and Willoughby 1982).

For a vortex with a rapidly decaying tangential wind profile, the response to a heat source outside the RMW at about 7.5 km height would be an increase in low-level tangential wind
near and outside the RMW, such as those shown in their Fig. 11 for a Rankin vortex with $v_\theta \propto r^{-1}$. In this case, the RMW could experience little change. In contrast, for a vortex with a slowly decaying tangential wind profile, the response of low-level tangential wind to a mid-tropospheric heat source outside the RMW at about 5 km height would be an increase outside the RMW with a maximum increase near the radius of the heat source. Shapiro and Willoughby (1982) showed such examples in their Fig. 15 for vortices with tangential wind profiles of $v_\theta \propto r^{-1/2}$ and $v_\theta \propto r^{-1/4}$, respectively. In these cases, heating outside the RMW would be expected to result in an expansion of the RMW.

In our simulated storm, the radial profile of low-level tangential wind (Fig. 7a) is close to the case of $v_\theta \propto r^{-1/2}$ discussed in Shapiro and Willoughby (1982). Condensational heating in the simulated storm is roughly proportional to the vertical velocity (Figs. 3 and 4), giving deep heating near the RMW in the non-annular phase (Fig. 5c) and outwardly tilted heating with maximum in the middle-lower troposphere in the annular phase (Fig. 6c). As a result, the response of low-level tangential wind to the condensational heating in the eyewall in the non-annular hurricane phase would be either a contraction or with little change in the RMW. However, the response of low-level tangential wind to the condensational heating in the outwardly tilted eyewall in the annular phase would be a decrease of low-level tangential wind inside and an increase outside the RMW (Shapiro and Willoughby 1982). This would prohibit the inward contraction of the RMW and even cause an increase in the RMW in extreme cases, such as heating in a very large outwardly tilted eyewall or heating in the secondary convective ring and the stratiform clouds outside the eyewall. We will show in the next section that this is exactly the case for the formation and maintenance of the annular storm in our simulation although the details are more complicated than this simple interpretation. The large outward
eyewall tilt is thus critical to the maintenance of the annular hurricane structure.

Since they studied the annular hurricanes based mainly on infrared satellite images and flight-level aircraft reconnaissance data, Knaff et al. (2003) were not able to either examine the detailed three-dimensional dynamical and thermodynamic structure of these storms or provide insights into how an annular hurricane can maintain its large eye and wide eyewall and why the annular hurricanes weaken at much slower rates than non-annular hurricanes. The numerical results from our model simulation thus provide insights into these issues as we discussed in this section. The formation of the simulated annular hurricane will be discussed in the next section.

4. Formation Mechanism of the Simulated Annular Hurricane

Knaff et al. (2003) found that the formation of annular hurricanes appears to be systematic, apparently resulting from asymmetric mixing of eye and eyewall components of the storms involving one or two possible mesovortices. The detailed processes/mechanisms, however, have not been investigated because of the lack of detailed observations. The environmental conditions favorable for the formation of annular hurricanes that Knaff et al. identified are all met in our model simulation (except for a slightly higher SST in this study). Knaff et al. (2007) recently show that only about 9% of the hurricanes that met environmental conditions eventually developed into annular hurricanes in the Atlantic during 2004-2006. This indicates that annular hurricanes are indeed rare events and must form with both very strict environmental conditions and internal storm dynamics. In this section, we will investigate the mechanisms that are responsible for the transition from the non-annular phase to the annular phase of our simulated storm.

Since the systematic increase in the eye size occurred during a 96-h period between 144 h and 236 h of simulation (Fig. 1), we first have a quick look at the evolution of surface rainrate
(Fig. 10) and vertical motion at 3 km height (Fig. 11) from 132 h to 246 h of simulation at every 6 h intervals. As expected, the increase in eye size with time is clearly seen in both surface rainrate and vertical motion fields. It appears that the evolution involves strong interaction between the inner spiral rainbands and the eyewall convection. This is particularly evident in the vertical motion fields (Fig. 11). As discussed recently in Wang (2007b), the strong shear deformation just outside the RMW favors the formation of well organized inner spiral rainbands. These rainbands are quite different from the outer spiral rainbands. The inner rainbands spiral cyclonically inward with a very large symmetric component due to the rapid filamentation of the shear deformation flow just outside the RMW. These inner spiral rainbands are axisymmetrized as they propagate inward and then become tightly-wound enough to form the secondary convective ring just outside the eyewall convection in our simulation (Figs. 10 and 11). We will see later that this secondary convective ring looks very similar to the concentric eyewall studied previously by Willoughby et al. (1982). However, because the secondary convective ring is very close to the eyewall, there is generally no corresponding secondary tangential wind maximum.

Figure 12 shows the radius-time Hovmöler diagrams of the azimuthal mean vertical velocity at 3 km height, surface rainrate, and the radial wind at the lowest model level. An interesting evolution in vertical motion fields is the six events with inward propagation of the organized secondary upward motion, namely secondary convective rings as seen already in Fig. 11, originated at the radius of about 60 km (Fig. 12a). These events occurred during 74-84 h, 132-144 h, 150-162 h, 168-186 h, 192-210 h, and 218-228 h. In each event, as propagating inward, the upward motion in the secondary convective ring intensifies while the updraft in the eyewall weakens and is eventually replaced by the secondary convective ring. Similar signals are evident in both rainrate (Fig. 12b) and the boundary layer inflow (Fig. 12c). As expected,
the rainfall outside the eyewall was largely suppressed during the annular phase after 228 h of simulation (Fig. 12b).

The contraction of the secondary convective ring and its eventual replacement of the eyewall updraft appear to be closely related to the changes in both the maximum tangential wind and its radius at the lowest model level as seen in Fig. 1. For example, after about 75 h of simulation, the azimuthal mean tangential wind at the lowest model level experienced a temporal weakening, which was accompanied by a small increase in the RMW (Fig. 1). This is indeed a result of the contraction and intensification of the secondary convective ring and the weakening of the eyewall updraft. By hour 83, the storm intensified and recovered its maximum tangential wind as the RMW contracted to its original value by about hour 94. On the contrary, in most of the later events, the replacement of the original eyewall by the secondary convective ring did not result in significant contraction of the eyewall, leading to an increase in the size of the eye or the RMW and an overall slow weakening of the azimuthal mean tangential wind (Fig. 1).

Therefore, it seems that there are two types of interactions between the eyewall and the inner spiral rainbands (secondary convective ring) in our simulated storm. The first type involves a contraction of the eyewall following the replacement of the original eyewall by the secondary convective ring, which in turn is due to the axisymmetrization of the tightly-wound, inner spiral rainbands. The second type of interaction involves an expansion of the eyewall. Since the later five events are similar and belong to the second type of interaction, we will discuss the first and the last events in some detail below to highlight the differing dynamics of these two interactions.

The evolution of the horizontal distribution of vertical motion at 3 km height at every 30 minutes for the first event between 75 h and 84.5 h of simulation is given in Fig. 13. The storm
developed strong inner spiral rainbands, which intensified at 75 h with two major spiral rainbands, one to the north and one to the south. Both rainbands spiraled cyclonically inward with reduced spiraling angle with time. By comparing Fig. 12 and Fig. 13, we can identify several distinct features of the evolution of the inner spiral rainbands and the secondary convective ring as mentioned above. First, the secondary convective ring outside the eyewall seen in Fig. 12 originated from the asymmetric convective spiral rainbands (t = 75 h in Fig. 13) that had a very weak projection onto the azimuthal mean component at this time (Fig. 12a). The asymmetric convective spiral rainbands evolved into very tightly-wound structure mainly due to the strong shear deformation and axisymmetrization process (Wang 2007b) near the radius of about 60 km (t = 75.5-77 h in Fig. 13). This seems to be an important dynamical process in strong hurricanes. The rainbands eventually evolved into the quasi-axisymmetric secondary convective ring by 77.5 h and started to contract.

As the secondary convective ring contracted, the original eyewall broke down and showed wavenumber-3 structure in the updraft (t = 76-78.5 h). The eyewall then weakened during a 3.5 hour period between 79 h and 82.5 h of simulation. This is also evident in the boundary layer inflow and rainrate shown in Figs. 12b and 12c. A single eyewall structure reformed and continued to contract and the storm re-intensified back to its original intensity (Fig. 1). The azimuthal mean behavior of the inner spiral rainbands and the secondary convective ring are very similar to the concentric eyewall cycle studied by Willoughby et al. (1982). However, in our case, the secondary convective ring formed very close to the original eyewall and had no corresponding secondary tangential wind maximum as observed in the typical concentric eyewall phenomenon documented in Willoughby et al. (1984).

The processes described above can be also viewed from the evolution of the vertical-radial cross-section of the azimuthal mean tangential wind and vertical motion fields as given
in Fig. 14. By 76 h of simulation, the projection of the inner spiral rainbands (Fig. 13) onto the symmetric component of the model storm is a weak, outward titled upward motion outside the deep eyewall ascent (Fig. 14). As the inner spiral rainbands were axisymmetrized, the secondary convective ring in the symmetric vertical motion strengthened and evolved into a secondary eyewall-like updraft and contracted at the same time between 77 h and 81 h of simulation. Note that as the secondary convective ring contracted, the outward tilt of its updraft reduced because the angular momentum surface reduced its outward slope toward the storm eyewall (Fig. 5f). Meanwhile, the original eyewall updraft weakened during 80 h and 82 h and was eventually replaced by the secondary convective ring by 83-84 h. As mentioned above, there was no secondary wind maximum associated with the secondary convective ring in this eyewall replacement process. By 85 h, the RMW increased by about 2.5 km as seen from both Figs. 1 and 14. The new eyewall continued to contract and reached the size of the original eyewall soon later (Fig. 1).

The last event during 218 h and 228 h is very similar to the first event in the early stage discussed above (Figs. 15 and 16). The main differences are the significant increase in the eye size (Fig. 15) and the large outward tilt of the new eyewall (Fig. 16) after the eyewall replacement. Note that the secondary convective ring is not a closed upward motion outside the eyewall updraft; rather, it consists of several curved convective line segments around the eyewall. This is also different from the first event. Further the breakdown of the original eyewall appeared to contribute to considerable mixing in the eyewall region (t = 223-227 h in Fig. 15), which was identified as an important process in the formation of the annular hurricanes by Knaff et al. (2003).

Figure 17 shows the vertical-radial cross-section of changes in the azimuthal mean tangential wind during the eyewall replacement for both the first and the last events discussed
above together with the azimuthal mean tangential winds just before the formation of the secondary convective ring. In both cases, the tangential winds increased immediately outside the RMW but decreased inside the RMW in the mid-lower troposphere. The changes in the last event are about 50% larger than those in the first event. The low-level tangential wind tendency is explained by the dynamical response of the azimuthal mean vortex to the imposed diabatic heating inferred from the balanced dynamics as discussed in Shapiro and Willoughby (1982) and Willoughby et al. (1982) and already mentioned in section 3. In our model results, the updrafts shown in the vertical-radial cross-sections in Figs. 14 and 16 are collocated with strong condensational heating (not shown). According to Shapiro and Willoughby (1982), the response of low-level tangential wind to diabatic heating in the eyewall (near the RMW) would be a negative tendency in the eye and a positive tendency near and outside the RMW but with a maximum just inside the RMW. This explains the contraction of the hurricane eyewall. However, when the heating source is some distance outside the RMW, such as the case in the formation of our simulated annular hurricane, the response would be a negative tangential wind tendency within and near the RMW and maximum positive tendency between the RMW and the location where the heating source is imposed (Willoughby et al. 1982). In our simulation, the extra condensational heating in the secondary convective ring indeed induced a low-level tangential wind increase outside the RMW and inside the secondary convective ring together with a decrease inside the RMW (Fig. 17). This tendency causes the contraction of the secondary convective ring as in the case for concentric eyewall studied by Willoughby et al. (1982) and in our case it also resulted in an increase in the RMW, as seen in Fig. 1.

Two questions remain to be addressed. The first question is why the new eyewall contracted to the original radius after the eyewall replacement in the first event but remained outside the original eyewall and led to an increase in eye size in most of the other events. This
can be understood by the difference in the vertical tilt of both the eyewall and the secondary convective ring as already discussed in section 3. Comparing Fig. 14 with Fig. 16, we can see that the vertical outward tilt of both the eyewall and the secondary convective ring is much larger in the last event than in the first event. The vertical outward tilt of the eyewall and the secondary convective ring implies the outward tilted condensational heating. The larger outward tilt of the eyewall in the latter events indicates larger heating outside the low-level RMW. The dynamical response of the storm to this titled heating is a maximum increase in low-level tangential wind outside the RMW and a decrease inside the RMW as seen in Fig. 17b, prohibiting the inward contraction of the new eyewall and thus maintaining the larger eyewall after the eyewall replacement. Therefore, the large outward tilt of the eyewall is critical to the maintenance of the large eye size in our simulated annular hurricane.

The second question is why the secondary convective ring cycle stopped after about 10 days of simulation as seen in Figs. 1 and 12. This is mainly determined by the structure of the simulated annular hurricane. As we discussed previously, the secondary convective ring results mainly from strong inner spiral rainbands. Since both inner and outer spiral rainbands are largely suppressed due to large subsidence in the annular hurricane phase as discussed in section 3, inner spiral rainbands are not strong enough to form secondary convective ring and thus no new cycle occurred in the annular hurricane phase in our simulation. However, it is not clear why the secondary convective ring cycle has a period of about 20-24 hours during the formation period of the simulated annular hurricane. The secondary convective ring cycle appears to be coupled with the activity of the outward-propagating outer spiral rainbands as seen in Figs. 12a and b. The mechanism for their origin and coupling is beyond the scope of this paper and would be an interesting topic for a future study.

In their axisymmetric, nonhydrostatic model experiment with warm rain cloud
microphysics, Willoughby et al. (1994) also found a series of “minor” eyewall replacements as documented above and the subsequent increase in the RMW. However, the period of the secondary convective ring cycle is only several hours, much shorter than that in our simulation. It thus seems that the mechanisms of the ring formation and the subsequent eyewall cycle could be different from what we discussed in this study from our three-dimensional model.

Finally, we should point out that detailed comparison of the mechanism discussed in this study with observations is not straightforward, however. First, the eyewall replacement process identified in this study would be difficult to observe either from infrared satellite images because of the canopy of cirrus clouds in the upper-level outflow layer and the tilt of the eyewall or from current low earth orbiting satellites due to their intermittent temporal resolution. Second, the observations show that the transition from a non-annular hurricane to an annular one is very quick and usually takes about 24 h (Knaff et al. 2003), while in our simulation this transition was gradual and took more than 96 h. This discrepancy could be partially due to the quasi-axisymmetric settings of our model simulation since in reality many processes can trigger convective asymmetries and thus enhance the mixing processes between the convective ring and the eyewall, as indicated by Knaff et al. (2003). As a result, with strong asymmetric forcing and the enhanced mixing, one or two eyewall cycles could be enough to complete the transition from the non-annular phase to the annular phase. Further, we may have offered one possible mechanism in this study for the formation of annular hurricanes, other mechanisms could be possible but yet to be investigated in future studies.

5. Conclusions

Annular hurricanes have been identified as a new category of strong tropical cyclones by Knaff et al. (2003). In the fully compressible, nonhydrostatic tropical cyclone model–TCM4,
the author simulated an annular hurricane that has all observed characteristics of the annular hurricanes documented in Knaff et al. (2003) based on satellite observations. The structure and formation mechanism of the simulated annular hurricane were analyzed in this study.

The model was initialized with an axisymmetric vortex on an $f$-plane in a quiescent environment and thus the transition from the non-annular hurricane to the annular hurricane was attributed to the internal dynamics. As observed, the simulated annular hurricane has a quasi-axisymmetric structure with a wide eyewall, a large eye, and high intensity with suppressed major spiral rainbands. A striking feature of the simulated annular hurricane is its large outward tilt of the wide eyewall, which is critical to the quasi-steady high intensity and responsible for the maintenance of the large eye size of the storm. Although the annular hurricane has a quasi-axisymmetric structure, marked low-wavenumber asymmetries, characterized by vortex Rossby waves (Chen and Yau 2001; Wang 2001, 2002b), exist in the eyewall region.

The formation of the annular hurricane in the simulation is found to be closely related to the interaction between the inner spiral rainbands and the eyewall convection. We show that the inward propagating inner spiral rainbands experience axisymmetrization due to strong shear deformation and filamentation just outside the eyewall, as recently studied by Wang (2007b). As a result, the inner spiral rainbands become tightly wound and evolve into quasi-symmetric secondary convective ring, which intensifies as it contracts while the eyewall breaks down and weakens. Eventually, the secondary convective ring replaces the original eyewall. The new eyewall is wider and tilts more outward with height than the original eyewall. The dynamical response of the low-level tangential wind to the tilted condensational heating in the eyewall is an increase outside and a decrease inside the RMW, prohibiting a further contraction of the new eyewall. Several such eyewall cycles would eventually produce the annular hurricane with
large eyewall slope, large eye, and wide eyewall. For such an annular storm, the strong massflux in the eyewall updraft corresponds to strong convective overturning flow, greatly suppressing the development of any major convective rainbands outside the eyewall.

This eyewall replacement process is very similar to the concentric eyewall cycle previously studied by Willoughby et al. (1982). The only difference is that no local maximum in the azimuthal mean tangential wind corresponds to the secondary convective ring in the annular hurricane formation in our simulation but it is one of the criteria for the concentric eyewall cycle. This is mainly due to the fact that the secondary convective ring in the annular hurricane formation is too close to the eyewall to have its own local maximum tangential wind. We should point out that we have offered one possible mechanism for the formation of the annular hurricane in this study, other mechanisms could be possible but yet to be investigated in future studies.

Although the eyewall cycle discussed in this study contributes to the formation of annular hurricanes, it could be one of the processes causing the increase in eye size of real hurricanes as well. The process discussed here is easily distinguished from the vertical motion fields while it is difficult to see either from infrared satellite images because of the canopy of cirrus clouds in the upper-level outflow layer and the tilt of the eyewall or from current low earth orbiting satellite products due to their intermittent temporal resolution.

It should also be pointed out that we have successfully simulated an annular hurricane in a quiescent environment on an \( f \)-plane. Several sensitivity experiments show that changing the structure of the initial vortex would alter the timing of the annular hurricane formation in the model, implying that the annular hurricane appears to be a final stable regime in the simulation with such an idealized setting. In another experiment on a \( \beta \)-plane, we have successfully simulated the typical concentric eyewall very similar to that studied in Willoughby et al.
(1982). Strikingly, we got intermittent annular hurricane structures after each cycle of the eyewall replacement, indicating that concentric eyewall cycle could be another route towards the annular hurricanes. This has recently been reported by J. Knaff as well (personal communication, 2007) for the case of Hurricane Isabel (2003). Our results will be reported separately with the focus on the formation of the typical concentric eyewall. Meanwhile, the potential effect of environmental flow in the formation of annular hurricane would be another topic that needs to be investigated in future studies.

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References


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Wang, Y., 2007a: A multiply nested, movable mesh, fully compressible, nonhydrostatic


Figure Caption

Figure 1. Maximum azimuthal mean wind speed in m s$^{-1}$ (dashed curve and right legend) at the lowest model level (35.6 m above the sea surface) and its radial distance from the simulated hurricane center, namely, the radius of maximum azimuthal mean wind (solid curve and left legend).

Figure 2. The plan view of the simulated hurricane after 120 h (left) and 288 h (right) of simulation: (a, d) surface rainfall rate (mm h$^{-1}$); (b, e) vertical velocity at 3 km height (m s$^{-1}$); (c, f) potential vorticity (in PVU, 1 PVU=10$^{-6}$ K m$^2$ kg s$^{-1}$) at 1 km height. The circles are at every 30 km radius from the storm center.

Figure 3. West-east vertical cross-section through the storm center after 120 h of simulation: (a) radar reflectivity (dBZ); (b) vertical velocity (m s$^{-1}$); (c) condensational heating (K hr$^{-1}$); (d) potential vorticity (in PVU); (e) equivalent potential temperature (K).

Figure 4. As in Fig. 3 but after 288 h of simulation when the storm at its annular stage.

Figure 5. The azimuthal mean structure of the simulated hurricane averaged between 96 h and 144 h of simulation: a) tangential wind (contour interval 10 m s$^{-1}$), b) radial wind (contour interval 3 m s$^{-1}$), c) vertical velocity (contour interval 0.5 m s$^{-1}$), d) perturbation temperature (contour interval 2 K), e) potential vorticity (contour interval 10 PVU plus contour of 4 PVU), and f) relative angular momentum (contour interval 3×10$^5$ m$^2$ s$^{-1}$).

Figure 6. As in Fig. 5 but averaged between 240 h and 288 h of simulation for the annular stage.

Figure 7. The radial profiles of the azimuthal mean (a) tangential wind in m s$^{-1}$ at 10 m height, (b) vertical velocity in m s$^{-1}$ at 3 km height, (c) surface rainrate in mm h$^{-1}$, (d) PV in PVU at 1 km height, (e) perturbation temperature at the lowest model level, and (f) equivalent potential temperature in K at the lowest model level. Solid (dashed) curves are averaged between 96 h and 144 h (240h and 288 h) of simulation.
Figure 8. Vertical-radial distribution of the azimuthal mean total (a), wavenumber-1 (b), wavenumber-2 (c), wavenumber-3 (d), wavenumber-4 (e), and wavenumber>4 (f) eddy kinetic energy (EKE, in m$^2$ s$^{-2}$) averaged between 72 h and 144 h of simulation. Note that the contour intervals are 2 m$^2$ s$^{-2}$ in (a), 1 m$^2$ s$^{-2}$ in (b, c, f), and 0.5 m$^2$ s$^{-2}$ in (d, e).

Figure 9. As in Fig. 8 but averaged between 240 h and 312 h of simulation.

Figure 10. 6-hourly surface rainrate in mm h$^{-1}$ from 132 h to 246 h of simulation with the model time given at the top of each panel.

Figure 11. As in Fig. 11 but for vertical velocity in m s$^{-1}$ at 3 km height.

Figure 12. Radius-time Hovmöller diagrams of the azimuthal mean vertical velocity in m s$^{-1}$ at 3 km height (a), surface rainrate in mm h$^{-1}$ (b), and radial wind in m s$^{-1}$ at the lowest model level (c) based on every 3 hour model output.

Figure 13. Half-hourly vertical velocity in m s$^{-1}$ at 3 km height from 75 h to 84.5 h of simulation with the model time given at the top of each panel.

Figure 14. Hourly vertical-radial structure of the azimuthal mean tangential wind (contours at interval of 5 m s$^{-1}$) and vertical velocity (m s$^{-1}$, shaded) from 76 h to 85 h of simulation.

Figure 15. As in Figure 13, but from 218.5 h to 228 h.

Figure 16. Hourly vertical-radial structure of the azimuthal mean tangential wind (contours at interval of 5 m s$^{-1}$) and vertical velocity (m s$^{-1}$, shaded) from 221 h to 230 h of simulation.

Figure 17. Vertical-radial distribution of the azimuthal mean tangential wind speed in m s$^{-1}$ (shaded) at 76 h (a) and 221 h (b) of simulation and the differences of the azimuthal mean tangential wind speed (contours) between 86 h and 76 h (a) and between 231 h and 221 h (b) of simulation.
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