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 nonannular 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-wavenumber 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 further contraction of the new eyewall. Strong convective mass flux 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, hereafter KKD03) 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 “annular structure” to distinguish it from the nonannular 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. KKD03 found that the annular hurricanes have systematic formation characteristics, strong and steady intensities, and exist in only specific environmental conditions. Once formed, the annular hurricanes can maintain their annular structure and intensity for several days if specific environmental conditions are maintained. KKD03 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 hur-

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annular hurricanes pose a challenge to tropical cyclone structure and intensity forecasting.

Based on infrared satellite images, KKD03 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, KKD03 speculated that the weak southeasterly shear can offset the opposite directional shear due to the β effect on a baroclinic hurricane vortex (e.g., Wang and Holland 1996a,b), prohibiting the development of convective asymmetries that may result from the β 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 KKD03 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 maintenance dynamics of the annular hurricanes. Understanding the formation mechanisms and the evolution of a 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, primitive equation model TCM4—recently developed by the author at the International Pacific Research Center, University of Hawaii at Manoa. 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 (W07; W08). A full description of the model can be found in W07 together with an analysis of the development of asymmetries in the inner core of a tropical cyclone simulated in the model. W08 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, two-way interactive multiple nesting, and automatic mesh movement with its hydrostatic counterpart TCM3 (Wang 2001, 2002a). The model equations are formulated on 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 $E-e$ 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 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), W07, and W08, 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 W07. The model is initialized with an axisymmetric cyclonic vortex on an $f$ plane at 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 settings for the numerical experiment are identical to that described in W07 and W08.

As mentioned in W08, in a 240-h 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 W08 for another 120 h, namely, from 240 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 nonannular 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) and its radial distance from the simulated hurricane center, namely, the radius of maximum azimuthal mean wind (solid curve and left legend).
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 and 84 h, the RMW maintained small until 144 h of simulation, which was followed by an overall increase from 144 to 240 h. The RMW almost doubled from 144 to 240 h and remained a nearly constant value between 32.5 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 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 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 KKD03, we thus refer to the large eye phase as the annular hurricane phase and the small eye phase as the nonannular hurricane phase to avoid any ambiguity. We will discuss the structural difference between the nonannular 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 “snapshot” plan views of surface rain rate, vertical velocity at 3-km height, and potential vorticity (PV) at 1-km height for the nonannular hurricane after 120 h (left) and the annular hurricane after 288 h (right) of simulation. In the nonannular 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 rain rate and vertical motion fields (Figs. 2a,b). The inner spiral rainbands are well organized and have finescale 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 W08. 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,b). Potential vorticity 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,e) are more than doubled compared to that in its nonannular phase (Figs. 2a,b). The storm is quasi-axisymmetric in both annular and nonannular phases but it is more symmetric in the annular phase than in the nonannular phase. In contrast to the nonannular phase, the storm in the annular phase has much less distinct inner spiral rainbands and has suppressed major outer spiral rainbands (Figs. 2d,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 nonannular phase (Figs. 2a,d). The convection outside the core is largely suppressed by subsidence (Fig. 2e), giving an overall annular hurricane structure as identified by KKD03.

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 nonannular and annular phases. Comparing Figs. 3 and 4, we can see several distinct differences in the vertical structure of the storm between the nonannular 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 nonannular phase (Fig. 3a). We can see from Figs. 4a and 4b 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 KKD03, 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 nonannular 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 nonannular 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 nonannular storm (Figs.
4d and 3d). Potential vorticity is large just inside the eyewall updraft with little vertical tilt in the nonannular 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 nonannular 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 nonannular 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 nonannular 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 nonannular phase averaged between 96 and 144 h of simulation and in Fig. 6 for the annular phase averaged between 240 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 nonannular 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 nonannular 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 nonannular
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 nonannular 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 nonannular phase (Figs. 5e and 6e). As mentioned already, the PV maximum in the midtroposphere 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 nonannular (averaged between 96 and 144 h of simulation) and annular (averaged between 240 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 an-

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**Fig. 4.** As in Fig. 3 but after 288 h of simulation when the cyclone is at its annular stage.
nullar phase than in the nonannular 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 nonannular phase (Fig. 7b). Although the maximum rain rate is only about 18% larger in the eyewall, the rain rate 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 nonannular phase (Figs. 7e,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 nonannular hurricanes in nature, as documented in KKD03, 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 nonannular 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

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$^1$ Eddy kinetic energy is defined as $(u'^2 + v'^2)/2$, 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 $v'$. 

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lower troposphere in the large-eyed annular phase than in the small-eyed nonannular phase. The asymmetries are dominated by the azimuthal wavenumber-2 component in both phases (Figs. 8c and 9c). As shown in W07, 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 \( \geq 4 \) are suppressed greatly in the inner core region in both phases (Figs. 8f and 9f). This has been attributed to the rapid filamentation and axisimmetrization due to the strong shear deformation just outside the eyewall by W08. Two distinct differences in the asymmetric structure can be identified between the nonannular and annular phases. First, the storm in the nonannular phase shows much stronger wavenumber-1 and high-wavenumber (with wavenumber \( \geq 4 \)) 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 nonannular 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 balanced vortices can be applied. Here, we are not going to perform the calculation but cite the results of Shapiro and Willoughby (1982, hereafter SW82) and Willoughby et al. (1982). According to SW82, 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 (SW82).

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 SW82’s Fig. 11 for a Rankin vortex with \( v_0 \propto r^{-1} \). 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 midtropospheric 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. SW82 showed such examples in their Fig. 15 for vortices with tangential wind profiles of \( v_0 \propto r^{-1/2} \) and \( v_0 \propto r^{-1/4} \), 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 \( v_0 \propto r^{-1/2} \) discussed in SW82. 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 nonannular phase (Fig. 5c) and outwardly tilted heating with maximum in the middle–lower tro-
posphere 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 nonannular 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 titled eyewall in the annular phase would be a decrease of low-level tangential wind inside and an increase outside the RMW (SW82). 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, KKD03 were not able to either examine the detailed three-dimensional dynamical and thermodynamic structure of these storms or provide insight into how an annular hurricane can maintain its large eye and wide eyewall and why the annular hurricanes weaken at much slower rates than nonannular hurricanes. The numerical results from our model simulation thus provide insight into these issues as 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

KKD03 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 meso-

![Figure 8. Vertical–radial distribution of the (a) azimuthal mean total, (b) wavenumber-1, (c) wavenumber-2, (d) wavenumber-3, (e) wavenumber-4, and (f) wavenumber >4 eddy kinetic energy (EKE; m² s⁻²) averaged between 72 and 144 h of simulation. Note that the contour intervals are 2 m² s⁻² in (a), 1 m² s⁻² in (b), (c), (f), and 0.5 m² s⁻² in (d), (e).]
vortices. 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 KKD03 identified are all met in our model simulation (except for a slightly higher SST in this study). Knaff et al. (2008) recently show that only about 9% of the hurricanes that met environmental conditions eventually developed into annular hurricanes in the Atlantic during 2004–06. 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 nonannular 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 and 236 h of simulation (Fig. 1), we first have a quick look at the evolution of surface rain rate (Fig. 10) and vertical motion at 3-km height (Fig. 11) from 132 to 246 h of simulation at 6-h intervals. As expected, the increase in eye size with time is clearly seen in both surface rain rate 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 W08, the strong shear deformation just outside the RMW favors 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 Hovmöller diagrams...
of the azimuthal mean vertical velocity at 3-km height, surface rain rate, 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, 132–144, 150–162, 168–186, 192–210, 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 con-

Fig. 10. Six-hourly surface rain rate (mm h⁻¹) from 132 to 246 h of simulation with the model time given at the top of each panel.
vective ring. Similar signals are evident in both rain rate (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 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 min for the first event between 75 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 with 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 a very tightly wound structure
mainly due to the strong shear deformation and axisymmetrization process (W08) 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-h period between 79 and 82.5 h of simulation. This is also evident in the boundary layer inflow and rain rate shown in Figs. 12b,c. A single eyewall structure reformed and continued to contract and the storm reintensified 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 tilted 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 eyewallike updraft and contracted at the same time between 77 and 81 h of simulation. Note that, as the secondary convective ring contracted, the outward tilt of its updraft decreased because the angular momentum surface reduced its outward slope toward the storm eyewall (Fig. 5f). Meanwhile, the original eyewall updraft weakened during 80 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 after (Fig. 1).

The last event during 218 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 KKD03.

Figure 17 shows the vertical–radial cross section of changes in the azimuthal mean tangential wind during 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 SW82 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 SW82, 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 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. 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 re-
sults mainly from strong inner spiral rainbands. Since
both inner and outer spiral rainbands are largely sup-
pressed due to large subsidence in the annular hurri-
cane phase as discussed in section 3, inner spiral rain-

Fig. 15. As in Fig. 13 but from 218.5 to 228 h.

bands are not strong enough to form a secondary con-
vective 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 h during the formation period
of the simulated annular hurricane. The secondary con-
vective ring cycle appears to be coupled with the activ-
ity of the outward-propagating outer spiral rainbands as seen in Figs. 12a,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. (1984) 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

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**Fig. 16.** Hourly vertical–radial structure of the azimuthal mean tangential wind (contour interval is 5 m s⁻¹) and vertical velocity (m s⁻¹, shaded) from 221 to 230 h of simulation.
current low earth-orbiting satellites due to their intermittent temporal resolution. Second, the observations show that the transition from a nonannular hurricane to an annular one is very rapid and usually takes about 24 h (KKD03), 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 KKD03. 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 nonannular 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 KKD03. 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 KKD03 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; thus the transition from the nonannular 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 W08. 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 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 mass flux 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 an-
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 remain to be investigated.

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 β 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 a concentric eyewall cycle could be another route toward the annular hurricanes. This has recently been reported by J. Knaff (2007, personal communication) as well 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 hurricanes would be another topic that needs to be investigated in future studies.

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