Rapid Filamentation Zone in a Numerically Simulated Tropical Cyclone*

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ABSTRACT

In a recent study, Rozoff et al. proposed a possible mechanism to explain the formation and maintenance of the weak-echo annulus (or moat) outside of the primary eyewall of a tropical cyclone observed in radar images. By this mechanism, the moat is determined to be a region of the strain-dominated flow outside of the radius of maximum wind in which essentially all fields are filamented and deep convection is hypothesized to be highly distorted and even suppressed. This strain-dominated region is defined as the rapid filamentation zone wherein the filamentation time is shorter than the overturning time of deep convection. An attempt has been made in this study to test the hypothesis in a full-physics tropical cyclone model under idealized conditions and to extend the concept to the study of the inner-core dynamics of tropical cyclones. The foci of this paper are the evolution of the rapid filamentation zone during the storm intensification, the potential roles of rapid filamentation in the organization of inner spiral rainbands, and the damping of high azimuthal wavenumber asymmetries in the tropical cyclone inner core.

The presented results show that instead of suppressing deep convection, the strain flow in the rapid filamentation zone outside the elevated potential vorticity core provides a favorable environment for the organized inner spiral rainbands, which generally have time scales of several hours, much longer than the typical overturning time scale of individual convective clouds. Although the moat in the simulated tropical cyclone is located in the rapid filamentation zone, it is mainly controlled by the subsidence associated with the overturning flow from eyewall convection and downdrafts from the anvil stratiform precipitation outside of the eyewall. It is thus suggested that rapid filamentation is likely to play a secondary role in the formation of the moat in tropical cyclones. Although the deformation field is determined primarily by the structure of the tropical cyclone, it can have a considerable effect on the evolution of the storm. Because of strong straining deformation, asymmetries with azimuthal wavenumber >4 are found to be damped effectively in the rapid filamentation zone. The filamentation time thus provides a quantitative measure of the stabilization and axisymmetrization of high-wavenumber asymmetries in the inner core by shearing deformation and filamentation.

1. Introduction

Tropical cyclones are rapidly rotating, warm-cored, atmospheric vortices. A distinct feature in radar images of many intense tropical cyclones is the existence of an area (called the moat) characterized by relatively weak radar echoes immediately outside of the deep eyewall convection. Subsidence induced by the eyewall convection and downdrafts associated with the accompanying anvil stratiform precipitation are considered to play an important role in the formation and maintenance of the moat (e.g., Willoughby 1998; Dodge et al. 1999; Houze et al. 2007). Thus, until recently, the moat has been considered mainly from the viewpoint of a by-product of the tropical cyclone circulation with little attention devoted to its dynamics.

From a dynamical perspective, the moat coincides with a region of large radial shear of the tangential winds immediately outside the radius of the maximum wind. The strong shear may act to effectively damp small-scale asymmetries with high azimuthal wavenumbers and thus play an important role in the axisymmetrization process in the storm (Guinn and Schubert 1993; Smith and Montgomery 1995; Montgomery and Kallenbach 1997). The moat is also a region with strong strain flow with strong horizontal deformation, which is hypothesized to distort or even suppress deep convection locally (Kossin et al. 2000; Rozoff et al. 2006).

Guinn and Schubert (1993) were among the first to

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introduce the concepts of potential vorticity (PV) waves, wave breaking, and the surf zone used in stratospheric dynamics (McIntyre and Palmer 1984; Juckes and McIntyre 1987) to the understanding of tropical cyclone spiral rainbands. In their analysis, the tropical cyclone is viewed as an elevated high-PV core with sharp radial PV gradients at its edge surrounded by a surf zone with a comparatively weak PV gradient where PV wave breaking occurs frequently. This frequently occurring PV wave breaking was envisaged by McIntyre and Palmer (1984) as the rapid, irreversible deformation of material substances.

Potential vorticity wave (or vortex Rossby wave) breaking is a fundamental process leading to the axisymmetrization of the storm (Melander et al. 1987; Smith and Montgomery 1995; Montgomery and Kallenbach 1997). Once excited on the vortex edge by, for example, convective processes in the eyewall, vortex Rossby waves may experience nonlinear breaking, characterized by a spiral-banded PV structure or PV filaments, due to the effects of strain and adverse shear in the surf zone surrounding the PV core. These breaking waves tend to lead to a downgradient flux of PV, spreading PV radially (Guinn and Schubert 1993). This process has been considered to be one of the major mechanisms responsible for the generation of inner spiral rainbands in tropical cyclones as shown in dry, barotropic models by Chen and Yau (1993) and Montgomery and Kallenbach (1997) and in full-physics models by Chen and Yau (2001) and Wang (2001, 2002b,c).

In a recent study, Rozoff et al. (2006) extended the dry, barotropic dynamics approach further and proposed a mechanism to explain the observed weak-echo moat outside the eyewall of a tropical cyclone. By their argument, the moat is determined to be a region of strain-dominated flow in which essentially all fields are filamented and deep convection is supposed to be highly distorted and even suppressed. Rozoff et al. (2006) provided a criterion, namely, the filamentation time, to quantify the impact of horizontal strain on deep moist convection. The strain-dominated region is termed the rapid filamentation zone wherein the filamentation time is shorter than the overturning time for deep convection. The existence and evolution of such rapid filamentation zones in intense tropical-cyclone-like vortices were illustrated by Rozoff et al. (2006) in several dry, nondivergent, barotropic model experiments.

The above studies all indicate that the surf zone or the rapid filamentation zone is an area of importance to tropical cyclone dynamics. However, these studies were constructed and understood in terms of simple dry, barotropic settings without diabatic processes or friction to enlighten the basic principles. Although Rozoff et al. (2006) hypothesized that both subsidence and rapid filamentation are important to the formation and maintenance of a moat, an evaluation of the relative importance of the two effects is beyond their simple barotropic model.

Questions arise as to what extent those concepts based on barotropic arguments can be applied to reality since the tropical cyclone involves both diabatic and frictional processes in a three-dimensional setting. We have the following questions in mind: 1) How does the rapid filamentation process modify the tropical cyclone structure and intensity? 2) How does the filamentation zone evolve during the rapid intensification of tropical cyclones and does it affect the tropical cyclone intensification? 3) Can the filamentation time be used as a quantitative measure of damping of high azimuthal wavenumber asymmetries in the tropical cyclone core? As a first step toward bridging the gap between theory and the observed structure and dynamics of tropical cyclones, this study attempts to extend the dry, barotropic concepts obtained from earlier research to tropical cyclone behavior simulated in a fully compressible, nonhydrostatic, cloud-resolving model. Our foci will be on the dynamics of the rapid filamentation zone and their potential roles in controlling the structure of the simulated tropical cyclone under idealized conditions.

The rest of the paper is organized as follows. The next section briefly reviews the basic concept of filamentation following Rozoff et al. (2006). Section 3 describes the tropical cyclone model used and the experimental design. Section 4 briefly describes the intensity evolution and the axisymmetric structure of the model storm and analyzes the rapid filamentation zone during the mature stage of the model storm and its evolution during the storm intensification. The possible role of rapid filamentation in affecting the inner-core asymmetric structure of the simulated tropical cyclone is discussed in section 5. Concluding remarks are given in the last section.

2. A review of the basic concept of filamentation

Using the Cartesian coordinate notion of Rozoff et al. (2006), we can write the $f$-plane, nondivergent, barotropic vorticity conservation equation as

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (\psi, \zeta)}{\partial (x, y)} = 0,$$  \hspace{1cm} (1)

where the relative vorticity is $\zeta = \nabla^2 \psi$, $\partial(a, b)/\partial(x, y)$ is the Jacobian operator, and $\psi$ is the streamfunction for the nondivergent flow $(u, v) = (-\partial \psi/\partial y, \partial \psi/\partial x)$. Com-
puting $\partial(1)/\partial x \leq i\partial(1)/\partial y$, one obtains the equation governing the evolution of the vorticity gradient (Okubo 1970; Weiss 1991):

$$\frac{D}{Dt} \begin{pmatrix} \xi_x + i\xi_y \\ \xi_x - i\xi_y \end{pmatrix} = \begin{pmatrix} \frac{1}{2} i\xi_x & -\frac{1}{2} (S_1 + iS_2) \\ -\frac{1}{2} (S_1 - iS_2) & -\frac{1}{2} i\xi_x \end{pmatrix} \times \begin{pmatrix} \xi_x + i\xi_y \\ \xi_x - i\xi_y \end{pmatrix},$$

(2)

where

$$S_1 = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \text{ and } S_2 = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$$

(3)

are the rates of strain due to stretching deformation ($S_1$) and shearing deformation ($S_2$), respectively, and $D/Dt = \partial/\partial t + u\partial/\partial x + v\partial/\partial y$ is the material derivative. As indicated by Rozoff et al. (2006), in many intense tropical cyclone situations, strain rate and vorticity can be considered to be nearly constant along a trajectory because the azimuthal wind is much larger than the radial wind and the flow is nearly axisymmetric. As a result, under the assumption of the nearly circular particle trajectories in a quasi-axisymmetric tropical cyclone, the eigenvalues of the $2 \times 2$ matrix on the right-hand side of (2) can be considered nearly constant or slowly evolving along the Lagrangian trajectories and the solutions of (2) can be approximated by linear combinations of

$$\exp \left[ \pm \frac{1}{2} i(\xi^2 - S_1^2 - S_2^2)^{1/2} t \right], \text{ if } \xi^2 > S_1^2 + S_2^2,$$

(4)

or

$$\exp \left[ \pm \frac{1}{2} (S_1^2 + S_2^2 - \xi^2)^{1/2} t \right], \text{ if } \xi^2 < S_1^2 + S_2^2.$$ 

(5)

Although the above assumption is very strict and is not always valid in reality, it appears to be a good approximation for our settings in our numerical simulation, namely, the quasi-axisymmetric nature of the simulated tropical cyclone on an $f$ plane in a quiescent environment, as discussed in the next section. This is particularly true for the quasi-steady evolution of the simulated tropical cyclone in its mature stage in this study.

The quantity

$$Q = \frac{1}{4} (S_1^2 + S_2^2 - \xi^2)$$

(6)

measures the relative magnitudes of the strain and vorticity and is often called the Okubo–Weiss criterion after Okubo (1970) and Weiss (1991). In regions where $Q < 0$, trajectories of two neighboring particles do not separate exponentially in time, and vice versa (Schubert et al. 1999). The solutions for $Q < 0$ given in (4) are oscillatory. That is, in regions where vorticity dominates strain, coherent structures such as mesovortices can survive. Conversely, the solutions for $Q > 0$ given in (5) are exponential. This means that in regions where strain dominates vorticity, the vorticity gradient intensifies, forming long, thin vorticity-gradient sheets across which vorticity changes rapidly along the trajectories. In such regions fluid elements are stretched and there is exponential divergence of nearby particles, the so-called chaotic stirring in two-dimensional turbulence (Okubo 1970; Weiss 1991; Elhmaidi et al. 1993; Kevlahan and Farge 1997). Apparently, the solutions are not mutually exclusive. For example, in the coherent monopolar vortices that emerged during two-dimensional decaying turbulence, McWilliams (1984) found strong negative $Q$ in the central regions surrounded by regions with weakly positive $Q$. This property of Lagrangian particle trajectories was studied by Guinn and Schubert (1993) in tropical-cyclone-like vortices (see their Fig. 4). They attributed the tropical cyclone spiral bands to the deformation and PV filaments during the axisymmetrization process of an elliptic vortex.

To facilitate the application of the filamentation concept to tropical cyclones, Rozoff et al. (2006) defined the filamentation time as the $e$-folding time of the exponential solution in the strain-dominated regions:

$$\tau_{fil} = 2(S_1^2 + S_2^2 - \xi^2)^{-1/2} \text{ for } S_1^2 + S_2^2 > \xi^2.$$

(7)

Since deep, moist convection in the tropical cyclone core region has a typical overturning time scale of about 30–45 min, Rozoff et al. (2006) defined the rapid filamentation zone as the region in which $\tau_{fil} < 30$ min. In cylindrical coordinates moving with the tropical cyclone, one obtains

$$S_1^2 + S_2^2 = \left( \frac{\partial v}{\partial r} - \frac{v}{r} \right)^2 + \left( \frac{\partial u}{\partial r} - \frac{u}{r} + \frac{\partial v}{\partial \theta} \right)^2$$

(8)

and

$$\xi^2 = \left( \frac{\partial u}{\partial r} + \frac{u}{r} - \frac{\partial v}{\partial \theta} \right)^2,$$

(9)

where $v_r$ and $u$ denote the radial and azimuthal winds, respectively; $r$ the radius; and $\theta$ the azimuth. It is clear in (8) that $S_1$ is the stretching deformation and $S_2$ is the shearing deformation in cylindrical coordinates now. In
the near-core environment of intense tropical cyclones, the primary flow is quasi axisymmetric and rapidly rotating. As a result, the shearing deformation generally dominates the stretching deformation in the mid- to lower troposphere. The existence and evolution of such rapid filamentation zones in intense tropical-cyclone-like vortices are illustrated by Rozoff et al. (2006) in several dry, nondivergent, barotropic model experiments.

As indicated by Rozoff et al. (2006), the solutions of (4) or (5) are derived from the vorticity equation, but they are applicable to any quasi-barotropic flow for any scalar variables, such as PV as shown in their Eq. (20). In three-dimensional settings, the flow strain is much more complicated than in two-dimensional settings because of the extra degree of freedom. Fortunately, the inner-core region of an intense tropical cyclone is inertially very stable and can be described, to a considerable extent, by quasi-balanced, quasi-barotropic dynamics, especially in the mid- to lower troposphere except for the relatively small areas with strong convective cells. This may explain why barotropic dynamics are still useful for understanding many aspects of tropical cyclones, in particular the inner-core dynamics (e.g., Guinn and Schubert 1993; Montgomery and Kallenbach 1997; Schubert et al. 1999). In the vortex-scale motion of intense tropical cyclones, the three-dimensional strain is dominated by its horizontal components. This relationship is similar to the vertical relative vorticity, which dominates the horizontal vorticity components in the core of an intense tropical cyclone. Therefore, in this study we will apply the concept of filamentation for two-dimensional vortex motion to a three-dimensional tropical cyclone simulated in a full-physics model.

It should be pointed out that Hua and Klein (1998) relaxed the assumption used in the Okubo–Weiss criterion that the velocity gradients are slowly evolving with respect to the vorticity gradient following a fluid parcel and obtained an improved criterion that is more precise than the Okubo–Weiss criterion. The improved criterion includes the effect of a Lagrangian acceleration gradient tensor, giving larger areas and greater values of positive $Q$ and thus producing somewhat larger rapid filamentation zones with smaller value of $\tau_{ij}$ (Rozoff et al. 2006). Therefore, the use of the original Okubo–Weiss criterion (6) and the corresponding filamentation time defined in (7) should be regarded as conservative as noted already by Rozoff et al. (2006). A more general criterion for three-dimensional fluid motion is not available and is yet to be developed in the future, which is beyond the scope of this study.

3. The model description and experimental design

a. Model description

The model used in this study is the fully compressible, nonhydrostatic, primitive equation model—version 4 of the Tropical Cyclone Model (TCM4). It is an extension of the hydrostatic model TCM3 (Wang 1999, 2001, 2002a), but with the hydrostatic dynamical core replaced by a fully compressible, nonhydrostatic dynamical core. Therefore, TCM4 shares the state-of-the-art model physics and the two-way interactive, multiply nesting, and automatically moving mesh with its hydrostatic counterpart, TCM3. A major feature of TCM4 is its capability of simulating the inner-core structure and the associated intensity change of a tropical cyclone at nearly cloud-resolving resolution. Additionally, the use of multiple nests and automatic mesh movement in TCM4 allows us to optimize the domain size of the finest-resolution meshes, resulting in a savings of computer time. A full description of TCM4 can be found in Wang (2007). Here, only the major features of the model are highlighted.

The model equations are formulated in Cartesian coordinates in the horizontal and in the mass coordinate in the vertical. An efficient two-time-level, forward-in-time, explicit time-splitting scheme, similar to that described by Wicker and Skamarock (2002), is used for model integration. The fifth-order upwind scheme, which takes into account the effects of spatial variation of the advective flow (Wang 1996), is used to calculate time tendencies due to horizontal advection. A similar second-order scheme is used to calculate the time tendencies due to vertical advection. Note that the model has a flat lower boundary at the surface with a uniform 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 physics include 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 1999, 2001), fourth-order horizontal diffusion with deformation-dependent diffusion coefficient for all prognostic variables except for that related to the mass conservation equation, a simple Newtonian cooling term added to the potential temperature equation to mimic radiative cooling as used in TCM3 and in Rotunno and Emanuel (1987), and dissipative heating due to molecular friction, which is included by
adding the turbulent kinetic energy dissipation rate ($\epsilon$) into the thermodynamic equation.

The model domain is multiply nested with two-way interactive nesting and with the inner meshes automatically moving to follow the model tropical cyclone as used in TCM3 (Wang 2001). As in Wang (2001, 2007), 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 used even in the two outermost coarse meshes in this study. In our current configuration, the model domain is quadruply nested with resolutions of 67.5, 22.5, 7.5, and 2.5 km and mesh sizes of 201 × 181, 109 × 109, 127 × 127, and 163 × 163 grid points, respectively. The model has 26 levels in the vertical and uses a vertically staggered grid such that horizontal winds, perturbation pressure, potential temperature, and all moist variables are located at the half levels while the vertical wind and the turbulent kinetic energy and its dissipation rate are arranged at the integer levels.

b. Experimental design

The experimental design follows Wang (2001, 2007). The model is initialized with an axisymmetric cyclonic vortex on an $f$ plane of 18°N in a quiescent environment over the ocean with a constant sea surface temperature of 29°C. The initial thermodynamic structure of the unperturbed model atmosphere is horizontally homogeneous and defined using the western Pacific clear-sky environment given by Gray et al. (1975). The tangential wind of the initial cyclonic vortex is defined by

$$ V_T(r, \sigma) = \begin{cases} V_m \left( \frac{r}{r_m} \right) \left\{ \exp \frac{1}{b} \left[ 1 - \left( \frac{r}{r_m} \right)^b \right] \right\} & , \quad \sigma > \sigma_T; \\
0, & , \quad \sigma \leq \sigma_T; \\
\end{cases} $$

(10)

where $\sigma$ is the vertical coordinate, defined as unperturbed pressure normalized by the unperturbed surface pressure (see Wang 2007), $\sigma_T = 0.15$, and

$$ V(r) = \begin{cases} V_m \left( \frac{r}{r_m} \right) \left\{ \exp \frac{1}{b} \left[ 1 - \left( \frac{r}{r_m} \right)^b \right] \right\} & , \quad r \leq R_o; \\
- \frac{|r - r_m|}{R_o - r_m} \exp \frac{1}{b} \left[ 1 - \left( \frac{R_o}{r_m} \right)^b \right] & , \quad r > R_o; \\
\end{cases} $$

(11)

where $V_m$ is the maximum tangential wind at the radius $r_m$, $r$ is the radius, $b$ is a nondimensional parameter that determines the rate of radial decay of tangential wind outside the radius of maximum wind, and $R_o$ is the radius at which the vortex wind vanishes. The mass and thermodynamic fields associated with the vortex are obtained by solving the nonlinear balance equation as described in the appendix of Wang (2001). In all numerical experiments discussed in this study, we set $V_m = 25$ m s$^{-1}$, $r_m = 80$ km, $R_o = 900$ km, and $b = 1.0$. The model was integrated for 10 days.

In our analysis, the inertial stability parameter $I^2$ for the quasi-symmetric storm can be written as (e.g., Shapiro and Montgomery 1993)

$$ I^2 = \left( f_0 + \frac{2A}{r} \right) \left( f_0 + \frac{v_0}{r} + \frac{\partial v_0}{\partial z} \right), $$

(12)

where $f_0$ is the Coriolis parameter at the storm center.

We first decompose the winds in Cartesian coordinates into cylindrical coordinates and then calculate the inertial stability parameter using centered finite differencing for (12). In the following discussions, the inertial stability parameter is normalized by the square of the local Coriolis parameter, $f_0$.

4. Rapid filamentation zone in the simulated storm

a. Intensity evolution and axisymmetric structure

Before discussing the rapid filamentation zone in the simulated tropical cyclone in the next subsections, we first examine the intensity evolution and axisymmetric inner-core structure of the simulated storm. Figure 1 shows the maximum wind speed at the lowest model level (35.6 m above the sea surface) and the minimum central sea level pressure of the simulated tropical cyclone. The storm intensified rapidly after an initial 9-h adjustment and the spinup of the boundary layer and moist processes. The storm reached a quasi-steady evolution after about 3 days of simulation but experienced some intensity oscillations afterward, especially in the maximum low-level wind speed. Over the 10-day simulation, the storm reached peak intensity with a maximum lowest model level wind speed of about 73 m s$^{-1}$ and a minimum central sea level pressure of 916 hPa.

The axisymmetric structure of the mature storm av-
eraged between 120 and 168 h of simulation is shown in Fig. 2, including the tangential and radial winds, vertical velocity, temperature anomalies, PV, and relative angular momentum. The storm has its maximum tangential wind at a radius of about 18 km near the surface (Fig. 2a), a shallow inflow layer in the boundary layer, and a relatively deep outflow layer in the upper troposphere (Fig. 2b). The eyewall ascent tilts radially outward with height, especially in the mid- to upper troposphere (Fig. 2c). The storm has a warm-core structure in the mid- to upper troposphere with a maximum temperature anomaly of above 14 K (Fig. 2d). The PV shows an off-centered maximum just within the radius of maximum wind (Fig. 2c) and high inertial stability coincides with the convective, rapidly rotating eyewall (Fig. 2d). The filamentation time is determined by both horizontal deformation and vertical relative vorticity (7). Figure 3e shows the square of the deformation field at 1-km height and the corresponding filamentation time is presented in Fig. 3f with the vorticity-dominated areas whitened out. We can see that deformation is very large under the eyewall (Fig. 3e) while the rapid filamentation zone, with filamentation time of less than 45 min, extends outward to the near-core environment (Fig. 3f).

Rozoff et al. (2006) speculated that convection might be distorted or even suppressed in the rapid filamentation zones and hypothesized that this could be one of the mechanisms for the formation of the echo-free moat observed outside of the tropical cyclone eyewall in radar images. Our results, however, show that convection takes the form of a well-organized, spiral structure in the rapid filamentation zone as seen from the precipitation and vertical motion fields (Figs. 3a and 3b). This result suggests that rapid filamentation plays a critical role in the formation and organization of inner spiral rainbands, rather than in significantly suppressing deep convection. Instead, the light rain areas outside of the eyewall correspond to the subsidence between the eyewall convection and spiral rainbands or between spiral rainbands (Figs. 3a and 3b). This indicates that the subsidence due to the overturning flow of eyewall convection or convection in the spiral rainbands, and downdrafts from the anvil stratiform precipitation re-}

b. Rapid filamentation zone in the mature storm

Figure 3 shows the snapshot plan view of various parameters, including surface rain rate, vertical velocity at 3-km height, PV, the normalized inertial stability parameter, the square of the total deformation rate $S^2 = S_1^2 + S_2^2$, and the filamentation time at 1-km height, all after 96 h of simulation. All fields are quasi axisymmetric with considerable asymmetries. In particular, heavy precipitation appears in the eyewall between radii of about 10 and 25 km; the eyewall is surrounded by inner spiral rainbands within a radius of about 40 km (Fig. 3a). These inner spiral rainbands have fine radial structure with smooth lateral boundaries, consistent with the narrow, spiral-banded structure in the vertical motion field (Fig. 3b), which also shows considerable asymmetric structure in the eyewall updrafts. These inner spiral rainbands, however, appear to be different from the very finescale rainbands that resulted from instabilities in the storm boundary layer, as discussed by Nolan (2005). As expected for a well-developed tropical cyclone, an elevated PV ring is well inside the radius of maximum wind (Fig. 3c) and high inertial stability coincides with the convective, rapidly rotating eyewall (Fig. 3d). The filamentation time is determined by both horizontal deformation and vertical relative vorticity (7). Figure 3e shows the square of the deformation field at 1-km height and the corresponding filamentation time is presented in Fig. 3f with the vorticity-dominated areas whitened out. We can see that deformation is very large under the eyewall (Fig. 3e) while the rapid filamentation zone, with filamentation time of less than 45 min, extends outward to the near-core environment (Fig. 3f).

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regions, may play the dominant role in the moat formation in the tropical cyclone. Note further that convection outside of the rapid filamentation zone is generally loosely organized as seen from both the precipitation and vertical motion fields (Figs. 3a and 3b), where the deformation is weak with prolonged filamentation time.

The west–east vertical cross sections along the storm center for radar reflectivity, vertical velocity, the square of the total deformation, filamentation time, and the normalized inertial stability parameter for the same model time as in Fig. 3 are shown in Fig. 4. There are several interesting and distinct features. First, high radar reflectivity occurs in the eyewall and convective spiral rainbands and tilts outward with height (Fig. 4a). The sharp vertical gradient near 5-km height is an indication of the melting level with ice-phase hydrometeors dominating above and liquid-phase hydrometeors dominating below. The outward tilt of the high reflectivity is consistent with the outward tilt in the vertical motion (Fig. 4b), which is slantwise following the angular momentum surfaces (Fig. 2f) as mentioned in section 3a. Second, the radar reflectivity shows the existence of hub clouds (with radar reflectivity larger than 30 dBZ) in the eye near the storm center. The hub’s cloud top reaches as high as 7–8 km (Fig. 4a) with light surface precipitation (Fig. 3a). These clouds appear to be mixed stratocumulus and cumulus clouds, or more likely cumulus congestus with weak upward motion, and are surrounded by subsidence just near the inner

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**Fig. 2.** The azimuthal mean structure of the simulated tropical cyclone averaged between 120 and 168 h of the simulation: (a) tangential wind (contour interval is 10 m s\(^{-1}\)), (b) radial wind (contour interval is 3 m s\(^{-1}\)), (c) vertical velocity (contour interval is 0.5 m s\(^{-1}\)), (d) perturbation temperature (contour interval is 2 K), (e) potential vorticity (contour interval is 10 PVU plus a contour of 4 PVU; 1 PVU = 10\(^{-6}\) K m\(^2\) kg s\(^{-1}\)), and (f) relative angular momentum (contour interval 3 \(\times\) 10\(^5\) m\(^2\) s\(^{-1}\)).
FIG. 3. The plan view of the simulated tropical cyclone after 96 h of simulation: (a) surface rainfall rate (mm h\(^{-1}\)), (b) vertical velocity at 3-km height (m s\(^{-1}\)), (c) potential vorticity (PVU), (d) the normalized inertial stability parameter, (e) square of the total deformation (s\(^{-2}\)), and (f) filamentation time (min) at 1-km height. The circles are every 30 km from the storm center. Note that negative areas in (d) indicate inertially unstable regions and areas whited out in (f) indicate vorticity-dominated regions.
FIG. 4. West–east vertical cross section through the tropical cyclone center after 96 h of simulation: (a) radar reflectivity (dBZ), (b) vertical velocity (m s$^{-1}$), (c) total deformation square (s$^{-2}$) and its stretching component (contours), (d) filamentation time (in min), and (e) the normalized inertial stability parameter.
edge of the eyewall clouds (Fig. 4b). Third, comparing the radar reflectivity and vertical motion, one can see that convective precipitation, defined as that with high radar reflectivity and low-level origin for the updrafts, occupies a relatively small portion of the areas with surface precipitation (Figs. 3a,b and 4a,b). Considerably larger areas are covered by stratiform precipitation with descending motion below the melting level and upward motion above, especially to the west of the eyewall at the time shown in Fig. 4.

Large deformation occurs in the near-core environment in the mid- to lower troposphere within a radius of about 60 km from the storm center (Fig. 4c). Note that the deformation is dominated by the shearing deformation throughout the troposphere. The contribution by stretching deformation (contours in Fig. 4e) is relatively small and only in the inflow boundary layer near the radius of the maximum wind due to the stretching of boundary layer inflow. Although small, this boundary layer stretching deformation may play a role in narrowing radially the eyewall updrafts (Fig. 4b) and maintaining the elevated PV inside the radius of maximum wind (Fig. 3c). The filamentation time is generally less than 45 min (rapid filamentation) within a radius of about 60 km from the storm center with a considerable outward tilting immediately outside the tilted eyewall. Within the radius of maximum wind, vorticity dominates the deformation with strong inertial stability throughout the troposphere (Fig. 4e). The eyewall updrafts are collocated with the radii where the low-level inertial stability is highest, while they are immediately inside of the rapid filamentation zone (Figs. 4c–e). Although the rapid filamentation zone to the east of the eyewall collocates with subsidence, strong updrafts occur to the west of the eyewall where a rapid filamentation zone exists. This again indicates that rapid filamentation could not be one of the major players in suppressing deep convection, as hypothesized by Rozoff et al. (2006).

The radius of maximum wind and the size of the simulated storm increased considerably after about 225 h of integration. It is interesting to see how the rapid filamentation zone changes with the storm’s eyewall size. Similar parameters as shown in Fig. 3, but after 240 h of simulation, are given in Fig. 5. The overall structure is similar to that shown in Fig. 3 for the small-eye stage except that the hub clouds in the eye now look like inner spiral rainbands in the eye. At this time, the size of the eye has almost doubled and there is considerable rainfall in the eye region (Fig. 5a) together with weak upward motion (Fig. 5b). The eyewall updrafts and precipitation are much wider than at the small-eye stage, yet the magnitude of the rain rate is essentially similar (Figs. 5a and 5b). Interestingly, the inner spiral rainbands also have relatively larger radial scales, indicating weaker shearing deformation or, equivalently, weaker filamentation than at the small-eye stage. The convection outside of the core is largely suppressed by subsidence (Fig. 5b), giving an overall annular hurricane structure as identified by Knaff et al. (2003). The potential vorticity exhibits a hollow structure with low PV in the eye region and high PV just inside the radius of maximum wind (about 35 km from the storm center at the given time).

As we can see from the normalized inertial stability parameter in Fig. 5d, the storm has an inertially stable eyewall structure but is less inertially stable than it is at the small-eye stage shown in Fig. 3d. The deformation outside of the radius of maximum wind is large (Fig. 5e) but it is smaller than that of the small-eye stage (Fig. 3e). Accordingly, although the rapid filamentation zone is wider, the filamentation time is relatively longer (Fig. 5f), giving rise to weaker filamentation and thus larger radial scales of the inner spiral rainbands (Figs. 5a and 5b). Precipitation, vertical motion, and PV features in the eye region at the large-eye stage (Figs. 5a–c) indicate some mixing processes and swirling clouds occurring in the eye region of the simulated storm as observed in some large-eye storms in nature (Kossin et al. 2002). A detailed examination of the mechanisms causing the transition from the small eye to the large eye is a very interesting topic and is been given separately in Wang (2008).

c. Evolution of the rapid filamentation zone during storm intensification

It is our intent in this section to examine the evolution of the rapid filamentation zone during the onset of rapid intensification of the model storm. As we see from Fig. 1, the storm experienced an initial adjustment of about 9 h, which was followed by a rapid intensification period. Figure 6 shows the 3-hourly surface rainfall rate from hour 6 to hour 30 of the simulation. Convection developed slowly near the ring of the initial radius of maximum wind in the first 6 h (Fig. 6a). The convective ring with embedded cells and the associated downdrafts produced both inward and outward propagating gravity waves (Figs. 6a and 7a). Strong convective cores and downdrafts emerged in the form of loosely organized convective vortical hot towers (Figs. 6b and 7b; Simpson et al. 1998; Montgomery et al. 2006). Downdrafts in the central region weakened as a result of the moistening of the atmospheric column in the core by 9 h (Figs. 7b and 7c). The collective heating
FIG. 5. As in Fig. 3 but after 240 h of simulation.
from the hot towers and the merging and strengthening of their PV (Figs. 8b and 8c) increased the inertial stability (Figs. 9b and 9c) and lowered the central surface pressure (Fig. 1). As a result of these processes, the central core region became inertially very stable (Figs. 9c and 9d) with convection tending to be well organized after 12–15 h of simulation (Figs. 6c–e and 7c–e). This indicates that convective heating became very efficient, intensifying the storm rapidly as discussed by Schubert and Hack (1982).

One interesting feature in the simulated storm is the formation of the curved structure of the organized convection between 9 and 12 h and the subsequent formation of the eyewall during hours 15 and 21 of the simulation. Convection occurred as convective cells at 9 h (Figs. 6b and 7b) while PV was relatively high in the inner 60 km around the vortex center (Fig. 8b). Between hours 9 and 12, the PV experienced an upscale cascade through the merging and coalescence of PV blobs due to diabatic heating forced low-level conver-
gence (Montgomery et al. 2006), leading to a PV concentration near the storm center (Figs. 8c and 8d). This process increases the cyclonic winds and the shearing deformation and thus results in filamentation (Figs. 10b–d), which seems to contribute to the subsequent axisymmetrization and formation of the relatively precipitation-free eye and nearly closed convective eyewall during hours 18–24 of the simulation (Figs. 6e–g and 7e–g). At the same time, large condensational heating quickly increases the low-level PV just inside of the eyewall (Figs. 8d–g) and thus the inertial stability of the storm core (Figs. 9d–g). Meanwhile, a rapid filamentation zone is well established after about 18–24 h of simulation (Figs. 10e–g), within which zone vertical motion, convection, and PV were organized in spiral-banded structures.

These results suggest that convective heating, filamentation, axisymmetrization, and an increase in inertial stability are all important processes and work in a cooperative way during the rapid intensification of the model storm. Again, there is no evidence for convection being suppressed in the rapid filamentation zone.
Rather, convection is generally distorted and elongated as spirals in the rapid filamentation zone (Figs. 6, 7, and 10). Regions with suppressed convection outside of the eyewall are collocated well with subsidence, which may result from the overturning flow from eyewall convection, the convective spiral rainbands, or the stratiform precipitation (Figs. 6 and 7). The filamentary spiral structure in rainbands in the near-core region outside of the radius of maximum wind is greatly stabilized by the adverse shear and the straining flow of the storm (Dritschel et al. 1991; Kevlahan and Farge 1997).

5. Rapid filamentation zone and inner-core asymmetric structure

Since filamentation is considered an important process toward the axisymmetrization of asymmetries in rapidly rotating vortices (Melander et al. 1987; Fuentes 2005), it is of interest to examine the relationship between the rapid filamentation zone and the asymmetries in the near-core environment of the simulated tropical cyclone. An example of the wavenumber-1 and wavenumber-2 asymmetries after 96 h of simulation is
given in Fig. 11. The corresponding total fields are shown in Fig. 3 and were discussed previously in section 4. As identified in Wang (2001, 2002b,c), these asymmetries are characterized by vortex Rossby waves.\footnote{Nolan and Montgomery (2002) identified similar asymmetries as equilibrated unstable modes due to the change in sign of the radial PV gradient. Since the distinction between a vortex Rossby wave and a mode is somewhat arbitrary and is not critical to this study, we simply call these asymmetries vortex Rossby waves.} The asymmetric perturbation pressure and the asymmetric winds are quasi balanced with cyclonic convergent (anticyclonic divergent) flow collocating with low (high) pressure perturbation for both wavenumbers 1 (Fig. 11a) and 2 (Fig. 11d). Both the maximum perturbation pressure and the anomalous circulation centers (Figs. 11a and 11d) are near the radius of maximum wind immediately across the large PV gradient under the eyewall (Fig. 4c). Asymmetries in both PV and vertical velocity are characterized by tightly wound, anticy-
clonic outward spirals, as predicted for vortex Rossby waves by Montgomery and Kallenbach (1997). Further, the PV and vertical motion in the vortex Rossby waves are positively correlated, indicating the strongly convectively coupled nature of the waves as discussed in Wang (2001, 2002b,c). One interesting feature in both the asymmetric PV and the vertical velocity is their small radial wavelengths between radii of 20 and 50 km in the rapid filamentation zone. This demonstrates that the strong horizontal deformation, especially due to shearing deformation, elongates and filaments most of the scalars in the rapid filamentation zone, thus axisymmetrizing and stabilizing the asymmetries.

Since the filamentation time varies with height (Fig. 4d), it is expected that the asymmetries could also vary with height in the simulated storm. This is examined by looking at the radial–vertical structure of the azimuthal mean eddy kinetic energy (EKE) in the model storm. Figures 12a–f show the vertical-radial distribution of the azimuthal mean EKE total and wavenumbers 1, 2, 3,
Fig. 11. Azimuthal wavenumber—(left) 1 and (right) 2 asymmetries in the model tropical cyclone after 96 h of simulation. Shown are (a), (d) perturbation pressure (in hPa) and winds (vectors) at 1-km height, (b), (e) perturbation PV (in PVU), and (c), (f) asymmetric vertical motion (in m s$^{-1}$). The circles indicate the radii of 20, 40, and 60 km from the storm center. The maximum wind vectors in (a) and (d) are 10 m s$^{-1}$. 
4, and \( >4 \) components, respectively, averaged between 96 and 144 h of the simulation. The asymmetries are dominated by low-wavenumber vortex Rossby waves with wavenumbers 1, 2, and 3. These asymmetries exhibit large amplitudes in the eyewall in the lower troposphere where the PV shows a hollow annulus structure and satisfies the necessary condition for barotropic instability (Fig. 1e). The wavenumber-1 asymmetries have a more coherent vertical structure than do the higher-wavenumber components and tilt outward with height following the tilted eyewall ascent along the angular momentum surfaces (Figs. 12 and 2c,f). There is a local maximum in the amplitude of EKE in the upper-level outflow layer outside of the eyewall between radii of 100 and 200 km (Fig. 12) where the outflow is strongest (Fig. 2b) and inertial stability is weak (Fig. 4e). As expected, the high-wavenumber asymmetries occur in the regions outside of about 60 km from the storm center (Fig. 12f), where deformation is weak, the filamentation time is long, and convection is loosely organized in one or two major outer spiral rainbands with wave-number-1 or -2 structures (e.g., Fig. 3a). The high-wavenumber (\( >4 \)) asymmetries have their maximum amplitudes in the mid- to upper troposphere and are most likely attributed to the slantwise convection in the outer spiral rainbands and the stratiform clouds outside of the eyewall (Figs. 4a and 4b).

To examine the distribution of asymmetries during the large-eye phase (Fig. 5), we show in Fig. 13 the azimuthal mean EKE for different wavenumber components averaged between 225 and 240 h of integration. Although the overall structure is similar to that shown...
in Fig. 12 for the small-eye phase, now the asymmetries have their maximum amplitudes at larger radii in the eyewall with a more coherent vertical structure, consistent with the larger size of the eyewall. Although the asymmetries with wavenumber >4 have amplitudes similar to those in the small-eye phase (Figs. 13f and 12f), the amplitudes of the wavenumber-4 asymmetries are significantly increased (Fig. 13e). This is likely due to the smaller shearing deformation and thus weaker damping from adverse shear and straining flow. Note that the wavenumber-2 asymmetries have the largest amplitude now, indicating that the elevated PV structure in the large-eye phase could favor the most unstable modes with wavenumber 2 (Schubert et al. 1999; Kuo et al. 1999).

We see from Figs. 12 and 13 that due to shearing deformation, filamentation, and axisymmetrization, only low azimuthal wavenumber asymmetries could survive in the modeled storm-core region. Since the deformation is quite weak at the early stage of storm intensification, as seen from Fig. 10, a natural question arises as to whether there is any decreasing trend of high-wavenumber asymmetries in the cyclone core region as the storm intensifies. To address this question, we plot in Fig. 14 the radius–time Hovmöller diagram of the azimuthal mean EKE of the total and the wavenumbers 1, 2, 3, 4, and >4 components vertically averaged between the surface and 10-km height. Note that the results shown here are based on 3-hourly model outputs so that the outward propagation of vortex Rossby waves near the eyewall discussed in Wang (2001, 2002c) could not be resolved in the figure.

The total EKE shows large amplitude in the eyewall throughout the time integration but with considerable variability. Asymmetries are relatively weak outside of
FIG. 14. Radius–time Hovmöller diagram for the (a) total, (b) wavenumber 1, (c) wavenumber 2, (d) wavenumber 3, (e) wavenumber 4, and (f) wavenumber >4 EKE (m$^2$ s$^{-2}$) averaged between the sea surface and 10-km height. Note the different contour levels in the different panels.
30-km radius except for during the first day of the integration and the last 30 h after the storm developed a large eye (Fig. 5). The radial extent of the asymmetries varies with azimuthal wavenumber and time. The low-wavenumber asymmetries are generally trapped in the core region (Figs. 14b–d) while high-wavenumber (>4) asymmetries, in contrast, are largely suppressed in the inner-core region (Fig. 14f). Since the model was initialized with an axisymmetric vortex, the asymmetries developed after several hours of simulation, commencing first with high wavenumbers (Figs. 14e and 14f) followed by low wavenumbers (Figs. 14b–d).

The high-wavenumber asymmetries developed as a result of convective bursts in the early stage of intensification as seen in panels a–d in Figs. 7–10. However, the high-wavenumber asymmetries weakened significantly after about 24 h of simulation. This is expected, since as the storm intensified, it developed a rapid filamentation zone immediately outside of the eyewall and high-wavenumber asymmetries were effectively filamented and axisymmetrized in this rapid filamentation zone. Outside of the rapid filamentation zone, however, high-wavenumber asymmetries are active throughout the simulation due to the lack of strong deformation and filamentation. The trapped nature of low-wavenumber asymmetries in the inner core (Fig. 14) demonstrates that they are quasi-balanced vortex Rossby waves whose restoring mechanism is associated with the strong radial PV gradients (Montgomery and Kallenbach 1997; Wang 2001, 2002c).

In addition, there are clear outward-propagating signals in the high-wavenumber asymmetries (Fig. 14f). These asymmetries are associated with the activities of the outer spiral rainbands and seem to originate repeatedly in the near-core environment with a quasi period of about 24 h. This indicates a possible inner-core origin of outer spiral rainbands in tropical cyclones, as recently studied by Chow et al. (2002) and Schecter and Montgomery (2006). A detailed analysis of this phenomenon is beyond the scope of this paper and is reserved for a future study.

6. Concluding remarks

Filamentation and axisymmetrization have been important concepts in geophysical fluid dynamics for decades, in particular, in two-dimensional turbulence and vortex dynamics (e.g., McWilliams 1984; Melander et al. 1987; Dritschel et al. 1991). These processes have been used successfully in conjunction with Rossby wave breaking to explain many phenomena in stratospheric dynamics, such as the polar vortex and stratospheric surf zone, as well as trace mixing (e.g., McIntyre and Palmer 1984; Juckes and McIntyre, 1987). The basic concepts were introduced into the study of the dynamics of tropical cyclone spiral bands by Guinn and Schubert (1993). This application was extended to inner-core dynamics together with the theoretical work on vortex Rossby waves (Smith and Montgomery 1995; Montgomery and Kallenbach 1997; Schubert et al. 1999). In a recent study, Rozoff et al. (2006) applied the concept of filamentation to explain the weak-echo annulus (or moat) outside of the primary eyewall of a tropical cyclone observed in radar images. By this mechanism, the moat is considered to be a region of strain-dominated flow in which all scalars are filamented and deep convection is hypothesized to be highly distorted and even suppressed.

An attempt has been made in this study to test the hypothesis of Rozoff et al. (2006) and to extend their work on tropical cyclone inner-core dynamics from a dry, barotropic framework to a moist, three-dimensional nonhydrostatic framework using an idealized, full-physics model simulation. The rapid filamentation zone in the numerically simulated tropical cyclone is analyzed. We have focused on the evolution of the rapid filamentation zone during the storm rapid intensification, the potential roles of rapid filamentation in the organization of inner spiral rainbands, and the damping of high azimuthal wavenumber asymmetries in the inner core of the simulated tropical cyclone.

Our results show that instead of suppressing deep convection, the strain flow in the rapid filamentation zone outside of the elevated potential vorticity core provides a favorable environment for the formation and organization of inner spiral rainbands, which generally have time scales of several hours, much longer than the typical overturning time scale of individual convective clouds. Although the moat area in the simulated tropical cyclone is in the rapid filamentation zone, its dynamics are controlled mainly by the subsidence associated with the overturning flow from eyewall convection and the stratiform precipitation outside of the eyewall. It is thus suggested that the rapid filamentation may play a secondary role in the formation of the moat in tropical cyclones. Although the deformation field is primarily determined by the structure of the tropical cyclone, it can have a considerable effect on the evolution of the storm. The filamentation zone initially develops as a result of storm intensification, while strain-induced deformation in the rapid filamentation zone plays an important role in the formation of curved spiral rainbands and the subsequent emergence of the annular eyewall during the onset of rapid intensification.

Previous studies have shown that adverse shear plays a critical role in damping high-wavenumber asymme-
tries in the inner-core region of a tropical cyclone by filamentation and axisymmetrization (Smith and Montgomery 1995; Montgomery and Kallenbach 1997). In our model results, we also found scale selection of damping in the inner-core region. Asymmetries with azimuthal wavenumber >4 were found to be damped effectively in the rapid filamentation zone. Therefore, the introduction of the filamentation time/zone provides a quantitative measure of the stabilization/axisymmetrization of high-wavenumber asymmetries in the inner-core region by straining deformation, filamentation, and axisymmetrization.

Finally, and also importantly, we should point out that Rozoff et al. (2006) applied the rapid filamentation
zone to explain the moat areas observed mainly between the primary eyewall and the concentric secondary eyewall in intense tropical cyclones (their Fig. 1). In the model tropical cyclone discussed in this study, the moat areas are generally small and are not always clearly seen (Figs. 3 and 5). However, it is obviously shown that the organized, inner spiral rainbands can occur in the rapid filamentation zone, implying the secondary role of rapid filamentation in the formation and maintenance of moats in observed tropical cyclones. Since TCM4 is capable of simulating the life cycle of the concentric eyewall in a tropical cyclone on a β plane instead of on an f plane, we show a snapshot of all of the parameters in Fig. 15 as shown in Figs. 3 and 5 but for the same initial vortex simulated on a β plane after 234 h of integration. By this time, the model tropical cyclone developed a typical concentric eyewall structure as observed in real tropical cyclones and discussed in Willoughby et al. (1982).

The moat can be found between the inner and outer eyewalls (Fig. 15a). In the moat area there is no strong precipitation (Fig. 15a), vertical motion is dominated by subsidence (Fig. 15b), and the PV and the normalized inertial stability parameter show relatively small values compared to those in both inner and outer eyewalls (Figs. 15c and 15d). The deformation is relatively small in this case (Fig. 15e) compared to the storm shown in Figs. 3e and 5e. The filamentation time shows the rapid filamentation zone in the moat area as discussed in Rozoff et al. (2006). However, the moat area extends outward by about 10–15 km beyond the rapid filamentation zone. This again indicates that the moat is largely controlled by subsidence and rapid filamentation is likely to play a secondary role in the formation and maintenance of moats in tropical cyclones.

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