A Comparison of Inner and Outer Spiral Rainbands in a Numerically Simulated Tropical Cyclone

QINGQING LI

International Pacific Research Center, and Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii, and Shanghai Typhoon Institute and Laboratory of Typhoon Forecast Technique/CMA, Shanghai, China

YUQING WANG

International Pacific Research Center, and Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii

(Manuscript received 14 September 2011, in final form 13 March 2012)

ABSTRACT

The simulated inner and outer spiral rainbands in a tropical cyclone are compared in this study. The inner rainbands are generally active immediately outside the eyewall in the rapid filamentation zone, while the outer rainbands are active in regions outside about 3 times the radius of maximum wind. The inner rainbands are characterized by the convectively coupled vortex Rossby waves. The movement of the outer rainbands follows the low-level vector winds associated with the azimuthally averaged low-level flow and the radially outward cross-band flow caused by the downdraft-induced cold pool in the boundary layer. Convective cells in outer rainbands are typical of convective systems and move cyclonically and radially outward (inward) at large (small) radii.

Net upward vertical mass transports (VMTs) appear throughout the depth of the troposphere in the whole inner-rainband region, while net downward VMTs are found below 4-km height in the outer-rainband region. In the whole inner-rainband region, only a very shallow layer with net horizontal convergence appears below 2-km height, while a deep layer with net convergence is found below 7.5-km height with net divergence aloft in the outer-rainband region. The inner rainband shows two tangential wind maxima, respectively, located near the top of the inflow boundary layer and immediately below the upper-tropospheric outflow layer. A secondary horizontal wind maximum occurs at about 4-km height on the inner edge of the outer rainband. Distinct features of the upwind, middle, and downwind sectors of the outer rainband are also discussed.

1. Introduction

A tropical cyclone (TC) typically consists of a precipitation-free eye surrounded by an eyewall with deep convection and spiral rainbands outside the eyewall. Spiral rainbands can be classified into inner and outer rainbands, according to their characteristics and locations (Guinn and Schubert 1993; Wang 2009). Inner rainbands occur in the inner-core region inside a radius of about 3 times the radius of maximum wind (RMW), as defined by Wang (2009). Inner rainbands are usually invisible on satellite imagery, but are evident on radar reflectivity. Outer spiral rainbands are defined as those rainbands that occur outside the inner core. They generally have larger horizontal scales than the inner rainbands. Although rainbands are distinct features of a TC, they may interact with the eyewall in one way or another, modulating the TC structure and intensity (May and Holland 1999; Franklin et al. 2006; Wang 2009; Wang and Xu 2010; Xu and Wang 2010a,b). Their activity, on one hand, is controlled by the TC internal dynamics (Li and Wang 2012) and, on the other hand, may be affected largely by different large-scale environmental forcings (Willoughby et al. 1984; Guinn and Schubert 1993).

Although both inner and outer rainbands display a spirally banded shape in TCs, they exhibit distinct dynamics. Many studies have investigated their dynamical
and thermodynamic characteristics, and corresponding contributions to the evolution of the TC structure and intensity. Previous studies suggest that inner spiral rainbands are associated with the activity of outward-propagating vortex Rossby waves (VRWs; Guinn and Schubert 1993; Montgomery and Kallenbach 1997; Chen and Yau 2001; Wang 2002a,b). In idealized full-physics model simulations, Wang (2002a,b) and Chen and Yau (2001) showed that cyclonic potential vorticity (PV) anomalies (VRWs) propagate azimuthally with a phase speed much slower than the local tangential wind speed and are coupled with elevated radar reflectivity in the inner rainbands, indicative of a strong connection between VRWs and inner rainbands. VRWs transport eddy angular momentum inward but eddy PV both inward and outward (Montgomery and Kallenbach 1997; Enagonio and Montgomery 2001). Therefore, VRWs or equivalently inner spiral rainbands play an important dynamical role in mixing PV between the eyewall and the eye, contributing to the balance of PV in the axisymmetric cyclone (Wang 2002a). Observational studies also support the VRW dynamics view of inner spiral rainbands (Reasor et al. 2000; Corbosiero et al. 2006). By examining the asymmetric structure of Hurricane Elena (1985), Corbosiero et al. (2006) showed that repeated inner bands were emanated from the eyewall and propagated azimuthally with an average azimuthal phase speed of ~68% of the local tangential wind speed and radially outward with the existence of a stagnation radius, consistent with the prediction of the linear VRW theory (Montgomery and Kallenbach 1997).

Outer spiral rainbands were predominantly explained dynamically as inertia–gravity waves in early studies (Diercks and Anthes 1976; Kurihara 1976; Willoughby 1978; Chow et al. 2002). However, recent studies indicate that traits of outer spiral rainbands are distinct from inertia–gravity waves (Shimazu 1997; Sawada and Iwasaki 2010; Li and Wang 2012). Observations show that outer rainbands are generally characterized by extensive stratiform precipitation regions with embedded convective cells having various degrees of organization (Barnes et al. 1983, 1991; May 1996). In the stratiform precipitation regions, mesoscale updrafts generally occur above the melting level with mesoscale downdrafts below. A secondary horizontal wind maximum (SHWM) is often observed at the midlevel in an outer rainband (Willoughby et al. 1984; May et al. 1994; Samsury and Zipser 1995; Hence and Houze 2008).

Barnes et al. (1983) found that convective cells in outer rainbands consist of a radially outward tilting updraft and a descending radial inflow, which brings low-equivalent potential temperature ($\theta_e$) air down into low levels. Powell (1990a) found that convective cells in rainbands moved downwind at speeds of approximately 85% of the lower-tropospheric averaged wind. Cellular reflectivity maxima were found to orient vertically or tilt outward, with tops up to 7–9-km altitude and stratiform precipitation extending outward as far as 20 km from the core of the convective cells (Ryan et al. 1992). Through analyzing airborne Doppler and in situ radar data, Barnes et al. (1991) found that airflow related to convective cells in outer rainbands was complicated, with subcloud and lower cloud layer air entering from the outer edge of the rainband and down the band from the cell, ascending, and finally flowing up the band and toward the inner edge of the rainband. Downdrafts could be traced to midlevel air invading from the downband side of the cell. Samsury and Zipser (1995) revealed that mesoscale reflectivity features were often near the SHWM, suggesting that outer rainbands likely contribute to the generation of an SHWM. Hence and Houze (2008) found that the radially inward edge of an outer rainband was bounded by a strong downdraft originating at upper levels, likely in response to heating in convective cells. They further showed that updrafts in outer rainbands had a net mass convergence below 3–4 km, which may enhance the SHWM.

Although the above studies have revealed various features of inner and outer spiral rainbands, respectively, a systematic comparison of their dynamical and thermodynamic structures, movement, and difference in vertical mass transport (VMT) is lacking. This is mainly due to the lack of observations covering both regions in a storm simultaneously for a relatively long time. Sufficient evidences suggest that inner and outer rainbands of a TC are active in different radial regions with different dynamical environments and have distinct mechanisms for their formation and movement. Moreover, the distinct dynamical and thermodynamic traits associated with inner and outer rainbands play potentially different roles in the overall structure and TC intensity change. An enhancement of VMT associated with inner rainbands may result in an amplifying secondary circulation that, in turn, enlarges the primary circulation and inner core inertial stability (Ooyama 1982; Schubert and Hack 1982). Additionally, Montgomery and Kallenbach (1997) and McWilliams et al. (2003) showed that the axisymmetrization of PV anomalies by the strong horizontal shear of the mean vortex was accompanied by outward-propagating VRWs (viz., inner rainbands), which accelerated the tangential winds near the radius of wave excitation.

Active outer rainbands and associated strong downdrafts can be regarded as an inhibiting factor to TC intensity (Barnes et al. 1983; Powell 1990a,b). Subsidence brings low $\theta_e$ air from the midtroposphere into the inflow
boundary layer. The air is advected to the core region and entrained into the eyewall, thereby suppressing eyewall convection and reducing the TC intensity. On the other hand, the dry and cool air becomes trapped between the eyewall and the outer rainband, reducing both mass and moisture convergence into the eyewall, and thus restraining the eyewall updrafts and convection, and limiting TC intensity. Therefore, to examine the similarity and dissimilarity in dynamical and thermodynamic features of inner and outer rainbands is an interesting topic. While current observations could not provide fine resolution data for such a comparison, as a first step and an alternative, we analyze the inner and outer spiral rainbands in a TC simulated in a high-resolution cloud-resolving model in this study to comparatively address the structure and evolution of these two kinds of bands. This study will complement ongoing and future observational and modeling work studying the convective and mesoscale aspects of inner and outer rainbands and their possible roles in TC structure and intensity changes.

The next section provides a brief description of the numerical model, experimental design, and an overview of the simulated TC. The dynamical features in regions with active inner and outer spiral rainbands are discussed in section 3. Section 4 presents the movement of inner and outer rainbands in the simulation. The dynamical and thermodynamic structures of the inner and outer rainbands as well as the convective cells embedded in outer rainbands are examined in section 5. Conclusions are drawn in the last section.

2. Model, experimental design, and an overview of the simulated TC

a. The numerical model and experimental design

The model used in this study is the fully compressible, nonhydrostatic, tropical cyclone model version 4 (TCM4) as used in Wang (2009) and Li and Wang (2012). A full description of TCM4 can be found in Wang (2007). The model has been shown to be able to simulate the inner-core structure of TCs, such as VRWs (Wang 2007), rapid filamentation zone (Wang 2008), annular hurricane structure (Wang 2008), and size change (Wang and Xu 2010; Xu and Wang 2010a,b).

TCM4 shares the state-of-the-art model physics, the two-way interactive multiple nesting, and automatic mesh movement with its hydrostatic counterpart TCM3 (Wang 2001). The model equations are formulated in Cartesian coordinates in the horizontal and in mass coordinate in the vertical. An efficient two-time-level, forward-in-time, explicit time-splitting scheme similar to that described in Wicker and Skamarock (2002) is utilized for model integration (Wang 2007). 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 assumes a flat lower boundary at the surface with a uniform unperturbed surface pressure of 1010 hPa. The model top is assumed at about 40 km above the sea level. A sponge upper boundary condition similar to that used in Durran and Klemp (1983) is applied to the model to absorb the upward-propagating sound and gravity waves. The physical parameterizations in the model include an $E-\varepsilon$ turbulence closure scheme for subgrid-scale vertical turbulent mixing (Langland and Liou 1996), a modified Monin–Obukhov scheme for surface flux calculation (Fairall et al. 2003), an explicit treatment of mixed-phase cloud microphysics (Wang 2001), a nonlinear fourth-order horizontal diffusion for all prognostic variables except for that related to the mass conservation equation, a simple Newtonian cooling term added to the perturbation potential temperature equation to mimic the longwave radiative cooling in the model (Rotunno and Emanuel 1987), and the dissipative heating related to the turbulent kinetic energy dissipation rate ($\varepsilon$) from the $E-\varepsilon$ turbulence closure scheme.

The model domain is quadruply nested with two-way interactive nesting and with the inner meshes automatically moving to follow the model storm. The model has 32 levels in the vertical and has mesh sizes of $201 \times 181$, $109 \times 109$, $127 \times 127$, and $163 \times 163$ grid points with their horizontal grid spacings of 67.5, 22.5, 7.5, and 2.5 km for the 4 meshes, respectively. As in Wang (2007, 2008, 2009), the same model physics are used in all domains. No large-scale environmental flow is considered in this study, and no cumulus parameterization is employed even in the two outermost coarse meshes since convection occurs mainly within 200 km from the storm center and is covered by the innermost mesh. The model is initialized with an axisymmetric cyclonic vortex on an $f$ plane at 18°N in a resting environment over the ocean with a constant sea surface temperature of 29°C. The model settings thus are identical to those in Li and Wang (2012). The model is integrated for 96 h. The first 24 h is considered as the model spinup of a tropical cyclone-like vortex, the analysis below will focus on the simulated results after the initial spinup period.

b. An overview of the simulated TC

Figure 1 displays the time evolution of the maximum azimuthal mean wind speed at the lowest model level and the minimum sea level pressure of the simulated TC. Prior to 57 h, the storm persistently intensified with the
minimum sea level pressure dropping at a rate of about 1.4 hPa h$^{-1}$. Afterward, the storm intensity oscillated quasi-periodically, which was found to be related to the quasi-periodic behavior of outer spiral rainbands in the simulated TC as already discussed in Li and Wang (2012).

Figure 2 shows the axisymmetric structure of the modeled TC after 59 h of simulation, including the tangential and radial winds, vertical velocity, temperature anomalies, PV, and relative angular momentum. The TC has its maximum axisymmetric tangential wind speed over 70 m s$^{-1}$ in the lowest 2-km layer at the radius of about 20 km, which shows a feature as a low-level jet with its axis rising radially outward (Fig. 2a). A strong inflow layer is found near the surface under the eyewall and its depth increases with radius. A relatively deep outflow layer appears in the upper troposphere, with the maximum outflow outside of the 60-km radius (Fig. 2b), where the outer spiral rainbands are frequently initiated (Li and Wang 2012). The eyewall ascent tilts radially outward with height, especially in the mid- to upper troposphere (Fig. 2c). The upper updraft cores outside the eyewall with weak downdrafts in the low troposphere reflect the activity of outer spiral rainbands (Fig. 2c).

A marked warm core with a temperature anomaly exceeding 13 K is found at the height of about 12 km, with the horizontal extent of the warm anomaly also expanding radially outward with height and a sharp thermal gradient tilting outward along the eyewall (Fig. 2d). One can also note the presence of cold anomalies in the lowest 3 km in Fig. 2d, indicating the possible cooling effect due to melting of snow and graupel and evaporation of rainwater in mesoscale downdrafts, which were observed in other studies (Hawkins and Imbembo 1976; Gamache et al. 1993; Halverson et al. 2006). These vertical thermal structures are consistent with prior observational findings and numerical simulations (Hawkins and Imbembo 1976; Kurihara and Bender 1982; Wang 2001). An annular PV ring structure extends throughout the depth of the troposphere (Fig. 2e), with the peak PV at about the 6-km height and just inside the RMW. Negative PV near the tropopause (Fig. 2e) is attributed to the divergent outflow. The angular momentum surface tilts radially outward with height, consistent with the outward tilt of the eyewall ascent (Fig. 2f).

Figure 3 shows the plan view of the modeled radar reflectivity at 3-km height after 59 and 64 h of simulation, respectively, as two examples of the modeled spiral rainbands. At hour 59 (Fig. 3a), the storm exhibits a cloud-free eye surrounded by a convective ring of the eyewall. Immediately outside the eyewall are several inner spiral rainbands with banded elevated radar reflectivity. Outside a radius of about 60 km, there are two loosely organized outer spiral rainbands with vigorous convective cells embedded in the upwind and middle sectors of the bands. Five hours later (Fig. 3b), inner rainbands are still active in the inner-core region, while only one major outer rainband exists at this time.

In general, inner rainbands in the simulated storm are always active immediately outside the eyewall up to a radius of about 60 km, while outer spiral rainbands dominate outside the 60-km radius though their activity shows a quasi-periodic nature (Li and Wang 2012). In our idealized simulation, outer spiral rainbands are active up to a radius of 180 km. This is mainly because no any environmental flow was considered in the simulation. Therefore, in the following discussion, we define the annular region between radii of 30 and 60 km as the inner-rainband region and that between radii of 80 and 160 km as the outer-rainband region. The annular region between radii of 60 and 160 km is regarded as the transition region between the inner and outer rainbands. The regions in the simulated storm as defined above are marked in Fig. 3b with the inner-rainband (outer rainband) region between the two white (black) dashed circles.

3. Dynamical features of the inner and outer rainband regions

Since inner and outer spiral rainbands are dominated in different regions in the simulated TC, it is our intent to compare the dynamical features of the two regions with active inner and outer spiral rainbands. We first examine the so-called filamentation time introduced to
understand TC inner core dynamics by Rozoff et al. (2006). They defined a rapid filamentation zone in a TC as the area immediately outside the eyewall with the filamentation time less than about 30 min, namely the overturning time of deep convection. They suggested that convection could be distorted or even suppressed in the rapid filamentation zone. However, Wang (2008) indicated that the rapid filamentation zone provides a favorable environment for well-organized inner spiral rainbands with relatively lower azimuthal wavenumber structure. Figure 4a portrays the distribution of the 12-h averaged filamentation time defined as 

$$hf(1/2)[(\partial hV_r/\partial r)\partial hV_t/\partial r]^{1/2},$$

where $V_t$ is tangential wind, $V_r$ is radial wind, $r$ is the radius from the storm center, and $\langle \rangle$ indicates the azimuthal mean and time average between 55 and 66 h of simulation. We can see that a rapid filamentation zone with filamentation time less than 30 min is within a radius of about 60 km immediately outside the eyewall. It is in the rapid filamentation zone that inner spiral rainbands are quite active (Fig. 3). In contrast, active outer spiral rainbands are located in the regions with the filamentation time larger than 30–40 min, which increases radially outward (Fig. 4a).

Another important dynamical parameter in the inner-core region of a TC is the so-called effective beta, which is a measure of the radial PV gradient. The effective beta is critical to the existence of VRWs in a TC (Montgomery and Kallenbach 1997). Figure 4b depicts the radius–height distribution of the effective beta,
which is defined, following Shapiro and Montgomery (1993), as \(\langle \xi \rangle / \langle q \rangle \partial q / \partial r\), where \(\langle q \rangle\) is the azimuthally and time averaged PV, \(\langle \xi \rangle = f + 2 \langle V_z / r \rangle\) is the local inertial parameter, and \(f\) is the Coriolis parameter. Although in the rapid filamentation zone the shear deformation dominates the vorticity, the TC is still PV-skirted with considerable cyclonic PV extending outward to a radius of about 60 km in the mid- to lower troposphere (Fig. 4b). This PV distribution assures the presence of the effective beta and thus the activity of VRWs and inner spiral rainbands in the rapid filamentation zone. The TC is also beta-skirted with a negative effective beta up to a radius of about 90 km at the low levels (Fig. 4b). Note that a positive effective beta exists in a region between 50- and 60-km radii above 3 km, which may play some role in affecting the outwardly propagating VRWs at those levels.

A convective–stratiform partitioning based on the algorithm in Rogers (2010) is conducted to further illustrate the precipitation characteristics of the TC (Figs. 3c,d). This partitioning algorithm depends on the horizontal distribution of modeled reflectivity, using three reflectivity criteria (Steiner et al. 1995): intensity of reflectivity, peakedness (excess of reflectivity over a background value), and surrounding area (all surrounding points within an intensity-dependent radius around a convective grid identified by one of the foregoing two criteria also included as convective area). As a result, precipitation grids are categorized as convective, stratiform, and other (anvil-type precipitation). A detailed description of the algorithm can be found in Steiner et al. (1995) and Rogers (2010). Qualitatively, the partitioning can separate the precipitation areas into convective and stratiform components (Figs. 3c,d).
from the reflectivity fields (Figs. 3a,b). A clear convective ring associated with the eyewall region surrounds the eye where anvil-type precipitation is observed, and spiral convective bands related to the inner rainbands are embedded in the broad stratiform areas in the inner-core region (Figs. 3c,d). In contrast, precipitation in outer rainbands is distinct from that in the inner-core region. More isolated convective cores are seen particularly in the upwind and middle sectors of outer rainbands, with stratiform precipitation predominant in the downwind region (Figs. 3c,d).

We examined the VMT (defined as $r_w$) features of the convective and stratiform precipitation regions in the inner and outer rainbands. Figure 5 shows the profiles of VMT associated with the convective, stratiform, and the whole regions in inner and outer rainbands averaged between 55 and 66 h of simulation and normalized by the respective maximum positive VMT values. As depicted in Fig. 3b, the annular regions between the two white dashed circles (i.e., between the 30- and 60-km radii) and between the two black dashed circles (i.e., between the 80- and 160-km radii) indicate the inner- and outer-rainband regions, respectively. Positive and negative VMT indicate upward and downward mass fluxes at a given level, respectively. In the inner-rainband convective region, upward VMTs are dominated, with the upward VMT maximum near 2-km height and very small downward VMTs (Fig. 5a). As a result, upward net (sum of upward and downward) VMTs occur throughout the depth of the troposphere in these regions (Fig. 5a). In the inner-rainband stratiform region, negative VMTs are more pronounced in the lower troposphere (Fig. 5b). Two upward VMT maxima are centered, respectively, around 4- and 11-km altitudes (Fig. 5b). The resultant net VMTs in these stratiform precipitation regions are thus positive but with very small values below 2 km and large positive values above. In the inner-rainband region as a whole, positive net VMTs appear throughout the depth of the troposphere (Fig. 5c). Both the positive and negative VMTs in the inner-rainband region are maximized at the height of about 3.5 km where the maximum positive net VMT also occurs (Fig. 5c), suggestive of the most intense updrafts occurring at this level in the region. A second maximum upward VMT occurs at about 12-km height (Fig. 5a), which results from the presence of relatively greater upward VMTs over the stratiform grids (Fig. 5b). The two maxima in the VMT are consistent with the convective heating at the mid- to lower troposphere and heating in stratiform clouds in the upper troposphere, respectively, as discussed in Liu et al. (1997).

The VMT profiles of the outer-rainband convective region (Fig. 5d) resemble those for the inner-rainband region (Fig. 5a). However, the VMT feature in the outer-rainband stratiform region (Fig. 5e) differs significantly from that in the inner-rainband stratiform region (Fig. 5b). First, more downward VMTs are concentrated at lower levels with the peak value in negative VMT occurring at about 2.5-km height (Fig. 5e). Second, only one updraft VMT maximum is observed at around 10-km height (Fig. 5e). Consequently, negative net VMTs exhibit below 4-km height in these regions and positive ones occur above (Fig. 5e). Figure 5f shows that the net VMT in the outer-rainband region as a whole is characterized by negative and positive VMTs below and above 4-km height, respectively. The peak positive VMTs occur at around 8–12 km and a second maximum positive VMT occurs in the lower troposphere between 2- and 4-km heights. Unlike in the inner-rainband region, the downward VMT shows its maximum at around 2-km height (Fig. 5f), which implies the existence of predominant subsidence in the outer-rainband region (Fig. 5e).

To quantify the dependence of the VMT on vertical motion, we show in Fig. 6 the contoured frequency by altitude diagrams (CFADs) for the VMT-weighted vertical velocity. In the inner-rainband region (Fig. 6a), much of the upward VMT is concentrated in vertical velocities around 0.4 m s$^{-1}$ and much of the downward VMT overpopulates vertical velocities around −0.6 m s$^{-1}$. The CFAD in the outer-rainband region shows that much of the upward VMT is attributed to vertical velocities around 0.2 m s$^{-1}$, while a great deal
of the downward VMT is related to vertical velocities around $-0.3 \text{ m s}^{-1}$ (Fig. 6b).

The vertical profiles of the horizontal wind divergence and convergence also differ in the inner- and outer-rainband regions (Fig. 7). The peak convergence and divergence occur near 1- and 0.7-km height, respectively, with weak net divergence between 2- and 10-km altitude and nearly nondivergence aloft in the inner-rainband convective region (Fig. 7a). In the inner-rainband stratiform region, the maximum convergence and divergence both appear at approximately 2.5-km height, with weak net convergence beneath 10-km altitude (Fig. 7b). Consequently, the maximum convergence occurs in the inflow boundary layer at about 0.8-km height in the inner-rainband region as a whole (Fig. 7c), while the maximum divergence is at 2-km height, both decreasing with height slowly below 9 km and rapidly above. A shallow net convergence layer appears in the lowest 2 km of the model atmosphere with the maximum at 0.6-km height. Very weak net divergence occurs above in the free troposphere in the inner-rainband region as a whole (Fig. 7c).

In the outer-rainband convective region (Fig. 7d), both the horizontal convergence and divergence are maximized near the surface, and the net convergence is found below 14-km height. In the outer-rainband stratiform region (Fig. 7e), however, the maximum convergence and divergence are at about 9-km height, with net divergence above 11 km and net convergence below. Both convergence and divergence in the outer-rainbands region peak at about 9-km height and both decrease rapidly with height above this level (Fig. 7f). Net convergence appears below 7.5-km height while net large divergence occurs aloft in the outer-rainband region. Figure 7f also suggests that the maximum net convergence is at the 0.6-km level and the maximum net divergence occurs at about 12-km height. The deep layer of divergence above 7.5-km height is mainly associated with the strong outflow in the upper troposphere (Fig. 2b).

The foregoing discussion demonstrates the distinct dynamical natures in the inner- and outer-rainband regions. Particularly, the different characteristics in the stratiform VMT between the inner- and outer-rainband regions play a key role in the differences in the vertical VMT distributions in the two regions. Note that the generation of PV is approximately proportional to the slopes of the vertical profiles of mass transport (Haynes and McIntyre 1987). Therefore, the different characteristics in the stratiform VMT may highly influence the generation of PV in inner- and outer-rainband regions.
stratified barotropic circular vortex in gradient wind balance. The derived local dispersion relation is

$$\omega = n\bar{\Omega} + \frac{n}{{R\bar{q}}} \frac{\partial \bar{q}}{\partial r} \left[ k^2 + \frac{n^2}{R^2} + \left( \frac{\bar{n}}{m^2} \right) \right],$$

where $\omega$ is the local wave frequency, variables with an overbar indicate the mean state quantities of the circular barotropic vortex, $n$ is the azimuthal wavenumber, $m$ is the vertical wavenumber, $k$ is the time-dependent radial wavenumber $[k = k_0 - nt\bar{\Omega}(R)]$, $\bar{\Omega}$ is the mean angular velocity, $\bar{\Omega}'(R)$ is the radial gradient of the mean angular velocity, $R$ is the reference radius, $\eta$ is the mean absolute vorticity ($\eta = \bar{\zeta} + f$, where $f$ is the Coriolis parameter and $\bar{\zeta}$ is the mean vertical component of relative vorticity), $\bar{\zeta}$ is the mean inertial parameter, $N^2$ is the static stability, and $\bar{q}$ and $\bar{q}'(R)$ denote the mean PV and its radial gradient at radius $R$. Using 40 km as the reference radius $(R)$, together with $\bar{V}_I = 48$ m s$^{-1}$, $N^2 = 1.5 \times 10^{-4}$ s$^{-2}$, $\bar{\zeta} = 2.4 \times 10^{-3}$ s$^{-1}$, $\bar{\eta} = 3 \times 10^{-4}$ s$^{-1}$, $\bar{q} = 2$ PVU, $\bar{q}' = -4 \times 10^{-4}$ PVU m$^{-1}$, all estimated from the modeled storm as well as the estimated radial wavelength of 34 km and vertical wavelength of 20 km, the calculated azimuthal phase speed $[\omega(n/R)]$ is 35 m s$^{-1}$, very close to the phase speed observed in Fig. 9a. From (1), VRWs in the form of a trailing spiral travel azimuthally in a retrograde sense relative to the local tangential winds for a negative effective beta. Therefore, the azimuthally propagating speed of the VRWs suggested in Fig. 9a is slower than the local tangential winds. However, the actual phase speed in the simulation is about 3 m s$^{-1}$ faster than that predicted by (1). This is mainly because the effect of diabatic heating is not included in the theoretical derivation of the VRW phase speed in (1). In the simulation, the VRWs are well coupled with deep convection. Convection, thus the cyclonic PV generation, is generally enhanced immediately downwind of the maximum cyclonic PV anomaly [see Figs. 4 and 6 in Wang (2002a)]. This favors a downwind shift of the maximum PV anomaly, implying a reduced retrograde azimuthal phase speed relative to the local tangential wind. Indeed, if we assume that the convective heating is proportional to the vertical motion in the thermodynamic equation, the effect of diabatic heating on the propagation of VRWs can be considered in (1) by simply using a reduced static stability $N^2$ (Emanuel et al. 1987; Reasor and Montgomery 2001; Schecter and Montgomery 2007). This will predict a reduced retrograde propagation relative to the local tangential wind speed, consistent with the results discussed above.

The inner rainbands appear to be emanated from a radius of ~30 km, where significant radial PV gradients

![FIG. 6. VMT-weighted vertical velocity CFADs averaged between 55 and 66 h of simulation in the annular regions between (a) the 30- and 60-km radii (inner-rainband region) and (b) the 80- and 160-km radii (outer-rainband region), contoured at -180, -140, -100, -80, -60, -40, -20, 20, 40, 60, 80, 100, 140, 180, and 220 $\times 10^7$ kg m$^{-2}$ s$^{-1}$ in (a) and at -1200, -800, -600, -400, -200, -160, -120, -80, -60, -40, -20, 20, 40, 60, 80, 120, 160, 200, 400, 600, and 800 $\times 10^7$ kg m$^{-2}$ s$^{-1}$ in (b).]
exist (Fig. 2c). The inner rainbands propagate radially outward at an average speed of 7.7 m s$^{-1}$ (Fig. 9b), also close to the theoretical prediction of the radial phase speed ($v/\kappa$) of 9.4 m s$^{-1}$. Note that the simulated outward propagation is slower than the theoretical prediction because of the low-level inflow that is not included in (1) while it reduces the outward propagation. Nevertheless, the overall movement of inner spiral rainbands can be approximately interpreted by the activity of VRWs. Furthermore, the maximum ascending motion in the simulation mostly leads the maximum cyclonic PV asymmetry in both the azimuthal and the radial directions (Fig. 9), indicating that the simulated VRWs are well coupled with convection and thus are convectively coupled VRWs (Chen and Yau 2001; Wang 2002a).

Figure 10 shows the evolution of outer rainbands from 58 to 63 h of simulation, overlapped by the temporally averaged low-level streamlines during this period. The outer rainbands are loosely organized in a spiral shape roughly following the low-level streamlines, while their movement does not follow the low-level azimuthally averaged flow. The activity of outer rainbands is not directly associated with VRWs, so that the movement of outer rainbands could not be explained by VRWs. Figure 11 illustrates the development and movement of two convective cells embedded in outer spiral rainbands. One was generated about 130 km east-southeast of the storm center at 52.5 h, then intensified with increasing horizontal extent, and moved cyclonically and radially inward (Fig. 11a). By 53.25 h, the cell continued augmenting and progressing cyclonically and radially inward. The estimated azimuthal speed of the cell is $\sim$21.5 m s$^{-1}$, close to the azimuthally averaged local tangential wind speed of 20 m s$^{-1}$. The estimated radially inward speed of the cell is about 0.5 m s$^{-1}$, whereas the inflow speed averaged below 3 km at this radius is approximately 3.5 m s$^{-1}$. Therefore, the cell core displayed in Fig. 11a has a radially outward speed of $\sim$3 m s$^{-1}$ relative to the local inflow. A nascent convective cell developed upstream at a slightly larger radius from the storm center. About 15 min later (53.5 h), both cells continued intensifying and eventually connected to form a convective system with precipitation associated with the new cell extending radially outward (Fig. 11a).

Another convective cell was initiated about 155 km west-southwest of the storm center. It moved and
intensified in a similar way to the case shown in Fig. 11a until 59.25 h (Fig. 11b). However, this cell was elongated in the azimuthal direction and split into two convective centers by 59.5 h, with a new convective center developed upstream. About 15 min later, both convective cells intensified rapidly and moved cyclonically and radially outward with expanding area coverage of precipitation. The azimuthal speed of the cell estimated from Fig. 11b is about 19 m s$^{-1}$, with the azimuthally averaged local tangential wind speed of 18.5 m s$^{-1}$. The radially outward speed of the cell at this time is about 2.5 m s$^{-1}$, while the mean low-level inflow speed at this radius is about 2 m s$^{-1}$, indicative of the radially outward-propagating speed of the cell of approximately 4.5 m s$^{-1}$ relative to the local low-level inflow. Figure 12a depicts the low-level asymmetric flow associated with the convective cells shown in Fig. 11b at 59.5 h. The relatively strong asymmetric flow in the vicinity of the cells is

![Fig. 8. Plan view of the cloud water mixing ratio (kg kg$^{-1}$, color shading) and cyclonic PV anomalies (contoured at 0.5, 1, 2, 3, 5, 10, and 15 PVU) at 3-km height at every 15-min interval from 59.25 (59:15) to 60.5 (60:30) h of simulation, superposed by the 3-km-height streamlines (purple) azimuthally and temporally averaged from 58 to 63 h of simulation. Green dashed curves denote the loci of an inner rainband.](image-url)
radially outward. This radially outward asymmetric flow was triggered by the pressure gradients associated with the cold pool caused by downdrafts, as discussed in Sawada and Iwasaki (2010). Downdrafts associated the convective cells were located radially on the inner side of the cells (Fig. 12c). These dry and cold downdrafts resulted in cold pools in the boundary layer (Fig. 12b), leading to high pressure perturbations (Fig. 12d), which

Fig. 9. (a) Azimuth–time Hovmöller diagram of the wavenumber-2 asymmetric PV (PVU; color shaded) and vertical velocity (contoured at \(-1, -0.7, -0.3, -0.1, 0.1, 0.3, 0.7, \) and \(1 \text{ m s}^{-1}\) with subsidence dashed) at a radius of 40 km at 3-km height. (b) Radius–time Hovmöller diagram of the wavenumber-2 asymmetric PV (PVU; shaded) and vertical velocity (contoured at \(-2, -1.5, -1, -0.5, -0.1, 0.1, 0.5, 1, 1.5, \) and \(2 \text{ m s}^{-1}\) with subsidence dashed) at 3-km height from the storm center to the east. Green thick lines in (a) and (b) track the cyclonic and radial movement of the inner spiral rainbands, respectively.
drove the low-level asymmetric flow radially outward. Therefore, the outward movement of the convective cells after 59.5 h of simulation shown in Fig. 11b was mainly driven by the asymmetric outflow associated with the convective downdrafts. This is consistent with the results of Sawada and Iwasaki (2010), who suggested that the asymmetric flow triggers cross-band movement, leading to the convective cells to deviate from the low-level flow and to move in the direction normal to the rainband in which they were embedded.

The above results suggest that inner rainbands in the simulated storm propagate cyclonically and radially outward in the inner-core region following the view of the convectively coupled VRWs, while the movement of outer rainbands, as seen from the movement of the embedded convective cells at different radii, is complicated. The movement of the embedded convective cells at large radii (Fig. 11b) is determined by the combined effect of the azimuthally averaged low-level flow and radially outward cross-band flow caused by the wind gusts in the boundary layer associated with the cold pools due to convective downdrafts. This leads cells in the upwind region of the outer rainband to move radially outward (Fig. 10). In contrast, the embedded cells at small radii (Fig. 11a) tend to move cyclonically and radially inward predominantly due to the steering of the

FIG. 10. Plan view of the vertically integrated liquid and solid water substance (kg kg$^{-1}$, shading) at every hour interval from 58 to 63 h of simulation and the streamlines at 300 m above the sea surface azimuthally and temporally averaged between 58 and 63 h of simulation.
low-level strong inflow (Fig. 2b). In addition, the radially outward asymmetric flow associated with the cold pools is relatively weak because higher humidity at small radii makes the downdrafts weaker (not shown). The radially outward expansion of precipitation of the upstream nascent cell (Fig. 11a) contributes partly to the outward propagation of the outer rainbands as well.

5. Structure of inner rainbands and convective cells in outer rainbands

a. Structure of inner rainbands

In addition to the differences in the radial range and movement, the inner and outer rainbands also differ greatly in their structures. Some differences in the basic structure between the inner and outer rainbands will be discussed in this section. An inner rainband featured by high reflectivity south of the eyewall is marked by curve $F_1$–$F_2$ in Fig. 3b. Figure 13 shows the along-band vertical structure of this inner rainband. Two tangential wind maxima appear in the rainband. One is located at approximately 1.5-km height above the inflow boundary layer, with the local maximum tangential wind greater than 56 m s$^{-1}$ at the downwind end of the rainband (Fig. 13a). The other maximum occurs in the upper troposphere between 8- and 10-km heights, with the height of the maximum wind axis increasing upwind along the rainband (Fig. 13a).

The radial wind in the inner rainband is featured by the strong inflow confined below the 1.8-km height (Fig. 13b). Another inflow layer with weaker wind speed extends from about the 4-km height at the downwind end to approximately the 11-km height at the upwind end of the rainband, with outflow below and above. The ascent in the inner rainband peaks at about 4-km height (Fig. 13c), with strong convergence and vertical vorticity immediately below and divergence above (Figs. 13e,f). Relatively low $\theta_e$ with small vertical gradient appears in the midtroposphere, particularly with the minima in the upwind portion of the rainband (Fig. 13d).

Figure 14 shows the cross-band structure of the inner rainband (see line segment $F_3$–$F_4$ in Fig. 3b). As the case shown in Fig. 13a, the tangential wind component indicates two maxima, respectively, in the boundary layer and in the upper troposphere (Fig. 14a). The low-level maximum is also located around the top of the strong inflow boundary layer (Fig. 14b) and its altitude tends to increase with radius (Fig. 14a), following the increase in the depth of the inflow boundary layer. Two marked $\theta_e$ minima are visible at 3.5- and 4-km heights on the outer and inner sides of the rainband, respectively, with a maximum in between (Fig. 14d), which is consistent with the outward-sloping updraft in the rainband (Fig. 14c). The low $\theta_e$ minima are coincident with the mesoscale downdraft, in particular on the inner side of the rainband (Fig. 14c). The alternating, outward-tilting convergence and divergence across the rainband (Fig. 14e) are correlated with the vertical motion field (Fig. 14c). Convergence is collocated with elevated relative vertical vorticity.
Fig. 14f, implying that horizontal stretching is a major vorticity source in the inner rainband.

**b. Structure of convective cells in outer rainbands**

Figure 15 plots the vertical cross section along the line segment C1–C2 in Fig. 3b, showing the vertical structure of a mature convective cell embedded in an outer rainband. The vigorous reflectivity core of the convective cell slightly tilts radially inward with height, with reflectivity over 36 dBZ extending as high as 9 km (Fig. 15a). Strong updrafts occur throughout the depth of the troposphere and are collocated with the high-reflectivity core (Figs. 15a,c) and high $\theta_e$ (Fig. 15f). Different from the boundary layer inflow in the core region, the inflow to the convective core occurs in a layer between 1- and 6-km heights on the inner side of the core while in a deep layer between 2- and 10-km heights on the outer side of the core (Fig. 15a). There is a returning flow in the layer between 8- and 10-km heights on the inner side of the core, indicative of the convective overturning associated with the updrafts in the convective cell (Barnes et al. 1983; Powell 1990a; Hence and Houze 2008). The upward motion in the convective cell is much stronger than that in the inner rainband (Fig. 14c) and has its maximum at
around 10-km height (Fig. 15c). A relatively weak downdraft originating at the upper level occurs radially on the outer side of the convective cell (Fig. 15c), most likely resulting from sublimation heating due to dry air intrusion associated with the deep layer inflow (Fig. 15a). Another strong downdraft originating from the melting level occurs on the inner side of the convective cell. This downdraft greatly lowers the equivalent potential temperature in the inflow boundary layer below (Fig. 15f), as found in previous studies (Barnes et al. 1983; Powell 1990a).

The tangential winds show maxima $>24 \text{ m s}^{-1}$ around the 3.0–3.5-km height on the inner side of the cell (Fig. 15b), suggesting the existence of the SHWM (Willoughby et al. 1984; May et al. 1994; Samsury and Zipser 1995; Hence and Houze 2008). Strong horizontal convergence tilts inward with height and is accompanied by divergence on both sides (Fig. 15d). Unlike in the inner rainband, the most intense divergence is found in the boundary layer under the convective core and corresponds to the strong downdraft radially in the inner side of the cell at the lower levels above. Two cyclonic–anticyclonic vertical vorticity couplets with reversed phases appear at the lower and upper levels, respectively (Fig. 15c). These vorticity couplets result mainly from the tilting of horizontal vorticity associated with the strong vertical gradients of tangential wind (Fig. 15b).

Figure 16 shows the vertical structure of another mature convective cell that is located downwind of the abovementioned cell. The high-reflectivity core of this cell is nearly upright (Fig. 16a) with an updraft of over 4 m s$^{-1}$ at 4.5-km height (Fig. 16c). Tangential winds in this cell peak in the midtroposphere at about 4–5-km height on the inner side of the convective cell and show...
a minimum at about 9-km height (Fig. 16b). Strong horizontal wind convergence tilts radially inward with height up to 5-km height, with very strong divergence near the surface below (Fig. 16d). A high-$\theta_e$ tongue is coincident with the updraft in the convective core at low levels and low-$\theta_e$ appears below 5-km height on the outer side of the cell (Fig. 16f).

For a comparison, the vertical structure of a dissipating cell embedded in the downwind stratiform region of the outer rainband is displayed in Fig. 17. Its structure evidently differs greatly from that of the mature cells discussed above. The high-reflectivity core (>32 dBZ) is confined below 4-km height and enhanced outflow exists in the upper troposphere (Fig. 17a). The vertical distribution of tangential wind is very similar to that in the inner rainband shown in Fig. 14a, with a SHWM in a layer between 3- and 4-km heights (Fig. 17b). Strong upward motion prevails above about 8-km height, whereas downward motion prevails below (Fig. 17c). Like in the inner rainband, low $\theta_e$ occurs at the low levels (Fig. 17f).

As noted above, the upwind region of an outer rainband generally contains convective cells in the early development stage. Most of the embedded convective cells in the middle sector of the rainband are fully developed. The downwind end of the outer rainbands is featured by dissipating cells with weaker, more stratiform precipitation. As a result of aforementioned differences, the VMT is expected to differ in different sectors of an outer rainband. This is examined for the outer rainband shown in Fig. 3d where regions K1 and K2 denote the downwind and midregions of the rainband, respectively. Region K3 in Fig. 3c indicates the upwind region, which is the tailing portion of the band.

In the upwind region (region K3 in Fig. 3c), convective cells are less well developed than in the midregion of the outer rainband (region K2 in Fig. 3d). They tend to exist

---

**Fig. 14.** As in Fig. 13, but along line segment F3–F4 shown in Fig. 3b and showing the cross-band structure of an inner spiral rainband.
on the inner edge of the rainband and exhibit a more individual appearance (Fig. 3a), in contrast to those enhanced and well-defined convective cells that prevail on the outer edge of the rainband in the midregion (Fig. 3b). The results of the convective-stratiform partitioning show that the percentages of convective and stratiform grids in region K3 are 16.4% and 11.5%, respectively. In the middle sector of the outer rainband (i.e., region K2), the percentage of convection (stratiform precipitation) rises to 34.8% (34.3%). The convective cells weaken and become more stratiform as they progress into the downwind sector of the outer rainband, and a significant reduction in the percentage of the convective area is seen in region K1 with the percentage of stratiform rainfall increasing to 66.2%.

In the upwind region, the upward VMT peaks in the 1.5–3.5-km layer with a second maximum at 11-km
height and the downward VMT peaks at 2-km height (Fig. 18c). The upward VMT peak at the lower levels is accounted for by the combined effect of weaker upward motion (<1 m s⁻¹; Fig. 19c) and the relatively large vertical motion (>1 m s⁻¹), while the peak at the upper levels is related to the greater vertical motion (Fig. 19c) mainly resulting from heat of fusion. In the upwind region, the net VMT is upward, peaking at about 11-km height. The downdrafts nearly cancel the updrafts at the lower levels, and thus the net VMT is small at those levels (Fig. 18c). The VMTs in the midregion are similar to those averaged in the whole outer rainband region as shown in Fig. 5b, with a peak upward VMT at about 11-km height and a maximum downward VMT at about 2-km height (Fig. 18b). The relatively broad distribution of enhanced upward motion related to heat of fusion at the upper levels (Fig. 19b) contributes to the upper-level maximum in the upward VMT. The mismatches between the updrafts and downdrafts are responsible for the significant net downward VMT below 8-km height and the upward VMT in the upper troposphere (Fig. 18b). The traits of the upward VMTs in

Fig. 16. As in Fig. 15, but along line segment B1–B2 shown in Fig. 3b, showing the cross-band structure of another mature convective cell in the middle sector of an outer spiral rainband.
the downwind region associated with the dissipating convective cells and stratiform precipitation are very similar to those in the upwind region where convective cells are generally growing, with the peak upward VMT near 1.5-km altitude and a second upward VMT maximum at 10-km height (Fig. 18a). The net VMT in region K1 (Fig. 18a) exhibits a more classic stratiform structure (Houze 1997). Below the mid troposphere, downdrafts outweigh updrafts to produce net negative VMT. In the upper levels the updrafts outweigh downdrafts to result in net upward VMT.

6. Conclusions

The inner and outer spiral rainbands in TCs are active in regions with substantially different dynamical and thermodynamic characteristics. Their activities are closely related to the TC structure (in particular the size) and intensity changes. Previous studies have mainly focused on the features and evolution of either inner or outer rainbands based on observations and numerical simulations. A detailed comparison of the activities and characteristics between the inner and
outer rainbands has been lacking. In this study, we have compared the kinematic and thermodynamic features of the inner and outer spiral rainbands in a TC simulated with the nonhydrostatic, cloud-resolving model TCM4. Our major results are summarized below:

- Behaviors of inner spiral rainbands are further confirmed to be very similar to the convectively coupled VRWs. Therefore, the movement of inner rainbands is closely connected with the waves.
- The movement of the outer rainbands follows the low-level vector winds associated with the azimuthally averaged low-level flow and the radially outward cross-band flow caused by the downdraft-induced cold pool in the boundary layer. Convective cells embedded in outer spiral rainbands move in different manners at different radii (Fig. 20a). The cells at large radii move cyclonically and radially outward, while the cells at small radii move cyclonically and radially inward.
- The inner-rainband region (viz., the annular region between the RMW and a radius of about 3 RMW) is generally coincident with the rapid filamentation zone, while the outer-rainband region (i.e., the annular region between radii of 80 and 160 km in our simulation) is characterized by relatively slow filamentation. A beta skirt with the negative effective beta (decrease in potential vorticity with radius) exists in the inner-rainband region and extends radially up to 90-km radius in the lower troposphere, indicating that VRWs might play some roles in triggering the outer spiral rainbands as recently documented in Li and Wang (2012).
- Predominant upward VMTs together with very small downward VMTs occur in the inner-rainband convective region, in contrast to negative VMTs peaking in the lower troposphere in the stratiform region. Net upward VMTs occur throughout the depth of the troposphere in the inner-rainband region as a whole, while net downward VMTs are found below 4-km height in the outer-rainband region. Both the upward and downward VMTs in the inner-rainband region peak at the height of about 3.5 km where the maximum net upward VMT is also located. More downward VMTs are concentrated at lower levels in the outer-rainband stratiform region, with only one upward VMT maximum around 10-km height. Consequently, the upward VMT peaks at the height of about 12 km in the outer-rainband region as a whole, a result of heating associated with the upper-level stratiform precipitation. The maximum downward VMT in the outer-rainband region occurs at around 2-km height.
In the inner-rainband region, large convergence and divergence appear below about 10-km height with net convergence in a shallow layer below 2-km height. In the outer-rainband region, net convergence is found in a deep layer below 7.5-km height and net divergence is found aloft.

The vertical structure of the inner rainband shows two tangential wind maxima, respectively, located near the top of the inflow boundary layer and immediately below the upper-tropospheric outflow layer. The upward vertical motion in the inner rainband peaks at 4-km height, with strong horizontal convergence immediately below and divergence above. Relatively low equivalent potential temperature appears in the mid-troposphere, particularly with the minima in the upwind portion of the inner rainband.

Convective cells in the upwind sector of the outer rainband tend to be clustered on the inner edge of the rainband, exhibiting more individual appearance (Fig. 20a). As the convective cells become mature, their high-reflectivity cores move to the outer edge of the rainband and extensive stratiform precipitation occurs on the inner side of the middle sector of the rainband (Fig. 20a).

Mature cells embedded in the outer rainband show a strong updraft coincident with the radially inward sloping high-reflectivity core and high $\theta_e$, extending from near the surface to the upper troposphere (Fig. 20b). Nevertheless, the observed reflectivity core in a convective cell embedded also in the middle sector of an outer rainband in Hence and Houze (2008) leaned radially outward. Different environmental flow is possibly responsible for the different reflectivity core tilts seen between the study of Hence and Houze (2008) and this study.

There are two types of downdrafts associated with the mature convective cells in the outer rainbands: one originating at the upper levels and one originating at the midlevels as conceptually depicted in Fig. 20b. The upper-level (midlevel) downdraft is located on the outer (inner) edge of the high-reflectivity core. The scenes of the two kinds of subsidence associated with the cell appear to be inconsistent with those in Hence and Houze (2008), which showed that the radially inward edge of the cell was bounded by a strong downdraft originating in upper levels, and the midlevel downdraft was found on the outer edge of the cell (see their Fig. 12b). Because of the radially inward slope of the simulated high-reflectivity core, the midlevel subsidence mainly due to precipitation evaporation is present on the inner edge of the core here. The upper-level downdraft likely results from sublimation heating due to dry air intrusion.

A secondary horizontal wind maximum (SHWM) occurs on the inner edge of the high-reflectivity core of the mature cell (Fig. 20b), similar to that previously observed in real hurricanes (Willoughby et al. 1984; Samsury and Zipser 1995) although its strength is relatively weaker.

The dissipating cells in outer rainbands show both upper-level and low-level tangential wind maxima, very similar to those in the inner rainband. Strong upward motion prevails above 8-km height, while downdrafts and very weak subsidence predominate below.
VMTs in the upwind sector and middle sector have similar vertical distribution, with two peaks in the upward VMT, respectively, around 2- and 11-km height, and with one peak in the downward VMT at 2-km height. VMTs in the downwind sector show the maximum upward VMT at about 1.5- and 10-km heights and maximum downward VMT at about 2-km height. The net VMT of the downwind region exhibits a more classic stratiform nature.

The results presented in this study are obtained based on an idealized numerical simulation of a tropical cyclone. Although many aspects of the simulated storm resemble those observed, the model resolution is still not high enough to resolve the strong convective updraft cores associated with convective cells in outer spiral rainbands. Therefore, the comparison between the inner and outer rainbands documented here is still preliminary. It is unclear how the behaviors of the inner and outer rainbands could differ in different environmental flows, in particular in vertical shear of large-scale horizontal wind. It is also unclear how the results depend on the model resolution used in the simulation. Nevertheless, the results presented here may provide a basis for future studies based on either observations or numerical simulations or both.

Acknowledgments. The authors wish to thank two anonymous reviewers for their constructive comments, which helped improve the manuscript. This study has been supported in part by NSF Grant ATM-0754039. Qingqing Li has also been supported by the National Natural Science Foundation of China under Grants 40922160381, 41005033, and 40905029. Additional support has been provided by the JAMSTEC, NASA, and NOAA through their sponsorships of the International Pacific Research Center (IPRC) in the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawaii.

REFERENCES


