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Vortex Rossby waves in a numerically simulated tropical cyclone. Part II: The role in tropical cyclone structure and intensity changes

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Abstract

In Part I, the author analyzed the asymmetric structure in the inner core of a numerically simulated tropical cyclone and found that the asymmetry near the eyewall in the mid-lower troposphere is dominated by wave-number-1 and -2 vortex Rossby waves. These waves are found to be well coupled with asymmetries in eyewall convection and thus may play an important role in the life cycle of a tropical cyclone.

Full Text

Headnote

Vortex Rossby Waves in a Numerically Simulated Tropical Cyclone. Part II: The Role in Tropical Cyclone Structure and Intensity Changes*

Headnote

ABSTRACT

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In Part I, the author analyzed the asymmetric structure in the inner core of a numerically simulated tropical cyclone and found that the asymmetry near the eyewall in the mid-lower troposphere is dominated by wavenumber-1 and -2 vortex Rossby waves. These waves are found to be well coupled with asymmetries in eyewall convection and thus may play an important role in the life cycle of a tropical cyclone. In this paper, analyses are extended to include the role of these vortex Rossby waves in tropical cyclone structure and intensity changes. The waves are found to transport angular momentum from the eyewall to the eye, accelerating tangential winds in the eye at the expense of decelerating the tangential wind in the eyewall, and thus they play an important role in the inner core dynamics of the tropical cyclone.

Convection in the eyewall is enhanced between the downstream trough and upstream ridge in the vortex Rossby waves but suppressed between the downstream ridge and upstream trough. This close relationship stems from inflow (outflow) associated with the waves in the former (latter) region. Propagation of these waves around the eyewall can produce changes in eyewall shape and polygonal eyewalls with cyclonic rotation. The waves also propagate radially outward and stagnate at radii of 70-90 km, where the radial potential vorticity gradient disappears or reverses its sign. It is at these radii where strong outer spiral rainbands most frequently occur. These outer rainbands spiral cyclonically inward and occasionally perturb the eyewall. In many cases, outward-propagating inner spiral rainbands can be initiated and emanated from the eyewall, especially when the eyewall is perturbed by an outer spiral rainband. When such a perturbation is strong and in phase with strong vortex Rossby waves in the eyewall, the eyewall may experience a breakdown and then be recovered through the axisymmetrization process. The eyewall breakdown (recovery) is accompanied by a weakening (intensifying) cycle of the tropical cyclone.

1. Introduction

Although the spiral rainbands in tropical cyclones were first hypothesized to be Rossby-type waves by MacDonald (1968), it was not until recent years that the dynamics of these vortex Rossby waves in hurricane-like vortex were clarified theoretically (Montgomery and Kallenbach 1997; Montgomery and Lu 1997; Montgomery and Enagonio 1998; Guinn and Schubert 1993; Schubert et al. 1999; Moller and Montgomery 1999, 2000; Enagonio and Montgomery 2001; Shapiro 2000), observationally (Reasor et al. 2000), and numerically (Wang 2001, 2002; Chen and Yau 2001).

Based on earlier work that identified vortex axisymmetrization as a universal process of smoothly distributed perturbed vortices (Melandar et al. 1987) and results from a shallow water model, Guinn and Schubert (1993) suggested that the spiral rainbands in tropical cyclones can be formed by breaking of the vortex Rossby waves when the core of a symmetric vortex is perturbed or by merger of a vortex with a patch of high potential vorticity (PV) air. Montgomery and Lu (1997) studied free waves on barotropic vortices and proposed a criterion to distinguish the balanced vortex Rossby waves from the unbalanced inertia-gravity waves. The characteristic properties of balanced and unbalanced motions were used by Wang (2001, 2002) to identify the vortex Rossby waves in a numerically simulated tropical cyclone. Montgomery and Kallenbach (1997, hereafter MK97) extending the work of Melander et al. (1987), and Guinn and Schubert (1993) developed a theory for the vortex Rossby waves and suggested a connection with the outward-propagating inner spiral rainbands and the structure and intensity changes of tropical cyclones, based on two-dimensional nondivergent inviscid flow and a shallow water equation model. They showed that axisymmetrization of asymmetric structure near the eyewall by the strong shearing of the tangential flow of the vortex is accompanied by generation of outward propagating vortex Rossby waves, which was suggested to be related to the inner spiral rainbands in hurricanes. MK97 also proposed that interaction between the waves and the symmetric vortex could cause the structure and intensity changes of the vortex.

This idea of wave-mean flow interaction was extended to study the role of convectively generated vortex Rossby waves in tropical cyclogenesis in a three-dimensional quasigeostrophic model by Montgomery and Enagonio (1998, hereafter ME98) and in tropical cyclone intensification and evolution in both barotropic and baroclinic models by Moller and Montgomery (1999, 2000). These studies revealed the significance of the axisymmetrization process in tropical cyclogenesis and intensification through imposition of PV asymmetries near the radius of maximum wind (RMW) of an existing circular (parent) vortex. The intensification of the parent vortex during the axisymmetrization process proceeds by ingestion of like-sign PV anomalies into the inner core region (the region circled by the RMW) and expulsion outward of opposite-sign PV anomalies, with azimuthally propagating discrete neutral or weakly unstable vortex Rossby waves around the vortex center (ME98). Using an estimated magnitude of PV injection based on observations and theoretical consideration, ME98 obtained spinup to a 15 m s⁻¹ cyclone on realistic timescales.

Moller and Montgomery (1999) examined the wave kinematics and wave-mean flow interaction in a barotropic shallow water model. They found that, for imbedded asymmetric PV anomalies near the RMW, the basic vortex can intensify through the axisymmetrization process by which energy is transferred from the asymmetries to the basic vortex with discrete vortex Rossby waves excited as a by-product, consistent with the findings of ME98. Moller and Montgomery (2000, hereafter MMOO) extended the work of ME98 to understand structure change and intensification of hurricanes by imposing asymmetric PV anomalies in a three-dimensional asymmetric balance model.

(Shapiro and Montgomery 1993). They showed that vortex Rossby waves propagate not only azimuthally and radially but also vertically and that the higher the wavenumber the weaker the vertical propagation of the waves and corresponding response of the basic vortex. They also found that the lower-level cyclonic PV anomaly intensifies the basic vortex while symmetrizing for a wide range of anomaly amplitudes but that, depending on the strength of asymmetries, the upper-level anticyclonic PV anomaly is expelled outward for a strong anomaly while it is symmetrized for a weaker anomaly. The evolution of the upper- and lower-level PV anomalies is in agreement with the earlier modeling studies of binary tropical cyclones by Wang and Holland (1995), who also observed a rapid deepening when two tropical cyclones merged in their primitive equation model.

The vortex Rossby waves have also been suggested to be related to the structure change of tropical cyclones. Kuo et al. (1999) attributed the elliptical eye and eyewall rotation of Typhoon Herb (1996) to the wavenumber-two vortex Rossby waves that propagate azimuthally around the eyewall. Schubert et al. (1999) related the polygonal eyewall of hurricanes to the breakdown of the eyewall due to barotropic instability of the hurricane vortex, which has a PV maximum near the RMW. More recently, Reasor et al. (2000) also related the cyclonic rotation of the elliptical eyewall radar reflectivity of Hurricane Olivia (1994) to the rotation of the associated vorticity asymmetry and the wavenumber-2 vortex Rossby waves. Based on the numerical results from a high-resolution nonhydrostatic mesoscale model, Chen and Yau (2001) show that the propagation properties of the spiral PV bands follow predictions of linear vortex Rossby wave theory of MK97 and MMOO.

In Part I of this paper (Wang 2002), we analyzed the overall structure of vortex Rossby waves in a numerically simulated tropical cyclone, and we also performed both PV and eddy kinetic energy budgets in order to understand the complex interactions between the vortex Rossby waves and the azimuthal mean cyclonic circulation. We showed that, although the divergent motion remains large, the geopotential height and wind fields of the vortex Rossby waves are quasi balanced with confluent cyclonic (divergent anticyclonic) flow collocated with low (high) perturbation geopotential height. An important feature is that the upward motion (and low-level convergence) of the waves slightly leads cyclonic vorticity in both the azimuthal and radial directions, indicating a strong coupling between the vortex Rossby waves and the asymmetries in eyewall convection. Convective heating is shown to be the major PV source for the vortex Rossby waves. Through wave-mean flow interaction, the vortex Rossby waves transport cyclonic PV from the eyewall to the eye, thus mixing the PV between the eyewall and the eye, and spinning up the tangential wind in the eye at the expense of weakening the tangential wind near the RMW.

In this paper, we extend our analysis to include the complex interactions and feedbacks that occur among the vortex Rossby waves, the eyewall convection, and their role in both structure and intensity changes of the simulated tropical cyclone discussed in Part I. The details of the numerical model and the overall structures of the simulated tropical cyclone and the vortex Rossby waves can be found in Wang (2001, 2002). Here we will examine how the vortex Rossby waves and the convective asymmetries in the eyewall are coupled (section 2), and how this coupling causes both structure and intensity changes of the simulated tropical cyclone (sections 3, 4, and 5). We will show that propagation of the vortex Rossby waves around the eyewall can produce changes in eyewall shape and polygonal eyewalls with cyclonic rotation, initiate outward-propagating inner spiral rainbands, and cause a breakdown of the eyewall accompanied by an intensity change of the tropical cyclone when the eyewall is perturbed by an outer spiral rainband. The major findings will be summarized and discussed in the last section.

2. The coupling between the vortex Rossby waves and eyewall convection

As already shown in Wang (2002), the near core asymmetric structure in the simulated tropical cyclone (Wang 2001) is dominated by vortex Rossby waves with low azimuthal wavenumbers. These waves typically propagate around the eyewall in a retrograde sense relative to the tangential flow of the azimuthal mean cyclone, and they propagate radially outward. A unique feature of the vortex Rossby waves is that the maximum in both the upward motion and low-level convergence leads the maximum in cyclonic vertical relative vorticity by one-quarter wavelength in both azimuthal and radial directions. Since the low-level convergence and upward motion are in phase with convective activities, the waves are thus well coupled with convective asymmetries in the eyewall. This coupling is crucial because the waves can be self-maintained by the associated convective heating. It is through this coupling that the vortex Rossby waves play a significant role in both structure and intensity changes of the simulated tropical cyclone. Since this coupling between the vortex Rossby waves and eyewall convection is a key to all analyses in the subsequent sections, we will start with, in this section, by demonstrating how the vortex Rossby waves are coupled with the eyewall convection and the consequences of such a coupling.

Figure 1 shows in color the asymmetric geopotential height (Fig. 1a), total vertical motion (Fig. 1b), total model simulated radar reflectivity (Fig. 1c), and the asymmetric PV (Fig. 1d) superposed by the asymmetric wind fields at 850 hPa after 86 h 30 min of simulation. The asymmetric structure in the inner core within a radius of about 60 km is dominated by wavenumber-1 vortex Rossby waves, as already shown in Wang (2001, 2002). The vortex Rossby waves are quasi balanced with a divergent anticyclonic circulation corresponding to a high geopotential height perturbation, and confluent cyclonic circulation around the low geopotential height perturbation (Fig. 1a). The maximum geopotential height perturbations occur near the RMW at about 30 km from the cyclone center. Such an asymmetric structure favors enhanced upward motion between an upstream low and a downstream high in perturbation geopotential height, but suppressed upward motion between an upstream high and a downstream low (Figs. 1a,b).

This correlation results from the strong inflow (outflow) in the former (latter) region in the lower troposphere. This inflow-outflow couplet also shifts the eyewall (defined as the strongest updrafts or elevated radar reflectivity in Figs. 1b,c) slightly inward toward the cyclone center in the inflow region, and outward in the outflow region (Fig. 1b), leading to both a polygonal eyewall structure in the vertical motion fields with an upward motion spiral that emanates from the eyewall to the north and spirals outward to the northwest, then to the west (Fig. 1b).

Corresponding to the asymmetric distribution of vertical motion shown in Fig. 1b is an asymmetric structure of simulated radar reflectivity in the eyewall (Fig. 1c). The maximum in radar reflectivity, however, occurs downwind of the enhanced updraft region. This downwind displacement is due to the fact that the hydrometeors in the eyewall clouds are advected cyclonically by the tangential flow of the primary cyclone, but the vertical motion is nearly locked in phase with the vortex Rossby waves. This also implies that the asymmetric features, such as vertical motion and PV, in the eyewall do not move with, but rather slower than, the tangential flow of the primary cyclone and therefore are associated with vortex Rossby waves. High radar reflectivity in the eyewall is far from circular and is not closed in circumference. Rather, it shows a broken eyewall and a polygonal eye structure and an inner spiral rainband (Fig. 1c), as already seen from the vertical motion fields (Fig. 1b). Note also that the high geopotential height perturbation (Fig. 1a) that is collocated with the high surface pressure perturbation is unlikely the result of downdrafts in the deep eyewall convection, since the outflow associated with the anticyclonic circulation is not coincident with, but further downwind of, the maximum in radar reflectivity. On the other hand, even in the outflow region, there is still upward vertical motion (Fig. 1b), indicating that it is not strong downdrafts in the eyewall that are responsible for the generation of high surface pressure perturbations. As already demonstrated in Wang (2001, 2002), these perturbations are driven by vortex Rossby wave dynamics.

Since vortex Rossby waves are PV-type waves that are supported by the radial PV gradient near the eyewall edge (MK97; Wang 2002), they can be easily detected in the corresponding asymmetric PV fields (Fig. 1d), which show a typical banded structure that spirals cyclonically inward. The cyclonic PV anomaly coincides with the enhanced upward vertical motion and elevated radar reflectivity (Figs. 1b,c), indicating that diabatic heating is the major PV source for the vortex Rossby waves, consistent with PV budget of Chen and Yau (2001) and Wang (2002). However, a positive feedback is operating in such a way that low-level convergence and upward motion associated with the waves play a crucial role in enhancing cumulus convection, while the convective heating provides an energy source for the waves. It is through this mutual positive feedback or coupling that both the waves and asymmetries in convection can maintain themselves in the eyewall.

The coherent coupled structure of the wavenumber-1 vortex Rossby waves is shown in Fig. 2, which gives the temporal evolution of the wavenumber-1 PV anomaly and vertical motion around the RMW in the azimuthal direction (Fig. 2a) and along a radius from the cyclone center out to 100 km to the east (Fig. 2b) during a 24-h period between 60 and 84 h of simulation. In both the azimuthal and radial directions, the upward motion associated with the waves is always collocated with the cyclonic PV anomaly as seen from the plan view of the two fields in Fig. 1. The waves consistently rotated cyclonically around the RMW with a period of about 10 min at the mature stage, about twice that of a parcel moving around the eyewall with the low-level mean tangential flow of the primary cyclone. The latter is about 48 min at the mature stage. This period is longer during the developing stage due to the weaker azimuthal mean flow. The waves also propagate radially outward with a phase speed of about 4–5 m s⁻¹ (Fig. 2b), but are distinguishable only within a radius of about 70 km. This is due to the fact that the radial PV gradient of the symmetric cyclone becomes quite weak or even reverses its sign (Fig. 3) and thus cannot support the vortex Rossby waves (MK97; Wang 2002). The relationship of these waves with the eyewall rotation and polygonal eyewall of the simulated tropical cyclone will be the subject of the next section.

Vortex Rossby waves and polygonal eyewall structure

Polygonal eyewall structure is a common feature of most tropical cyclones (Lewis and Hawkins 1982). Although there has been no observational evidence so far detailing the effect of polygonal eyewalls on the intensity change of real tropical cyclones, the polygonal eyewall structure can produce the inhomogeneous distribution of severe

weather in the tropical cyclone core, and therefore it challenges operational forecasts of torrential rainfall and hazardous winds, especially in landfalling tropical cyclones (Black and Marks 1991). Previous theories of polygonal eyewalls include that associated with inertia-gravity waves propagating around the eyewall proposed by Lewis and Hawkins (1982) and that of PV rearrangement arguments proposed recently by Schubert et al. (1999). Lewis and Hawkins (1982) explained the polygonal eyewalls as interfered internal gravity wave patterns due to superposition of waves with different wavenumbers and periods. Schubert et al. (1999) related the polygonal eyewalls to the development of barotropic instabilities near the RMW and suggested that polygonal eyewalls can be viewed as a byproduct of PV redistribution process. Kuo et al. (1999) attributed the elliptical eye rotation of Typhoon Herb (1996) to a wavenumber-2 vortex Rossby wave that propagated around the eyewall. Reasor et al. (2000) related the cyclonic rotation of the radar reflectivity ellipse of Hurricane Olivia (1994) to the rotation of the associated vorticity asymmetry. However, they did not find general agreement between the observed phase evolution of the reflectivity ellipse and the simple linear dispersion relation of the vortex Rossby edge waves, except between two legs of observations. They attributed the discrepancies between the observations and the linear theory to physical complications such as convection, which were not included in the linear theory prediction. We would further emphasize that a real tropical cyclone evolves not only as a result of internal dynamical and thermodynamic processes, but also largely due to complex interactions with the underlying surface conditions and the surrounding environmental flow. Therefore, numerical simulations with full model physics and idealized initial conditions can help isolate the dominant internal dynamics from external forcing.

In this section we will provide some evidence that a strong connection exists between the vortex Rossby waves and the polygonal eyewall structure and its cyclonic rotation. As indicated in the last section, coupling between the vortex Rossby waves and the convective asymmetries in the eyewall is responsible for the formation and cyclonic rotation of the polygonal eyewall structure. As seen from Fig. 1, the eyewall of the model tropical cyclone was usually shifted inward just to the front (rear) of the wave trough (ridge) if facing down the local tangential flow, due to the relative inflow that helps force stronger updraft in the eyewall. On the contrary, the eyewall was shifted outward just to the rear (front) of the wave trough (ridge). Such a combined action can thus cause changes in eyewall shape from time to time when the waves are active. Different eyewall shapes may be expected due to the activity of the vortex Rossby waves with different wavenumbers. For example, the wavenumber-2 waves are responsible for the generation of elliptical eyewalls, and a combination of wavenumber-1 and -2 waves may result in polygonal (such as square, or hexagonal) eyewalls. Note that since the waves with low azimuthal wavenumbers (1 or 2) are usually dominant in the eyewall (MK97; Wang 2001, 2002), only limited shapes of the eyes and eyewalls are possible. It appears that the elliptical eyewalls are most frequently observed in our simulated tropical cyclone.

Figure 4 shows the total model estimated radar reflectivity at 850 hPa at every 15-min interval for the 2h period between 118 and 120 h. It gives a typical example of the elliptical eyewall structure and its cyclonic rotation in our simulated tropical cyclone. We can see that the major axis of the reflectivity ellipse was aligned in the northwest-southeast direction at 118 h, rotated cyclonically (clockwise) afterward and completed one cyclonic rotation by 119 h 45 min. This indicates a rotation period of about 105 min, which is consistent with the period of the vortex Rossby waves that we have already shown in Fig. 2.2 The major axis of the eyewall reflectivity ellipse was well-aligned with the axis of cyclonic PV anomalies in the eyewall (Figs. 4 and 5), and both have the same phase evolution. This close relationship between the reflectivity ellipse and the asymmetric PV fields in the eyewall is in agreement with that in Hurricane Olivia found by Reasor et al. (2000). The asymmetric PV anomalies in the eyewall were dominated by a wavenumber-2 component (easily seen from Fig. 5) as observed in Typhoon Herb by Kuo et al. (1999) and in Hurricane Olivia as discussed by Reasor et al. (2000).

To further understand the close relationship between the vortex Rossby waves and the elliptical eyewall structure, we show in Fig. 6a the total asymmetric wind field; in Figs. 6b and 6c its wavenumber-1 and wavenumber2 components, respectively, and in Fig. 6d the residual after subtracting both wavenumber- and -2 components from the total asymmetric field, superposed by the total radar reflectivity at 850 hPa after 119 h 45 min of simulation (see Fig. 4 for the same time). The wavenumber2 vortex Rossby wave dominates the asymmetric wind fields. The wavenumber-2 wind field shows a deformational flow near the eyewall region with inflow to both northeast and southwest, while outflow is present to the northwest and southeast of the cyclone center (Fig. 6c). It is this deformational flow that was largely responsible for the deformation of the eyewall reflectivity. The inflow shifted the eyewall inward while the outflow shifted the eyewall outward, as was already discussed in the last section and seen in Figs. 1 and 6. The eyewall thus became elongated in the same direction as the outflow but shrank in the direction of inflow. As a result, the major axis of the eyewall reflectivity ellipse is nearly aligned in the same direction as the outflow, but with a small downstream deflection. This downstream deflection of the major axis is due to the fact that hydrometeors (which determine reflectivity) in the eyewall were advected by the tangential flow of the azimuthal mean cyclone at velocities about twice the phase speed of the vortex Rossby waves.

An inference can be made from the asymmetric flow associated with the vortex Rossby waves regarding the asymmetries in the total wind fields that include both the symmetric vortex and the embedded waves. Questions arise as to whether and how the asymmetric distribution of winds in a tropical cyclone is related to the activity of vortex Rossby waves. To shed some light on this issue, we show in Fig. 7 the distribution of total wind speed at the lowest model level (about 26 m above the sea surface) for the same time period as shown in Figs. 4 and 5. The wind distribution (Fig. 7) in the eyewall has a quite similar pattern to that of radar reflectivity (Fig. 4). In particular, the maxima in wind speeds are nearly collocated with the maxima in radar reflectivity in the eyewall. Such a close relationship can be easily understood from a simple linear superposition of the flow associated with the waves and that of the azimuthal mean symmetric cyclone. For example, in Fig. 6c at 119 h 45 min, the winds (both tangential and radial components) associated with the waves to the northeast and southwest in the eyewall are in the same direction as the tangential winds and radial inflow of the mean cyclone. The linear superpositioning of these winds then leads to two maxima in total wind speeds in the eyewall because both the tangential and radial wind speeds of the cyclone are enhanced by the wave flow. By the same reasoning, the wind speeds to the northwest and southeast are reduced due to an opposite situation ($T = 119$ h 45 min in Fig. 7). Note that the asymmetries in wind speeds can be as large as 10%-20% of the azimuthal mean wind speed. The close relationship between the asymmetric distribution of the wind speeds and radar reflectivity thus has potential implications for operational forecasts. It indicates that torrential rainfall and hazardous winds usually occur at a similar time and similar location in the eyewall and modulated to a large extent by the vortex Rossby waves.

In addition to the elliptical eyewalls discussed above, we also observe a variety of polygonal eyewalls. The polygonal eyewalls in our simulated tropical cyclone occurred more frequently during the developing stage, especially when one or more strong outer rainbands existed. Some further examples of polygonal eyewalls as illustrated by the eyewall radar reflectivity in the simulated tropical cyclone are provided in Fig. 8 with the simulation time indicated for each case. Similar polygonal eyewalls were also observed in real tropical cyclones by Lewis and Hawkins (1982) and Muramatsu (1986) and in a numerically simulated tropical cyclone by Kurihara and Bender (1982). In our simulated tropical cyclone, the elliptical eyewalls occurred most frequently during the mature stage when the cyclone core became more stable. It is expected that any external perturbations (such as those from an outer rainband) to the eyewall convection and the internal vortex Rossby waves would produce polygonal eyewalls even in the mature stage. A typical example of this type of consequence will be given in section 5. In that case, perturbation from outer rainbands leads to a breakdown of the eyewall with polygonal shapes accompanied by a fluctuation in cyclone intensity.

4. Vortex Rossby waves and inner spiral rainbands

Spiral rainbands are a salient feature of tropical cyclones and may produce severe rainfall outside the eyewall. Interactions that occur between the rainbands and eyewall convection can cause intensity change of a tropical cyclone (May and Holland 2000). Most of the earlier theories of tropical cyclone rainbands were associated with inertia-gravity waves (Abdullah 1966; Kurihara 1976; Willoughby 1978) with one exception of that proposed by MacDonald (1968), who hypothesized that the rainbands were Rossby-type waves. This latter view was clarified theoretically by MK97, who related the vortex Rossby waves to the axisymmetrization of asymmetric structure in the eyewall. The axisymmetrization process is usually accompanied by emanating vorticity filaments that are part of vortex Rossby waves and are suggested to contribute to the generation of inner spiral rainbands in tropical cyclones (MK97). Reasor et al. (2000) found evidence of a close relationship between the vorticity filaments and inner spiral rainbands in Hurricane Olivia (1998). More recently, Chen and Yau (2001) investigated the PV bands in the near core region of a hurricane simulated with the Pennsylvania State University-National Center for Atmospheric Research fifth-generation, nonhydrostatic Mesoscale Model (MMS) and verified the existence of vortex Rossby waves in a three-dimensional primitive equation model.

We are interested in whether the vortex Rossby waves play roles in initiating the inner spiral rainbands in our simulated tropical cyclone. We believe from our simulation that part of the inner spiral rainbands are initiated by the vortex Rossby waves, in agreement with MK97. Actually we can see from Figs. 3 and 4 that cyclonic PV anomalies are mostly collocated with elevated radar reflectivity not only in the eyewall but also in the inner spiral rainbands, indicating a strong connection between the PV bands and inner spiral rainbands. Figure 9 shows the total radar reflectivity superposed by the total asymmetric wind fields at 850 hPa at every 15-min interval for the 2 h between 61 and 63 h. The asymmetric winds are superposed in order to easily track the vortex Rossby waves in the inner core region. The eyewall was quite symmetric with several small inner spiral rainbands during the 2-h period shown. The asymmetric wind and PV fields are dominated by wavenumber-1 structure in the near-core environment (Figs. 9 and 10). The waves, inner spiral rainbands, and eyewall all rotate cyclonically (Fig. 9), with some changes in the eyewall shape, following the mechanisms discussed in the last section. The cyclonic rotation of the inner spiral rainbands seems to be much slower than the rotation of the eyewall. This is due to the slower local tangential wind outside the eyewall. Although both the rainband and asymmetric PV anomaly spiral cyclonically inward, they have a local outward phase propagation (see also Fig. 2b).

By 61 h 30 min, the cyclonic (anticyclonic) circulation of the vortex Rossby wave moved to the southeast (northwest) quadrant in the eyewall (Fig. 9). At the same time, there was an outer rainband to the southeast just 90 km from the cyclone center. The cyclonic tangential wind and inflow were both enhanced at the inner end of the outer rainband. This flow impinged on the eyewall region and collapsed with the cyclonic circulation of the waves after only about 15 min at 61 h 45 min. The waves also experienced a temporary intensification from 61 h 45 min to 62 h 30 min (see also Fig. 2a). As the wave rotated cyclonically from the south to the southwest quadrants, the outflow associated with the waves occupied the southeast quadrant up to a radius of about 90 km from the cyclone center. Accompanied with this outflow was the formation of a broken eyewall and an active inner spiral rainband to the south just outside the eyewall (see $T = 62$ h and $T = 62$ h 15 min in Fig. 9). This was followed by an axisymmetrization process that led to a recovery of the eyewall ($T = 62$ h 30 min to $T = 63$ h in Fig. 9), but left narrow outward-propagating inner spiral rainbands. These bands were in phase with PV bands associated with the outward-propagating vortex Rossby waves as seen from the asymmetric PV anomaly in Fig. 10.

The initiation of inner spiral rainbands described above is a general process in our simulated tropical cyclone, although the eyewall was not necessarily broken in association with the formation of inner spiral rainbands. In most cases, the inner spiral rainbands apparently formed as a result of emanation of convection from the eyewall region. This outward emanation was due to the outward propagation of the vortex Rossby waves. It has been shown in the last section that stronger winds and heavy rainfall related to vortex Rossby waves are collocated in the eyewall (Figs. 4 and 7). In the inner spiral rainbands, however, these two phenomena appear to have a different phase outside the eyewall. The winds outside and downstream of the heavy rainfall are mostly stronger, while winds inside and upstream of the rainbands are weaker (Fig. 9, note that the symmetric winds are clockwise and inward).

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Footnote

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Footnote

1 This is a Southern Hemisphere (18 deg S) tropical cyclone so that cyclonic (anticyclonic) circulation is clockwise (counterclockwise) with a negative (positive) PV. However, we reversed the sign of PV in this paper so that positive (negative) PV represents cyclonic (anticyclonic) circulation, while we left the winds unreversed.

Footnote

2 Note that Fig. 2 shows only the wavenumber-1 waves, but the wavenumber-2 vortex Rossby waves have an azimuthal phase speed similar to the wavenumber-1 waves, see Figs. 8a and 9a in Wang (2002).

Footnote

3 Angular momentum is negative for a cyclone in the SH. The "increase" here means increase in negative angular momentum.

Footnote

4 Here we use "partial eyewall replacement" to distinguish the eyewall replacement processes discussed by Willoughby et al. (1982), who identified the replacement of the eyewall by a second eyewall developed outside the original eyewall.

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