Quadrant-Dependent Evolution of Low-Level Tangential Wind of a Tropical Cyclone in the Shear Flow

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(Manuscript received 20 June 2015, in final form 3 December 2015)

ABSTRACT

This study investigates the quadrant-by-quadrant evolution of the low-level tangential wind near the eyewall of an idealized simulated mature tropical cyclone embedded in a unidirectional shear flow. It is found that the quadrant-averaged tangential wind in the right-of-shear quadrants weakens continuously, while that in the left-of-shear quadrants experiences a two-stage evolution: a quasi-steady stage followed by a weakening stage after the imposing of vertical wind shear. This leads to a larger weakening rate in the right-of-shear and a stronger jet in the left-of-shear quadrants. The budget analysis shows that the quadrant-dependent evolution of tangential wind is controlled through the balance between the generalized Coriolis force (GCF; i.e., the radial advection of absolute angular momentum) and the advection terms. The steady decreasing of the GCF is primarily responsible for the continuous weakening of jet strength in the right-of-shear quadrants. For the left-of-shear quadrants, the quasi-steady stage is due to the opposite contributions by the enhanced GCF and negative tendency of advections cancelling out each other. The later weakening stage is the result of both the decreased GCF and the negative tangential advection. The combination of storm-relative flows at vortex scale and the convection strength both within and outside the eyewall determines the evolution of boundary layer inflow asymmetries, which in turn results in the change of GCF, leading to the quadrant-dependent evolution of low-level jet strength and thus the overall storm intensity change.

1. Introduction

Vertical wind shear (VWS) is one of the most important controls on the intensity of a tropical cyclone (TC; Wang and Wu 2004). Previous studies have shown that the shear-induced eddy fluxes play an important role in destroying the warm core and reducing the efficiency of a TC’s heat engine (Simpson and Riehl 1958; Frank and Ritchie 2001; Wu and Braun 2004; Tang and Emanuel 2010; Riemer et al. 2010; Gu et al. 2015). Therefore, the development of shear-induced asymmetries has been the central focus of investigations into the interaction between a TC and its large-scale environmental flow in recent years.

When a TC vortex is tilted by VWS, a wavenumber-1 couplet of vertical motion develops with ascent on the downshear side and descent on the upshear side, as confirmed both in dry (Jones 1995) and moist simulations (Bender 1997). To achieve an equilibrium state with the sheared environmental flow, the strongest updraft usually concentrates on the downshear-left side of a tilted TC vortex (Wang and Holland 1996; Reasor et al. 2004). The occurrence of these convective asymmetries has been further demonstrated in numerous numerical simulations (e.g., Frank and Ritchie 1999, 2001; Rogers et al. 2003; Braun et al. 2006; Braun and Wu 2007; Riemer et al. 2010; Xu and Wang 2013; Chen and Gopalakrishnan 2015).

Shear-induced kinematic and precipitation asymmetries have also been identified as common features in observations. Using airborne radar and in situ observations of two sheared TCs, Black et al. (2002) demonstrated that convection initiates in the downshear-right quadrant and matures while rotating cyclonically to the downshear-left quadrant. Enhanced lower- to midtropospheric downdrafts are found on the upshear-left quadrant of the eyewall and ascend around the upshear-right quadrant through the upper troposphere. This pronounced convective asymmetry has also been confirmed by other observational studies that used composite radar data (Reasor et al. 2013; DeHart et al. 2014),
observations (Corbosiero and Molinari 2002, 2003), and satellite-derived precipitation data (Chen et al. 2006; Cecil 2007; Hence and Houze 2011).

Using composite data from 1878 GPS dropsondes, Zhang et al. (2013) investigated the asymmetric inner-core structure of the hurricane boundary layer in relation to the VWS. They showed that the boundary layer inflow is deeper in the downshear quadrants, with the deepest being in the downshear-right quadrant, which is consistent with Reasor et al. (2013). The storm-relative tangential wind near the eyewall also varies along the azimuth; with a stronger wind speed in the left-of-shear quadrants than in the right-of-shear quadrants (see also Rogers et al. 2015).

The quadrant dependency of the eyewall jet strength suggests that the way in which the low-level tangential winds evolve in response to VWS may be different in different quadrants. As the overall TC intensity is often defined as the maximum of the azimuthally averaged tangential wind speed, such quadrant-dependent evolution indicates that there might be an essential part of the shear-induced asymmetries that contributes to the overall change in TC intensity. However, as the aforementioned mechanisms are based on an axisymmetric framework, it is unlikely that they will provide additional insights into the critical asymmetric processes, such as which part of the asymmetries is responsible for the weakening of a TC in the presence of large VWS and in which ways.

By exploring how the low-level tangential wind speed evolves in different quadrants of a sheared TC, this study aims to understand the mechanism for the quadrant-dependent evolution of the eyewall jet strength caused by the shear-induced asymmetries and how this subsequently affects the overall change in TC intensity. The remainder of this paper is organized as follows. A short description of the idealized experiments is provided in section 2 along with an overview of the basic kinematic structures. In section 3, the evolution of the low-level jet strength in different quadrants is examined first, followed by a detailed momentum budget analysis to explore the dynamical mechanism that causes the change of tangential wind in the different quadrants. The evolution of low-level inflow and related asymmetries is also presented. Section 4 gives a discussion on the critical inflow asymmetries that are important for TC intensity change. Finally, the main findings of this study are summarized in section 5.

2. Experiment description and overview of the simulated TC

a. Experiment description

Based on two experiments (SH10 and SH15, in which the VWS is 10 and 15 m s\(^{-1}\), respectively), Gu et al. (2015) suggested a new pathway for how VWS affects TC intensity: that is, the upward flux of high-entropy air, associated with shear-induced updraft from the boundary layer into midlevels outside the eyewall, could weaken the radial gradient of moist entropy across the eyewall and thus the TC intensity. Only the results of experiment SH10 are used here because the features of SH15 are generally similar to those of SH10. In SH10, the VWS was superposed onto a mature TC with zero flow below a height of 2 km and flow varying linearly to a height of 10 km with an easterly flow of 10 m s\(^{-1}\). The time when the VWS is imposed is referred to as 0 h, and subsequent times are relative to this time. The idealized experiments are conducted on an f-plane at 15°N, using a nonhydrostatic, full-physics, 3D numerical model [i.e., the Weather Research and Forecasting (WRF) Model, version 3.3.1 (Skamarock et al. 2008)]. The WRF Model has 35 vertical levels and two nested domains with horizontal resolutions of 15 and 5 km. The Betts–Miller–Janjic cumulus parameterization (Betts and Miller 1986) is used only in the outer domain. The Yonsei University (YSU; Hong et al. 2006) and the WRF single-moment 5-class (WSM5; Hong et al. 2004) schemes were chosen for the parameterization of the planetary boundary layer and microphysical processes, respectively. Readers are referred to Gu et al. (2015) for further details of the experiment.

The output of the fine mesh domain was archived at an interval of 5 min. The storm-relative winds are derived by subtracting the translation speed from the total winds. All of the variables are interpolated from the model grids into the cylindrical grids with the storm center at the origin. Using the minimum sea level pressure as a first-guess position, the storm center is iteratively determined as the vorticity centroid within the radius of 100 km at a height of 3 km. We have confirmed that the general characteristics of the results are not sensitive to the choice of height levels.

b. Basic kinematic structure of the sheared TC

To illustrate that the numerical results are suitable for investigating the evolution of tangential wind in different quadrants, the basic kinematic structures of the idealized simulations were inspected quadrant by quadrant relative to the shear direction and compared with the previous observations. For the convenience of the analysis carried out below, the direction of the VWS is assumed to be exactly the same as at the initial time (i.e., an easterly wind shear). The azimuth rotates counterclockwise due east at 0°. The four quadrants are defined as downshear right (DR), downshear left (DL), upshear left (UL), and upshear right (UR), which correspond to the azimuthal intervals of 90°–180°, 180°–270°,
270°–360°, and 0°–90°, respectively. The sum of UR and DR is referred to as the right-of-shear quadrants, and the sum of UL and DL as the left-of-shear quadrants.

The time- and quadrant-averaged vertical motion is shown in Fig. 1. In the DR quadrant, the eyewall updraft has two maxima in the vertical, with one in the lower troposphere and the other at a height of about 10 km (Fig. 1b). A weak downdraft is also found along the outer edge of the eyewall between heights of 4 and 10 km. In addition, there is a weak midlevel updraft between radii of 70 and 120 km. This branch of updraft is not present in other quadrants and might be associated with convection in the outer region (Corbosiero and Molinari 2003). The DL quadrant has the strongest eyewall updraft throughout the troposphere (Fig. 1a), indicating the presence of deep and mature convection.

A narrow downdraft is located along the inner edge of the eyewall through the mid- to upper troposphere, which is probably a forced stable response to the strong convective updrafts in the eyewall (DeHart et al. 2014). Outside the eyewall and below the melting layer, precipitation-driven downdrafts (Black et al. 2002) are found between radii of 90 and 150 km. Cyclonically to the UL quadrant, the updraft weakens a little, with the strongest upward motion above the 5-km level (Fig. 1c), and this is probably the result of acceleration caused by latent heat release from ice processes aloft (Zipser 2003; Fierro et al. 2009). A second maximum is found near a height of 2 km, as in the DR quadrant but of larger magnitude. Intense downdrafts are located along the inner and outer edges of the eyewall straddling the updraft. The downdraft on the radially outward side extends from a height of 10 km into the boundary layer.
The low-level downdraft is most probably precipitation driven and associated with the precipitation spiraling cyclonically inward from the DL quadrant. The downward motion above the melting layer is probably a response to the dynamical forcing by the shear-relative inflow at the upper levels of the UL quadrant (Xu and Wang 2013). The intense downdraft along the inner edge of the eyewall extends from the 12-km level (or higher) down to the lower troposphere. This branch of downdraft is probably caused by dynamical forcing in response to the high-altitude convective updrafts, as in the DL quadrant, and further accelerated by evaporative cooling (Liu et al. 1999). Downwind into the UR quadrant, the updraft weakens significantly, with only one maximum at the 10-km level (Fig. 1d). The mean vertical motion within the lower eyewall is less than 1 m s\(^{-1}\). The downdrafts flank the eyewall, with the inner downdraft at lower levels mostly driven by the evaporative cooling and the outer downdraft in the upper troposphere being the result of the storm-relative inflow in the upshear. These shear-relative patterns of updrafts and downdrafts around the eyewall are consistent with previous observations (Black et al. 2002; Reasor et al. 2013; DeHart et al. 2014).

Accompanying the asymmetries of vertical motion, the kinematic structures in the boundary layer also have obvious shear-relative features. Figure 2 shows the radius–height distribution of the time- and quadrant-averaged tangential wind velocity (\(\text{m s}^{-1}\)) below the height of 2 km and within the radius of 25–90 km for the four quadrants relative to the shear direction: (a) DL quadrant; (b) DR quadrant; (c) UL quadrant; and (d) UR quadrant. The black dashed line depicts the height of the maximum tangential wind speed varying with radius. The black arrow denotes the shear direction.

![Figure 2](image-url)

**Fig. 2.** Time- (0–10 h) and quadrant-averaged radius–height plot of tangential wind velocity (\(\text{m s}^{-1}\)) below the height of 2 km and within the radius of 25–90 km for the four quadrants relative to the shear direction: (a) DL quadrant; (b) DR quadrant; (c) UL quadrant; and (d) UR quadrant. The black dashed line depicts the height of the maximum tangential wind speed varying with radius. The black arrow denotes the shear direction.
The height of the maximum tangential wind in all quadrants increases with the radius, which is consistent with the symmetric behavior reported by Zhang et al. (2011) and Kepert and Wang (2001). Consistent with the results of Zhang et al. (2013), the jet cores in the left-of-shear quadrants are higher than those in the right-of-shear quadrants, and the mean tangential winds in the left-of-shear quadrants are larger than those in the right-of-shear quadrants, with the weakest in the DR quadrant.

Figure 3 shows the radius–height plot of the time- and quadrant-averaged radial velocity in the boundary layer. The general patterns of radial inflow are similar to the composite observations of Zhang et al. (2013), with the boundary layer inflow much stronger and deeper in the downshear quadrants than that in the upshear quadrants and the shallowest inflow layer in the UR quadrant. The inflow layer in this simulation is, however, deeper than those shown in the previous observational studies using dropsonde and radar data, but consistent with the elevated jet cores in Fig. 2. This discrepancy is probably related to the particular boundary layer parameterization used in the present study. In a high-resolution numerical simulation, Gopalakrishnan et al. (2013) found that the reduction of vertical diffusion results in a significant decrease in the height of the inflow layer.

The overall features of the boundary layer kinematic structures in the simulation are consistent with Zhang et al.’s (2013) composite analysis. However, there are also some different characteristics in the details. The largest jet strength occurs in the UL quadrant in the simulation rather than in the DL quadrant as in the composite analysis. As a result of the interaction between the TC vortex and the large-scale flow, the direction of shear evolves from easterly to east-northeasterly during the simulation (not shown). This may contribute to the shift of
maximum jet strength from the DL to the UL quadrant. Moreover, the deepest inflow layer is found in the DL quadrant rather than in the DR quadrant. This distinction probably results from the difference between the environmental shear flow in the current simulation and those in the real-case analysis.

After imposing the unidirectional shear in the current simulation, the originally erect TC vortex tilts to the downshear side and achieves a stable configuration with the upper-level vortex located in the DL quadrant, as discussed in the theoretical study of Reasor et al. (2004). The downward projection of upper-level cyclonic circulation (Wang and Holland 1996) induces inflow across the low-level inner core from the left-of-shear quadrants, leading to the stronger and deeper inflow in the DL quadrant. In the real atmosphere, the vertical shear of the environmental wind varies case by case and may differ significantly to the one in our simulation. The presence of nonunidirectional shear might lead to a larger angle between the storm motion and the shear direction [60°–120° (Zhang et al. 2013)] than that in our simulation (less than 60°, not shown). In the situation of a larger angle, the environmental flow at the middle and lower levels might come across the inner core from the right-of-shear quadrants, thus leading to the deepest inflow layer in the DR quadrant.

As the deepest inflow layer and the strongest jet strength both move cyclonically to the next quarter quadrant as compared with the composite analysis of Zhang et al. (2013), the shear-relative boundary layer kinematic structures in our simulation are self-consistent and reasonable. In the next section, the dataset is further explored to investigate the mechanism that drives the quadrant-dependent evolution of the low-level tangential wind.

3. Quadrant-dependent evolution of low-level tangential wind speed

a. Evolution of low-level jet strength

Figure 4 shows the evolution of the azimuthal-mean jet strength and the jet strength averaged in the downshear, upshear, left-of-shear, and right-of-shear quadrants during the first 10 h after imposing the VWS. The jet strength is represented by averaging the tangential wind speed within the annulus of the 30–60-km radius and between heights of 1 and 1.6 km, where the wind cores are mainly located in the four quadrants (Fig. 2). The dashed lines in Fig. 4 represent the overall evolution trend, which was extracted using the empirical mode decomposition method (Huang et al. 1998; Wu and Huang 2004).

In the presence of VWS, the azimuthal-mean jet strength decreases steadily with small oscillations. There is no apparent difference between the evolution in the downshear and upshear quadrants in the first 8 h, with the jet strength similar in both and decreasing (Fig. 4a). Little divergence appears until hour 8. In contrast, the evolution
of jet strength in the left-of-shear and right-of-shear quadrants demonstrates a markedly different behavior (Fig. 4b). In the right-of-shear quadrants, the overall evolution trend indicates that jet strength decreases continuously during the 10-h period. However, the evolution of jet strength in the left-of-shear quadrants shows two stages: a quasi-steady stage and a weakening stage. Although the jet strengths in the right-of-shear and left-of-shear quadrants are similar at the initial time, their evolution diverges after the VWS is imposed: the jet strength in the right-of-shear quadrants has a larger weakening rate, and the jet strength in the left-of-shear quadrant is much stronger. In addition, it is interesting to note that the left-of-shear and right-of-shear jet strengths evolve with their oscillations out of phase.

To illustrate the possible mechanism that determines the out-of-phase oscillations of the jet strength in the left-of-shear and right-of-shear quadrants, Fig. 5 shows the time–azimuth Hovmöller diagram of jet strength superimposed by the relative vorticity averaged within the annulus of the 30–60-km radius and between the heights of 1 and 1.6 km. At the beginning, jet strength has maxima in both the UL and DR quadrants, showing a wavenumber-2 pattern. A wavenumber-1 asymmetry gradually develops, showing an obvious out-of-phase evolution of jet strength in the left-of-shear and right-of-shear quadrants. Larger jet strength concentrates in the left-of-shear quadrants, and the jet strength in the right-of-shear quadrants weakens more rapidly. It is also apparent that there is a wavelike structure, propagating from the left-of-shear to the right-of-shear quadrants, with a period of 1.5–2 h. The relative vorticity also goes through a transition from wavenumber-2 to wavenumber-1 asymmetry in accord with the jet strength. The propagation of relative vorticity and jet strength has almost the same period. To the first-order approximation, the inner-core vorticity evolution in response to VWS could be viewed as the vortex Rossby waves discussed by Reasor and Montgomery (2001). The azimuthal phase speed of vortex Rossby waves was predicted to be slower than the tangential wind speed because of the negative vorticity gradient (Montgomery and Kallenbach 1997; Wang 2002a,b). Taking 45 km as the mean radius of the eyewall and 1.5–2 h as the propagation period, the phase speed of this wavelike structure was estimated to be 40–52 m s\(^{-1}\), which is between 57% and 74% of the mean flow speed within the eyewall. Therefore, the out-of-phase evolution of jet strength in the left-of-shear and right-of-shear quadrants is probably associated with vortex Rossby wave activities.

b. Momentum budget analysis

As outlined above, the differing evolution of the low-level tangential wind speed in the left-of-shear and right-of-shear quadrants contrasts markedly with the essentially similar evolution in the upshear and downshear quadrants. To explain the different evolution, we used a momentum budget analysis to elucidate the physical processes responsible for the weakening trend of jet strength in the right-of-shear quadrants and the two-stage evolution of tangential wind speed in the left-of-shear quadrants.

The governing equation of tangential wind speed on an \( f \) plane in the cylindrical coordinates is given as follows:

\[
\frac{\partial v}{\partial t} = -u \left( f + \frac{v}{r} \frac{\partial u}{\partial r} \right) - v \frac{\partial v}{\partial r} - w \frac{\partial u}{\partial z} - \frac{1}{\rho} \frac{\partial p}{\partial \lambda} + F_v, \tag{1}
\]

where \( v, u, \) and \( w \) are the storm-relative tangential, radial, and vertical velocities, respectively; \( f \) is the Coriolis parameter; \( r \) is the distance from the storm center; \( \rho \) is the air density; \( p \) is the pressure; and \( F_v \) is the boundary layer friction. On the right-hand side of Eq. (1), the first
term represents the radial advection of absolute angular momentum and is usually referred to as the generalized Coriolis force (GCF; Smith et al. 2009); the second and the third terms are the tangential and vertical advections of the tangential wind, respectively; the fourth term denotes the tangential pressure gradient force; and the last term is the friction force. All of the terms are individually calculated in the cylindrical grids and then averaged vertically between the heights of 1 and 1.6 km and azimuthally in the left-of-shear and right-of-shear quadrants.

Figure 6 shows the results of the momentum budget analysis in different quadrants. Because of the relatively low horizontal resolution used in the simulation, the intense radial gradient around the inner edge of the eyewall could not be accurately calculated in the cylindrical coordinates. Therefore, only the results within the 40–60-km radius are shown. In this region, the evolution of the low-level tangential wind speed (Fig. 6a) in the different quadrants shares similar characteristics, as shown in Fig. 4, with the right-of-shear jet strength weakening and the left-of-shear jet strength experiencing a quasi-steady oscillation over the first 5 h, followed by a 5-h period of weakening. The time series of jet strength in the different quadrants diagnosed by the budget analysis are shown in Fig. 6b. Compared with Fig. 6a, the calculation of budget analysis generally captures the dominant features of the evolution of jet strength in the different quadrants. Despite the difference in the detailed magnitudes between the budget calculation and the model output, the overall trends of low-level tangential wind change for both quadrants are well reproduced. In passing, the larger magnitude of the jet strength in the budget analysis, especially for the left-of-shear quadrants, is primarily caused by the overestimation of the GCF term in the cylindrical coordinates (not shown). Moreover, the out-of-phase oscillation superimposed on the overall evolution trend in the right-of-shear and left-of-shear quadrants has also been reproduced, with the timing and period agreeing well with the model output. Therefore, the calculation is suitable for inspecting the mechanism driving the evolution of tangential wind speed in the different quadrants. The tendency related to boundary layer friction is not shown here because the friction is larger in the left-of-shear quadrants than in the right-of-shear quadrants and thus could not contribute to the larger jet strength in the left-of-shear quadrants as illustrated in Fig. 6a.

Figure 6c shows the time series of tangential wind tendency caused by the GCF. The GCF tendency in the right-of-shear quadrants decreases continuously over the 10 h, changing sign from positive to negative at about hour 5 after the imposing of VWS. The GCF tendency in the left-of-shear quadrants increases in the first 5 h and then decreases in the following 5 h. The diverse evolution of the radial advection of the angular momentum indicates that the radial flow in the right-of-shear quadrants gradually decreases, evolving from inflow to outflow, while the radial inflow in the left-of-shear quadrants first strengthens and then decreases. Figure 6d shows the evolution of tangential advection. As the tangential winds in the left-of-shear quadrants are generally stronger than those in the right-of-shear quadrants, the tangential advection in the left-of-shear quadrants usually remains negative and evolves in opposite phase with the positive tangential advection in the right-of-shear quadrants. There is little obvious decreasing (increasing) trend in the tangential advection in the left-of-shear (right-of-shear) quadrants until hour 5. The vertical advectons are illustrated in Fig. 6e. In the right-of-shear quadrants, the vertical advection gradually increases from negative to positive. However, this tendency first decreases within the 0–5-h period and then increases a little in the left-of-shear quadrants. The enhanced negative (positive) tendency of vertical advection in the left-of-shear (right-of-shear) quadrants indicates that the height of the maximum tangential wind speed moves upward (downward). Figure 6f shows the tangential gradient force of pressure. The tendencies in both quadrants oscillate about the zero line, and thus have little impact on the differing evolution of jet strength in these quadrants.

Generally, in the right-of-shear quadrants, as the tangential and vertical advections gradually increase with time and mostly remain positive over the 10 h, the decreasing negative GCF is the only contributor to the weakening trend of jet strength. In the left-of-shear quadrants, the quasi-steady stage in the first 5 h mainly results from the balance between the increasing positive tendency of the GCF and the decreasing negative tendency of the tangential and vertical advections, with the vertical advection more dominant. That is to say, the enhanced radial advection of absolute angular momentum into the eyewall is partly advected downwind and largely transported upward to elevate the wind maximum, resulting in the higher and stronger jet core in the left-of-shear than that in the right-of-shear (Fig. 2). During the last 5 h, the gradually decreasing GCF and the enhanced negative tangential advection contribute together to the weakening phase. In brief, the jet strength in the right-of-shear quadrants is mostly determined by the radial advection of absolute angular momentum (i.e., the GCF), while the left-of-shear jet strength is affected by both the radial advection of absolute angular momentum and the advections.

To illustrate why these tendencies behave differently in the various quadrants, Fig. 7 shows the vertically...
FIG. 6. Temporal evolution of (a) mean tangential wind speed (m s$^{-1}$) in the simulation, (b) mean tangential wind speed (m s$^{-1}$) by momentum budget analysis, (c) tendency of generalized Coriolis force (×10$^{-3}$ m s$^{-2}$), (d) tendency of tangential advection (×10$^{-3}$ m s$^{-2}$), (e) tendency of vertical advection (×10$^{-3}$ m s$^{-2}$), and (f) tendency of tangential pressure gradient force (×10$^{-3}$ m s$^{-2}$) in different quadrants, averaged radially from 40 to 60 km and vertically from 1 to 1.6 km. The solid lines represent azimuthally averaged evolution in the overall (black), RS (blue), and LS (red) quadrants. The dashed lines represent the trend of evolution with time extracted by the empirical mode decomposition method.
FIG. 7. The plane view of vertically averaged (1–1.6 km) momentum budget results from hour 4 to hour 5: (a) tangential wind speed difference (m s\(^{-1}\)) between hour 5 and hour 4 in the simulation; (b) tangential wind speed tendency (m s\(^{-1}\)) by the budget calculation; (c) tendency of generalized Coriolis force (m s\(^{-1}\); shaded) and radial flows (m s\(^{-1}\); contours), with black and white lines representing outflows (positive values) and inflows (negative values), respectively; (d) tendency of tangential advection (m s\(^{-1}\); shaded) and time-averaged (4–5 h) tangential wind speed (m s\(^{-1}\); contours); (e) tendency of vertical advection (m s\(^{-1}\); shaded) and time-averaged (4–5 h) vertical velocities (m s\(^{-1}\); contours; black for positive value and upward motion and white for negative value and downward motion); and (f) tendency of tangential pressure gradient force (m s\(^{-1}\); shaded) and time-averaged (4–5 h) pressure anomaly (Pa; contours; black for positive value and white for negative value). The tendencies have all been multiplied by 3600 s. The black arrow denotes the shear direction.
averaged (1–1.6 km) plane view of each tendency within 4–5 h, during which the jet strength in the right-of-shear quadrants is decreasing and that in the left-of-shear quadrants begins to increase (Fig. 6b). Although the budget calculation does not capture some of the detailed structures of the tangential wind speed tendency, it has reproduced the general patterns, such as the increase in the left-of-shear quadrants and decrease in the right-of-shear quadrants, and several extrema in both the negative and positive tendencies. Moreover, our focus is on the evolution of tangential wind speed within the eyewall (40–60 km), and, therefore, the budget analysis is reasonable. We also performed budget analysis during other time periods, such as earlier and later in the storm. The features of each budget term during these periods are consistent with those within the 4–5-h period.

Figures 7a and 7b show the tangential wind tendency within the 4–5-h period from the WRF Model and budget analysis, respectively. The budget calculation captures the dominant features of tangential wind speed change within the inner core: increasing in the left-of-shear quadrants and decreasing in the right-of-shear quadrants, with the positive maximum in the DL quadrant and the negative maximum in the UR quadrant. Figure 7c shows the GCF and the radial velocity. The coincidence of the positive GCF with the radial inflow suggests that the radial inflow transports the absolute angular momentum inwards and thus accelerates the tangential wind speed on the downshear side. Meanwhile, the radial outflow transports the angular momentum outwards and results in negative GCF to decelerate the tangential wind speed on the upshear side. As shown in Fig. 7d, the tangential advection is negative in the downshear and positive in the upshear, with the maximum negative tendency in the DL quadrant and the maximum positive tendency in the UR quadrant, because the minimum and maximum tangential wind speeds locate in the DR and UL quadrants, respectively. Figure 7e shows the vertical advection along with the vertical velocity. Within the eyewall, the vertical motion has an obvious wavenumber-1 structure, with the strongest ascent in the DL quadrant, which is consistent with the observations (Reasor et al. 2013; DeHart et al. 2014). Outside the eyewall, there are two spiral rainbands with upward motion greater than 1 m s$^{-1}$. The vertical advection is positive from the UL quadrant to the DR quadrant counterclockwise and negative in the DL quadrant within the radius of 60 km, indicating that the wind core in the DL quadrant is higher than in other quadrants. Overall, the vertical advection is positive in the right-of-shear quadrants and negative in the left-of-shear quadrants. The tangential pressure gradient force and the pressure anomaly are shown in Fig. 7f. During this time, the low- and high-pressure centers are located on the downshear and upshear sides, respectively, leading to the positive pressure gradient force in the right-of-shear quadrants and negative pressure gradient force in the left-of-shear quadrants. However, the pressure anomalies rotate cyclonically over the 10 h (not shown), so their overall effect on the tangential wind can be ignored.

Based on this detailed momentum budget analysis, it can be seen that the evolution of jet strength in the different quadrants of the sheared TC is primarily contributed by the GCF and advections.

c. Inflow evolution

As demonstrated by the momentum budget analysis above, the GCF is very important to the maintenance of low-level jet strength. The positive or negative tendency of the GCF is largely determined by the radial inflow asymmetries. Therefore, the evolution of the low-level radial flow and the underlying physical processes need to be explored. As shown in Figs. 4b and 6, the hour 5 is an approximated dividing line for the two-stage evolution of the jet strength in the left-of-shear quadrant. Therefore, the period between hour 0 and hour 5 is regarded as the first stage and hour 5 to hour 10 as the second stage in the following analysis of radial inflow change.

Figure 8 shows the radius–height plot of the quadrant-averaged inflow difference between hour 5 and hour 0. During this stage, the radial inflow is strengthened on the downshear side (Figs. 8a,b) with the maximum in the DL quadrant and is much weakened in the upshear side (Figs. 8c,d) with the maximum in the UR quadrant. In all quadrants, there is a broad area of inflow change outside the radius of 60 km. This indicates a storm-relative flow from the downshear to the upshear side caused by the differential storm motion and mean environmental flow at low levels. As the TC vortex moves with the steering flow, which is approximately the midlevel mean environmental flow, the TC vortex moves faster than the environmental flow at low levels. Therefore, the low-level storm-relative flow moves inward on the downshear side and outward on the upshear side.

The above features of inflow evolution can be further confirmed from the wave decompositions. Figure 9 shows the plane view of vertically averaged (1–1.6 km) radial inflow difference between hour 5 and hour 0 and its wave components. It is apparent that the radial inflow is enhanced mostly on the downshear side and is much weakened on the upshear side, especially in the UR quadrant (Fig. 9a). This pattern of inflow change is generally dominated by the wavenumber-1 asymmetry, with enhanced inflow downshear and weakened inflow upshear (Fig. 9b), confirming the presence of storm-relative
flow at the vortex scale. In addition, there is a nontrivial contribution from the higher-wavenumber components (Figs. 9c,d), suggesting that the low-level inflow also evolves at the convective scale within the eyewall (30–60-km radius).

Figure 10 shows the radius–height plot of the quadrant-averaged inflow difference between hour 10 and hour 5, during which the jet evolution in the left-of-shear quadrants is going through the second stage. As shown in Fig. 10, within the eyewall (30–60 km), the radial inflow is reduced in the DL, DR, and UR quadrants (Figs. 10a,b,d) and enhanced in the UL quadrant (Fig. 10c). Outside the eyewall, the radial inflow is further weakened between radii of 80 and 100 km in the DR quadrant and between radii of 90 and 120 km in the UR quadrant.

The above features are confirmed by the vertically averaged (1–1.6 km) difference of radial inflow between hour 10 and hour 5 (Fig. 11). Within the eyewall, the radial inflow weakens obviously in the DR and DL quadrants, which are located with the weakening eyewall convection. Outside the eyewall, there is enhanced upward motion associated with a convective rainband, starting from the UR quadrant near a radius of 120 km and spiraling cyclonically inward to a radius of 60 km in the DL quadrant (not shown). The general pattern of the weakening radial inflow is captured by a wavenumber-1 asymmetry (Fig. 11b), which is locally confined within a radius of 60 km, unlike the broad distribution in the first 5 h (Fig. 9b). The weakening trend of radial inflows in the DL, DR, and UR quadrants is also contributed by the components larger than a wavenumber-2 structure (Figs. 11c,d). The wavenumber-1 component of the weakening low-level radial inflow is along the inner edge of the rainband. Besides, several maxima of the reduced radial inflow of

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**Figure 8.** Radius–height plot of the quadrant-averaged radial wind velocity difference (m s⁻¹) between hour 5 and hour 0 in the quasi-steady stage of LS jet evolution below the height of 2 km and within the radius of 150 km for the four quadrants relative to the shear direction: (a) DL quadrant; (b) DR quadrant; (c) UL quadrant; and (d) UR quadrant. The black arrow denotes the shear direction.
the higher-wavenumber components are located at the inner side of convective cells in the outer rainbands (not shown). Therefore, the evolution of low-level radial inflow in the second stage is determined by the evolution of eyewall convection and the shear-organized outer rainbands.

To further confirm the processes proposed above leading to the evolution of radial inflow, Fig. 12a shows the time–azimuth Hovmöller diagram of the reflectivity and vertical velocity averaged within the annulus of 30–60 km (the eyewall region) and vertically between heights of 2 and 4 km. It is evident that the eyewall convection evolves from a wavenumber-2 to a wavenumber-1 structure, with intense convection and strong upward motion concentrated in the left-of-shear quadrants. In the first 5 h, the eyewall convection gradually strengthens in the DL quadrant and weakens in the UR quadrant. This evolution pattern of convection may be associated with the vortex-scale storm-relative inflow on the downshear side and outflow on the upshear side and further contributes to the inflow change within the eyewall at the convective scale (Figs. 8, 9). In the following 5 h, the eyewall convection in the DL, DR, and UR quadrants weakens noticeably in accord with the weakening of inflow between radii of 30 and 60 km in most of the quadrants (Figs. 10, 11). Various mechanisms may contribute to the weakening of eyewall convection, such as midlevel ventilation (Tang and Emanuel 2010) and low-entropy downflux into the boundary layer by downdrafts (Riemer et al. 2010). The exploration of these mechanisms is beyond the scope of this study.

Figure 12b shows the time–azimuth Hovmöller diagram of reflectivity within the eyewall and the vertical velocity outside the eyewall between radii of 80 and 120 km. Accompanying the overall weakening of the
eyewall convection, abundant convection associated with outer rainbands with vertical motion of about 1 m s\(^{-1}\) arises in the right-of-shear quadrants. The effect of the outer rainbands on the low-level inflow has two sides. On one hand, the low- to midlevel inflow is enhanced on the radially outward side of the rainbands and results in a local tangential wind jet in the downwind stratiform portion. It has been suggested that this process might be favorable for broadening the zone of strong tangential winds and subsequently lead to the structure change of TCs (Moon and Nolan 2010; Didlake and Houze 2013a,b; Qiu and Tan 2013). On the other hand, the outer convection provides a source of diabatic heating, and a transverse circulation with outflow at low levels would be induced inside the heat source (Shapiro and Willoughby 1982). As a result, the low-level inflow outside the eyewall would be blocked by the wrapped outer rainbands in the right-of-shear quadrants (Figs. 10b,d). Based on the analysis of 26 aircraft passes across the rainbands, Barnes et al. (1983) found that the spiral rainband is a barrier for the low-level moist radial inflow into the eyewall and might have a negative impact on TC intensity. This has also been indicated in numerically simulated TCs. By modifying the diabatic heating in the outer spiral rainbands, Wang (2009) found that the effect of the increased diabatic heating rate in rainbands is to weaken the TC intensity. Gu et al. (2015) further confirmed the negative influence of outer rainbands in the thermodynamic framework in sheared TCs. They found that the shear-enhanced convection outside the eyewall could reduce the radial gradient of moist entropy across the eyewall and thus weaken the TC vortex.

To summarize, the low-level radial flow also experiences a two-stage evolution, corresponding to the evolution of the left-of-shear jet strength. During the first stage, the low-level radial flow is primarily influenced by the vortex-scale storm-relative flow across the inner-core region, with inflow in the downshear side and outflow in the upshear side, and the subsequent evolution of the eyewall convection in response to VWS. In the second stage,...
stage, the radial inflow in most of the quadrants is further reduced by the eyewall convection’s overall weakening and the shear-triggered outer rainbands forcing.

4. Discussion

Although this study investigates the dynamic processes governing the evolution of low-level jet strength in different quadrants of a sheared TC, the results obtained here could also be used to deepen our understanding of TC intensity change associated with VWS, as the overall TC intensity is usually defined as the maximum of the azimuthally averaged tangential wind speed.

On one hand, the key asymmetric structural changes occurring in the UR quadrant are primarily responsible for the weakening of the simulated TC in the presence of moderate to strong VWS. Imposing the VWS induces a vortex-scale storm-relative flow, which counteracts the low-level radial inflow in the UR quadrant. At the same time, in the UR quadrant, the eyewall convection, and therefore the secondary circulation, is strongly suppressed. These two processes significantly reduce the low-level radial inflow and the GCF in the UR quadrant, leading to the weakening of jet strength in the right-of-shear quadrants. On the other hand, the asymmetric structural changes on the downshear side, especially in the DL quadrant, are critical for the maintenance of TC intensity. The vortex-scale storm-relative flow induced by VWS is inward toward the storm center and strengthens the radial inflow in the DL quadrant. Also, as a result of the constraint of the VWS, the deep mature convection is concentrated in the DL quadrant and so enhances the secondary circulation therein. Consequently, the strength of DL inflow can be maintained or reduced less. In addition, larger relative vorticity is located in the left-of-shear quadrants (Fig. 5) and is almost in phase with the stronger radial inflow. As a result, the low-level jet strength is not easily decelerated when compared with other quadrants.

Fig. 11. As in Fig. 9, but for the radial wind velocity difference between hour 10 and hour 5.
Based on the above, it is likely that a TC will survive or even intensify in the presence of strong VWS as long as the radial inflow on the downshear side, especially in the DL quadrant, can be significantly enhanced through the evolution of downshear convection adjacent to the inner core. Several rapid intensification events have been reported in the literature and lend support to this hypothesis. Using cloud-to-ground lightning data, reconnaissance aircraft data, and satellite imagery, Molinari et al. (2004) found that the persistent downshear convective outbreaks in the presence of 5–11 m s\(^{-1}\) VWS became progressively more intense and closer to the center during the development of Hurricane Danny (1997). Molinari et al. (2006) and Molinari and Vollaro (2010) investigated the rapid intensification of Tropical Storm Gabrielle (2001) in the presence of strong VWS of 12–13 m s\(^{-1}\). They showed that an intense convective cell resembled a vortical hot tower developing DL of the center and moving cyclonically inward. The growth of the convective cell within a region of high-efficiency latent heating much enhanced the downshear boundary layer inflow and favored the rapid deepening of the storm. Nguyen and Molinari (2012) examined the rapid intensification of Hurricane Irene (1999) in the presence of increasing storm motion and VWS. It was hypothesized that the strongly asymmetric diabatic heating resulted from large VWS, and rapid storm motion was responsible for the rapid intensification, since it developed within the radius of maximum wind and was of sufficient intensity to increase the azimuthally averaged heating. However, why the intense convective cells occur and grow within the radius of maximum wind in the presence of VWS is unclear. Therefore, the mechanism that determines the evolution of downshear convection, including its strength and location, requires further in-depth exploration.

As a first step, the case of an idealized unidirectional easterly VWS is examined in this study. In the simulation, the storm-relative flow moves inward on the downshear side and outward on the upshear side. However, when the mean environmental flow veers with height, the vortex-scale storm-relative flow may be different during the first stage after imposing the VWS, leading to a different evolution pattern of low-level inflow. In addition to the vortex-scale flow, convection may also evolve differently in the case of curved shear flows. Environments with wind profiles that turn with height in the lower troposphere are favorable for long-lasting convective cells (Brooks and Wilhelmson 1993;)

![Diagram](image-url)
In idealized simulations, Nolan (2011) found that the clockwise-turning hodograph is much more favorable for TC development than the counterclockwise-turning hodograph. Compared with this study, the evolution of the vortex-scale storm-relative flows and eyewall convection may be different in the nonunidirectional shear flow and may have different impacts on the evolution of jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants. Therefore, future studies on the effects of nonunidirectional shear flow on jet strength in different quadrants.

5. Summary

In this study, we performed idealized simulations using a 3D, full-physics numerical model to investigate the mechanism governing the evolution of low-level tangential wind in different quadrants of a mature TC embedded in unidirectional shear flow. We found that the jet strength in different quadrants evolves differently, with the jet strength weakening continuously in the right-of-shear quadrants and experiencing a two-stage evolution in the left-of-shear quadrants: a quasi-steady stage followed by a weakening stage. As a result, the tangential winds in the right-of-shear quadrants of the eyewall weaken more quickly than those in the left-of-shear quadrants, leading to stronger jet strength in the left-of-shear quadrants.

Detailed momentum budget analysis showed that the quadrant-dependent evolution of the low-level tangential wind speed is largely controlled by the generalized Coriolis force (GCF) and the advection terms. The GCF accelerates tangential winds on the downshear side through inward radial transportation of absolute angular momentum. The enhanced tangential winds are, in turn, transported upward and downwind, leading to an elevated and strengthened wind core in the left-of-shear quadrants.

Whether the GCF acts as a source or a sink within the tangential wind budget depends mainly on the radial inflow evolution. After imposing the vertical wind shear, the vortex-scale storm-relative flow develops throughout the inner-core region. The radial inflow is strengthened on the downshear side and reduced to outflow on the upshear side during the first stage. Although there is a more positive contribution from the GCF driven by the strengthened radial inflow, this is largely offset by the advection and leads to the quasi-steady evolution of jet strength in the left-of-shear quadrants. During the second stage, the weakening of eyewall convection and the presence of shear-triggered outer rainbands are responsible for the reduced low-level inflow in most of the quadrants, and this leads to a decrease in the overall storm jet strength.

In addition to the vortex-scale storm-relative flow, it is the clustering effect of the shear-induced convective asymmetries in the eyewall and the outer rainbands that contributes to the quadrant-dependent evolution of the low-level tangential winds, rather than the transient variations associated with some isolated convective cells. Despite a 5-km horizontal resolution being used in the current simulation, the cluster distribution of convection under the forcing of VWS was consistent with those seen in high-resolution numerical simulations (Braun et al. 2006; Braun and Wu 2007; Chen and Gopalakrishnan 2015). Therefore, the results presented in this study do not change qualitatively when applied to high-resolution simulations.

Finally, although this study has primarily focused on the evolution of low-level tangential winds, it is not impossible that the cyclonic circulation weakens from the top and down to the surface (Frank and Ritchie 2001). Based on tangential wind budget analysis, Xu and Wang (2013) found that the shear-induced eddy momentum flux could weaken the tangential wind speed in the upper levels. The relative importance of the processes occurring at different vertical levels leading to TC intensity change is not straightforward and is worthy of more in-depth investigations.

Acknowledgments. This research is sponsored by the National Natural Science Foundation of China through Grants 41461164008, 41130964, 41505044, and 41575053 and the National Key Project for Basic Research (973 Project) under Grants 2015CB452803 and 2013CB834102. The authors also thank Dr. Yuqing Wang and two anonymous reviewers for their careful reading, critical comments, and constructive suggestions that brought significant improvements to the manuscript.

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