Effect of Boundary Layer Roll Vortices on the Development of an Axisymmetric Tropical Cyclone

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ABSTRACT

In this study, the authors numerically investigate the response of an axisymmetric tropical cyclone (TC) vortex to the vertical fluxes of momentum, heat, and moisture induced by roll vortices (rolls) in the boundary layer. To represent the vertical fluxes induced by rolls, a two-dimensional high-resolution Single-Grid Roll-Resolving Model (SRM) is embedded at multiple horizontal grid points in the mesoscale COAMPS for Tropical Cyclones (COAMPS-TC) model domain. Idealized experiments are conducted with the SRM embedded within 3 times the radius of maximum wind of an axisymmetric TC. The results indicate that the rolls induce changes in the boundary layer wind distribution and cause a moderate (approximately 15%) increase in the TC intensification rate by increasing the boundary layer convergence in the eyewall region and induce more active eyewall convection. The numerical experiments also suggest that the roll-induced tangential momentum flux is most important in contributing to the TC intensification process, and the rolls generated at different radii (within the range considered in this study) all have positive contributions. The results are not qualitatively impacted by the initial TC vortex or the setup of the vertical diffusivity in COAMPS-TC.

1. Introduction

The vertical momentum, heat, and moisture transports caused by the turbulent motions in the boundary layer (BL) are critical in the development and maintenance of a tropical cyclone (TC). The BL parameterizations used to represent the vertical turbulent fluxes in current TC models are mostly adapted from those developed for moderate wind conditions. These schemes are typically based on $K$ theory and assume that the vertical fluxes induced by the unresolved motions are downgradient and depend on the vertical gradients of the mean (or resolved) variables. The general form for the parameterized vertical fluxes can be written as $-K_\phi(\partial \phi / \partial z)$, where $\phi$ represents an arbitrary variable resolved by the TC model and $K_\phi$ is the turbulent diffusivity for $\phi$. A hierarchy of parameterizations for $K_\phi$ with different levels of complexity has been used in existing TC models, and these parameterizations are well summarized by Kepert (2012). Several modeling studies suggest that the development of the TC and its dynamical structure is very sensitive to the turbulent diffusivity parameterization. For example, Gopalakrishnan et al. (2013) found that reducing turbulent diffusivity led to a decrease in the inflow-layer height and affected the size and intensity changes in the modeled TC based on the idealized simulations performed using the Hurricane Weather Research and Forecasting (HWRF) system. Zhang et al. (2015) further evaluated the impacts of the turbulent diffusivity on the performance of retrospective HWRF forecasts and indicated that constraining the

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vertical diffusion based on observations (Zhang et al. 2011a) improved the TC track and intensity forecasts, as well as the modeled TC structure, such as the storm size, surface inflow angle, and near-surface wind profile.

The BL parameterizations used in current TC models may not adequately capture all the fluxes induced by subgrid-scale motions, which is possibly one of the factors limiting their intensity forecast accuracy. Particularly, the BL parameterizations do not properly represent the contribution of coherent large eddies, commonly referred to as the roll vortices (rolls), which have been observed and modeled in the TC BL (Katsaros et al. 2000; Morrison et al. 2005; Ellis and Businger 2010). Rolls consist of vertically overturning circulations in the plane roughly perpendicular to the mean wind direction [a schematic diagram of rolls can be found in Morrison et al. (2005, their Fig. 8)]. Studies focusing on the formation mechanism of rolls in the TC BL based on linearized models (Foster 2005; Gao and Ginis 2014) suggest that inflection points in the basic-state radial wind profiles cause the instability and lead to the generation of rolls. Since this type of instability is related to inflection points in the boundary layer wind profile, it is commonly referred to as the inflection point instability. Several studies (Zhu 2008; Nakanishi and Niino 2012; Wang and Jiang 2017) based on large-eddy simulation (LES) generally support the notion that the rolls in the TC BL are driven by the inflection point instability, and the mean wind shear is the primary energy source.

Because of their large vertical extent, the rolls can transport momentum and entropy throughout the TC BL. Zhang et al. (2008) found that rolls significantly enhanced the total turbulent momentum and moisture fluxes in the TC BL based on in situ aircraft turbulence observations. By comparing the turbulent fluxes parameterized by a traditional BL scheme (i.e., the Yonsei University scheme) and those explicitly resolved by the LES under Hurricane Ivan (2004), Zhu (2008) found that the BL scheme significantly underestimated the turbulent fluxes because the effect of coherent large eddies was not considered. Based on the spectral analysis of LES-resolved turbulent fluxes, Wang and Jiang (2017) found that the roll-scale fluxes constituted a large portion (up to 40%) of the total turbulent fluxes in the TC BL. Using a roll-resolving BL model Gao and Ginis (2016) found that the along- and cross-roll components of the roll-induced momentum fluxes are fundamentally different: while the roll-induced cross-roll (approximately radial) momentum flux is mostly downgradient, the roll-induced along-roll (approximately tangential) momentum flux is largely countergradient. Therefore, the commonly used BL parameterizations based on K theory cannot reasonably capture the vertical fluxes caused by rolls. By considering the roll-induced momentum fluxes in a TC BL model, Gao and Ginis (2016) found that rolls could significantly affect the magnitude and structure of the radial inflow in the TC BL.

Even though the potential importance of rolls in the vertical transport in the TC BL is well recognized, there is still limited understanding of their role in the evolution of the entire TC. In the modeling system used by Gao and Ginis (2016), the upper TC vortex is fixed with time, and therefore the effect of rolls on the entire TC cannot be explored. In this study, we aim to implement the roll modeling approach proposed by Gao and Ginis (2014, 2016) into a three-dimensional full-physics TC model and investigate the response of the entire TC vortex to the roll-induced vertical fluxes. Specifically, we focus on the impact of rolls on an axisymmetric TC vortex in a quiescent environment. The following scientific questions will be addressed:

1. What is the impact of rolls on the intensification process of the TC vortex from the axisymmetric perspective?
2. Through what physical mechanisms do the rolls affect the TC intensification?

2. Method

a. Overview of the modeling approach

The full-physics TC model used in this study is the Coupled Ocean–Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC), which is the U.S. Navy’s operational and research tropical cyclone prediction system (Doyle et al. 2014). To represent the roll-induced vertical fluxes, we embedded the two-dimensional roll-resolving model [referred to as the Single-Grid Roll-Resolving Model (SRM)] developed in Gao and Ginis (2014, 2016) at multiple horizontal grid points in COAMPS-TC. The

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1 Some BL parameterizations additionally consider a “nonlocal” component, and can be written as \(-K_\phi(\partial\phi/\partial z - r_\phi)\), in which \(r_\phi\) is the correction to the local gradient of \(\phi\) (Hong and Pan 1996; Hong et al. 2006). The nonlocal flux component is dependent on the surface flux of \(\phi\) and represents the contribution of the convective eddies on the total flux of \(\phi\). These nonlocal schemes may not be able to capture the fluxes induced by rolls because the rolls are primarily generated by the shear instability (Foster 2005; Gao and Ginis 2014, 2016), and the roll-induced fluxes do not directly depend on the surface condition.

2 COAMPS-TC is a registered trademark of the Naval Research Laboratory.
primary assumption behind this approach is that the rolls can be mathematically separated from the relative large-scale TC flow because of their small spatial scales (~1 km). The SRM resolves the roll motions and provides the roll-induced vertical fluxes at a particular horizontal grid point of the TC model.

**b. The Single-Grid Roll-Resolving Model**

The roll motions at a single horizontal grid point in the TC model are described in a local Cartesian coordinate system (x, y, z), with y axis parallel to the direction in which the rolls are aligned. The y (x) axis is thus referred to as the along-roll (cross roll) axis. The along-roll variations are assumed negligible. The derivation of the governing equations for the mean flow and rolls in the cylindrical coordinates is given by Gao and Ginis (2014). Although the TC flow and rolls are described in the Cartesian coordinates in this study, the derivation remains largely unchanged and the details will not be shown. Following are the equations describing rolls at an arbitrary horizontal grid point (Xj, Yj) in the TC model, which are numerically solved by the SRM:

\[
\frac{\partial \eta'}{\partial t} + u' \frac{\partial \eta'}{\partial x} + w' \frac{\partial \eta'}{\partial z} = -\frac{\partial \eta}{\partial x} + w' \frac{\partial \eta}{\partial z}^2 + g \frac{\partial}{\partial x} \left( \frac{\theta'}{\theta_0} + 0.61q' \right) + D_{\theta'},
\]

Equations (1) and (2) describe the overturning circulations of rolls (u', w') in the x-z plane, where \( \psi' \) is the streamfunction (cross-roll velocity \( u' = -\partial \psi'/\partial z \)), vertical velocity \( w' = \partial \psi'/\partial x \), and \( \eta' \) is the along-roll vorticity \( \eta' = \partial \omega'/\partial x - \partial u'/\partial z \). Equations (3)–(5) describe the along-roll wind perturbation \( \nu' \), the potential temperature perturbation \( \theta' \), and the water vapor mixing ratio perturbation \( q' \) caused by the overturning circulations of rolls, respectively. The water phase changes associated with the roll motions are neglected for simplicity. Variables with the overbar represent the mean flow variables, and they are the prognostic variables of the mesoscale TC model at the horizontal grid point (Xj, Yj); \( \overline{u} \) and \( \overline{v} \) are the mean winds projected onto the cross-roll (x) and along-roll (y) directions, respectively, \( \overline{\theta} \) is the mean potential temperature, and \( \overline{q} \) is the mean water vapor mixing ratio. The mean flow variables (\( \overline{u}, \overline{v}, \overline{\theta}, \overline{q} \)) are assumed horizontally uniform in the SRM domain because the horizontal variation of the mean flow is not as significant as the vertical variation in the TC BL. Such an assumption makes the treatment of the lateral boundary conditions in the SRM simple, but it may not be valid at the locations close to the storm center, where the wind speed changes rapidly with radius. Therefore, the SRM is not embedded at relative small radii (radii smaller than 15 km) in the experiments we conduct in this study. It should be noted that the SRM is only aware of the vertical gradient of the mesoscale TC flow but unaware of the horizontal gradient. The acceleration effect of the radial inflow associated with roll circulations on TC azimuthal wind is thus neglected. Terms like \( T_{\nu'} \) represent the turbulent diffusion terms, which are in the form of \( D_{\nu'} = \frac{\partial (u' \partial \eta'/\partial x)}{\partial x} + \frac{\partial (v' \partial \eta'/\partial z)}{\partial z}, \) where \( v' \) is the turbulent diffusivity applied in the SRM calculations. Different from Gao and Ginis (2016), who used a unified turbulence parameterization at the grid points where the roll models are embedded, we use two separated turbulence parameterizations for COAMPS-TC and SRM in this study. A unified approach may result in discontinuity in the turbulent diffusivity in COAMPS-TC and also make it difficult to identify the impact of roll-induced fluxes because both the roll-induced flux and the roll-induced change in turbulent diffusivity could affect the TC BL structure. Here, we adopt a scheme commonly used in LES models (Sullivan et al. 1994) to parameterize \( v' \) in the SRM, which is in the form of

\[
v' = (C_s \Delta)^2 \left( 2S_{ij} \frac{\partial \eta}{\partial x_i} \frac{\partial \eta}{\partial x_j} \right)^{1/2},
\]

where \( C_s \) is the Smagorinsky constant (\( C_s = 0.18 \)); \( \Delta \) is the grid spacing of the SRM; and \( S_{ij} \) is the resolved strain rate tensor, given by

\[
S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right),
\]

where \( u_i \) and \( \theta_i \) are the total resolved velocity and virtual potential temperature (e.g., \( u_i = \overline{u_i} + u_i' \))\(^3\), respectively.

\(^3\) We adopt the same subgrid closure concept as the LES and assume that the Smagorinsky constant, which is appropriate for the LES subgrid closure, can be used for the two-dimensional SRM.

\(^4\) The horizontally averaged diffusivity in the SRM is typically (20%–40%) larger than the diffusivity at the corresponding grid in COAMPS-TC because the roll-induced flow strain rate is additionally considered in the SRM subgrid parameterization.
SRM uses a very fine grid spacing (30 m in both horizontal and vertical) and a small time step (1 s) to resolve the small-scale roll motions. Weak perturbations (with magnitude on the order of $10^{-5} \text{s}^{-1}$) are added to the along-roll vorticity field as the initial condition for the SRM. Periodic conditions are applied at the lateral boundaries of the SRM domain because the mean flow is assumed horizontally uniform. No-slip boundary conditions are applied at the upper and lower boundaries. The two-dimensional SRM domain is 3 km high in the vertical (from 0 to 3 km) and 15.36 km wide in the horizontal. Extensive tests show that such domain size is small enough to ensure computational efficiency and also large enough to prevent the lateral\(^5\) and upper boundaries from affecting the roll solution.

c. Implementing the SRM into COAMPS-TC

The strategy of embedding the SRM mesh into the COAMPS-TC mesh is illustrated in Fig. 1. The larger-size mesh with a coarse resolution represents the COAMPS-TC mesh, and the smaller-size mesh with a high resolution represents the SRM mesh. In Fig. 1, the SRM mesh is embedded at two horizontal grid points ($X_1, Y_1$) and ($X_2, Y_2$) in the COAMPS-TC mesh. In practice, multiple locations can be selected. To be consistent with observations (Morrison et al. 2005) and theoretical analysis (Foster 2005), we assume the rolls are aligned in the direction of the vertically averaged wind vector within the TC BL. Thus, the SRM mesh is oriented perpendicular to the direction of the wind vector averaged within the lowest 1-km layer at each selected horizontal grid point.

SRM and COAMPS-TC exchange information at each selected horizontal grid point: COAMPS-TC provides SRM with the vertical profiles of the horizontal winds ($U$, $V$), potential temperature $\Theta$, and water vapor mixing ratio $Q$ as the mean-flow variables for rolls; and SRM provides COAMPS-TC with the roll-induced vertical fluxes of momentum ($w'\bar{u}'$ and $w'\bar{v}'$), potential temperature ($w'\bar{\Theta}'$), and water vapor mixing ratio ($w'Q'$), which are all horizontally averaged in the SRM domain. Considering that COAMPS-TC uses a larger time step than SRM (see section 3), the roll-induced fluxes are time averaged during one COAMPS-TC time step.

With the SRM embedded, the total vertical boundary layer fluxes in COAMPS-TC consist of two components, the parameterized fluxes based on $K$ theory and explicitly resolved roll-induced fluxes, which can be written as

$$-K_\phi \frac{\partial \phi}{\partial z} + \bar{w}' \tilde{\phi}' ,$$

(6)

where $K_\phi$ is the turbulent diffusivity, and $\phi$ can represent the winds ($U$, $V$), potential temperature $\Theta$, and water vapor mixing ratio $Q$. The first component in (6) represents the fluxes induced by the unresolved small-scale turbulent motions and assumed to satisfy the downgradient assumption; the second component in (6) represents the roll-induced fluxes calculated by SRM. There are several options available in COAMPS-TC for parameterizing the turbulent diffusivity $K_\phi$. The $K_\phi$ scheme used in this study is based on turbulent kinetic energy and mixing length and will be described in section 3.

3. Experimental design

For simplicity, we only consider a stationary and axisymmetric TC vortex in this study, which is on an $f$ plane (20°N) and over the ocean with constant sea surface temperature (30°C). The horizontal domain is 1000 km wide in both east–west and north–south directions with uniform 5-km grid spacing in the Cartesian coordinates. Periodic boundary conditions are applied at the horizontal boundaries. Forty vertical levels are applied, which extend from 10 m to...
approximately 32 km with 18 levels below 3 km. The time step is set to 5 s. The cumulus and radiation parameterizations are not used for the purpose of this study. The microphysical parameterization used is a single-moment bulk scheme modified based on Lin et al. (1983) and Rutledge and Hobbs (1983), with changes accounting for temperature and pressure dependence in all thermodynamic coefficients and updated sedimentation calculation. The surface-layer parameterization follows Wang et al. (2002) and limits the values of the drag coefficient under high wind speeds (Powell et al. 2003; Donelan et al. 2004). The turbulent diffusivity parameterization is based on a 1.5-order scheme (Mellor and Yamada 1982); the dissipative heating is included based on TKE dissipation to ensure energy conservation (Jin et al. 2007). Specifically, the turbulent diffusivity is written as

$$K_{m,h} = S_{m,h} l \sqrt{e}, \quad (7)$$

where $K_m$ and $K_h$ represent the turbulent diffusivity for momentum and scalars, respectively; $S_{m,h}$ represent the polynomial functions of the flux Richardson number that accounts for the effect of static stability; $e$ is the turbulent kinetic energy [the prognostic equation for $e$ is shown in Hodur (1997)]; and $l$ is the mixing length, in this application expressed as

$$\frac{1}{\overline{e}} = \frac{1}{\kappa z} + \frac{1}{\lambda}, \quad (8)$$

where $\kappa$ is the von Kármán constant and $\lambda$ is the asymptotic mixing length (details described below).

The COAMPS-TC is first run without SRM to spin up a TC-like vortex. In the spinup run, the initial wind field contains a weak axisymmetric cyclonic vortex with a maximum tangential wind speed of $\sim 20$ m s$^{-1}$ at a radius of 90 km [see (57) and (58) in Hodur (1997)]. The wind speed is vertically uniform from the surface to $z = 10$ km, and then decreases sinusoidally to zero at $z = 20$ km. The initial unperturbed temperature and the moisture profiles are horizontally uniform, and the initial pressure and potential temperature fields associated with the vortex are in balance with the wind field and obtained by solving the nonlinear balance equations (Hodur 1997). In the spinup run, $\lambda$ is an integral length scale that has a form described in Mellor and Yamada (1982), written as

$$\lambda = \alpha \int \frac{zedz}{e}, \quad (9)$$

and parameter $\alpha$ is dependent on the static stability.

After a spinup period of 70 h, a typical TC vortex is generated (Fig. 2). Because the TC is stationary and nearly axisymmetric, we will focus on the azimuthally averaged fields throughout this study. Here, angle brackets denote the azimuthally averaged variable. By the end of the spinup period, the TC vortex has an axisymmetric structure (Fig. 2) that is generally consistent with those in other idealized numerical studies (Stern and Nolan 2011; Xu and Wang 2010) and in observations (Rogers et al. 2012). The maximum tangential wind $\langle V \rangle$ of 40 m s$^{-1}$ exists at a radius of 20 km and $z \sim 600$ m. The TC has a typical radial-flow structure characterized with the shallow radial inflow near surface (below $z = 1$ km) and the radial outflow at upper levels ($z = 12$–14 km). The eyewall convection exists in the vicinity of a radius of 20 km, which is characterized by relatively strong upward vertical motion $\langle W \rangle$ and relatively large diabatic heating rate $\langle H \rangle$. The model also produced a reasonable boundary layer thermal structure compared to the composite GPS dropsondes observations from Zhang et al. (2011b), with a shallow superadiabatic layer near the surface (below 200 m) that is mainly caused by the strong turbulence dissipative heating (Kepert et al. 2016). This spun-up TC vortex has not reached maximum intensity yet and will keep intensifying with time.

The spun-up TC is used as the initial condition for the experiments investigating the impact of rolls (sensitivity of the model results to the choice of the initial TC vortex is discussed in appendix B). The elapsed time is reset to 0 h in the experiments. Summary of the experiments is provided in Table 1. In these experiments, we set the asymptotic mixing length $\lambda$ in (8) to a constant value of 40 m. It should be noted that $\lambda$ is a critical parameter affecting the overall magnitude of the turbulent diffusivity, and it can vary substantially under the TC condition according to observations (Zhang and Drennan 2012). In our idealized process-oriented numerical experiments, we set $\lambda$ to a constant for simplicity. The sensitivity of the model results to the choice of $\lambda$ is discussed in appendix A.

Experiments ROLL and CTRL are designed to demonstrate how rolls affect the structure and intensity of the TC. The only difference between the two

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6 Because COAMPS-TC is a 3D model, the TC vortex is not perfectly axisymmetric and some wavenumber-4 structure exists after the spinup run (Fig. 3). But the TC remains nearly axisymmetric in all experiments, and the magnitude of the asymmetric feature is rather weak (not show). We focus on interpreting the results from the axisymmetric perspective, and the weak asymmetric features are averaged out by azimuthal averaging.
experiments is that ROLL has the SRM embedded into COAMPS-TC, but CTRL does not. In experiment ROLL, the SRM is embedded at all horizontal grid points in an annular area between radii of 15 and 50 km (≈300 horizontal grid points in total) (Fig. 3). The SRM is not embedded within radius of 15 km because the assumption that the mean-flow profiles are horizontally uniform within the SRM domain may not be valid at small radii. Meanwhile, the SRM is not embedded at radii larger than 50 km because of the computational resource limitation. The duration of all experiments is set to 7 h based on two considerations. First, there is still some uncertainty about the prevalence and life-span of the rolls in reality. The 7-h simulation allows rolls to develop in the TC model but also prevents them from living indefinitely. Second, we only seek to understand the deterministic response of the TC vortex to roll-induced fluxes. The 7-h simulation is sufficiently long for the entire TC vortex to respond to the roll-induced BL mixing.

Additionally, a group of experiments (group A) is designed to identify which components of the roll-induced fluxes are most important in affecting the development of the TC. In each of these experiments, only one component of the roll-induced fluxes is provided to COAMPS-TC. For example, in ROLL-U, the SRM is embedded at same locations as in ROLL, but only the roll-induced radial momentum flux is passed to COAMPS-TC. Another group of experiments (group B) is designed to assess the effect of rolls formed at different radius ranges on the development of the TC. In each of these experiments, SRM is only embedded at the horizontal grid points within a narrow annular area with 5-km width. For example, ROLL-R20 is designed to investigate the effect of rolls formed near 20-km radius, and therefore the SRM is only embedded at the horizontal grid points within the annular area between radii 17.5 and 22.5 km.

4. Characteristics of rolls

This section focuses on the characteristics of rolls in experiment ROLL. At a given horizontal grid point of the TC model, the rolls form from the initial weak perturbation and quickly reach finite amplitude if the local mean flow is dynamically unstable. A series of consecutive snapshots of the vertically averaged roll-induced cross-roll momentum flux \( \langle \tilde{w}\tilde{u}\rangle \) are shown in Fig. 4 to illustrate the formation locations of rolls. Each pixel in

\[ \text{Fig. 2. The azimuthally averaged cross sections of the TC after the 70-h spinup: (a) radial wind (m s}^{-1}), (b) tangential wind (m s}^{-1}), (c) vertical wind (m s}^{-1}), and (d) the diabatic heating rate (K s}^{-1}). \]
Fig. 4 represents a single horizontal grid point in the COAMPS-TC domain. The grid points where rolls are generated have nonzero fluxes. Figure 4 suggests that rolls are first formed at some horizontal grid points at the outer (∼50 km) and inner (∼20 km) radii after 4 h of simulation, and with time they are formed at more and more locations and fill up nearly the entire selected domain after 7 h of simulation. To understand their formation mechanism, we consider the cross-roll averaged equation for the overturning kinetic energy of rolls [(A5) in Gao and Ginis (2016)]:

\[
\frac{\partial e'}{\partial t} = \frac{\partial w}{\partial z} + \frac{g}{\theta_0} w \theta' + \frac{\partial w}{\partial z} - \frac{\partial w}{\partial z} - \frac{\partial w}{\partial z} - \frac{\partial w}{\partial z} - \frac{\partial w}{\partial z} - \frac{\partial w}{\partial z},
\]

where the overturning kinetic energy \(e'\) is defined as \(e' = 0.5(u'^2 + w'^2)\). The terms on the right-hand side represent: cross-roll mean shear production (term A), buoyancy work (term B), dissipation (term C), vertical advection (term D), and pressure redistribution (term E). The shear production and buoyancy work terms are directly affected by the mean flow. Figure 5 shows the Hovmöller diagrams of the azimuthally averaged cross-roll mean shear \(\langle \partial u/\partial z \rangle\) and the roll-induced cross-roll momentum flux \(\langle w'u' \rangle\) at 25-, 35-, and 45-km radii. The black lines represent the heights of the inflection point where \(\langle \partial u/\partial z \rangle\) reaches the maximum value. At all selected locations, \(\langle w'u' \rangle\) negatively correlates with \(\langle \partial u/\partial z \rangle\), and \(\langle w'u' \rangle\) reaches maximum magnitude in the vicinity of the inflection point. Such distribution of \(\langle w'u' \rangle\) is an important signature of the rolls generated by the inflection point instability (Gao and Ginis 2014). The magnitude of \(\langle \partial u/\partial z \rangle\) generally decreases with time at the selected radii, which is likely caused by the smoothing effect the rolls have on the mean wind shear.

Figure 6 shows the vertical profiles of the cross-roll mean shear production and the buoyancy work terms at 25-, 35-, and 45-km radii, which are all azimuthally and time (6–7 h) averaged. The magnitude of the shear production terms are clearly the dominant source terms for the overturning kinetic energy of rolls at these radii, while the buoyancy work terms mostly have negative contributions. The magnitude of the shear production term decreases with radius because the magnitude of the mean wind shear decreases (Fig. 5). The above
analysis suggests that the rolls are generated by the inflection point instability of the TC BL flow, as discussed by Foster (2005) and Gao and Ginis (2014, 2016). The absolute value of the ratio between the vertically integrated shear production (the roll kinetic energy production term) and buoyancy work (the roll kinetic energy destruction term) is smallest at 35-km radius among the three selected radii shown in Fig. 5, which might be the cause of the weakest rolls in the middle of the selected domain. The effect of the shallow near-surface superadiabatic layer on rolls is insignificant. This is mainly because rolls have much larger vertical extent (~1 km) than the superadiabatic layer (~100 m), and they are mostly under the influence of the stable stratification above the superadiabatic layer.

The rolls at different locations have similar structures. Figure 7 shows the typical structures of rolls resolved by the SRM. The structures are also similar to those derived by Gao and Ginis (2016) and Foster (2005). The angle between the along-roll axis and the local azimuthal axis is generally smaller than 15°. The spatial scales and velocity magnitudes vary with time and location, mostly because the mean flow that determines the characteristics of the rolls changes. The horizontal wavelengths of rolls (defined as the distance between two nearby \(w'\) peaks) are in the range 2–5 km, the maximum along-roll wind perturbations \(u'\) are in the range 5–10 m s\(^{-1}\), and the maximum vertical velocities \(w'\) are in the range 1–3 m s\(^{-1}\). These values are consistent with the observations (Katsaros et al. 2000; Morrison et al. 2005; Ellis and Businger 2010).

Figure 8 shows the representative profiles of the azimuthally averaged roll-induced fluxes and the parameterized turbulent fluxes for comparison. The profiles of the roll-induced radial and tangential momentum fluxes are, in general, consistent with those in Gao and Ginis (2016). The vertical distribution of roll-induced radial momentum flux resembles the parameterized radial momentum flux. This is because the rolls...
generated by the inflection point instability induce cross-roll momentum flux, which is approximately the radial momentum flux, negatively correlated with the cross-roll mean wind shear (Fig. 5). On the contrary, the vertical distribution of the roll-induced tangential momentum flux is very different from the parameterized tangential momentum flux. This is because the roll-induced along-roll momentum flux, which is approximately the tangential momentum flux, is not dependent on the mean wind shear (Gao and Ginis 2016). The distribution of the roll-induced tangential momentum flux has important implications for the role of rolls in the TC BL dynamical balance, which is discussed in section 6. The vertical distribution of the roll-induced heat and moisture fluxes suggest that rolls tend to enhance the vertical mixing of heat and moisture throughout the TC BL. The effect of these roll-induced fluxes on the development of the TC is discussed next.

5. Effect of rolls on the TC structure and intensity

To investigate the effect of rolls on the TC structure and intensity, we compare the simulated TCs in experiments ROLL and CTRL. Here, we use the term “change” (denoted by $\delta$) to refer to the differences between the TCs in experiments ROLL and CTRL (calculated as the TC in ROLL minus the TC in CTRL). Figure 9 shows the radius–height sections of the changes in the azimuthally averaged wind fields, which are time averaged during three sequential 1-h periods. During the 4–5-h period (Figs. 9a–c), the most significant radial and tangential wind changes are limited to the lower levels (roughly $z < 4$ km). The
wind changes demonstrate complicated vertical variations that can be attributed to the adjustment of the TC BL wind fields to the roll-induced momentum fluxes.\(^8\) During the 5–6-h period (Figs. 9d,e), the magnitudes of the wind changes increase, and some significant wind changes appear at upper levels (roughly \(z > 4\) km). Specifically, the TC in ROLL has a stronger inflow in the TC BL \((z < 2\) km) and outflow at upper levels \((z = 12–16\) km), a larger tangential wind speed above \(z = 4\) km, and also a more intense eyewall updraft (entire vertical column) than the TC in CTRL. During the 6–7-h period (Figs. 9g–i), the wind changes are similar to those during 5–6h, but with larger magnitudes.

To demonstrate the impact of rolls on the evolution of TC intensity, we consider the evolution of the changes in the maximum tangential wind speed\(^9\) and the minimum pressure at all model levels (Fig. 10). There are two stages

\(^8\) Specifically, the alternating values of the radial wind change result from the change of the depth and strength of the radial inflow and the weak outflow immediately above; similarly, the alternating values of the tangential wind change result from the change of the depth and strength of the supergradient jet and the weakly sub-gradient wind immediate above.

\(^9\) The radius of the maximum wind (RMW) slopes radially outward with height, and the slope becomes smaller as the TC intensifies. Overall, the RMW near surface ranges from 15 to 25 km, and the RMW at 10-km height ranges from 20 to 35 km over the period shown in Fig. 10.
in ROLL (Fig. 11b), suggesting that rolls cause a ~15% increase in the TC intensification rate. Similarly, if the maximum surface wind speed is used to represent the TC intensity, inclusion of rolls leads to a ~20% increase in the TC intensification rate.

The above analyses indicate that rolls positively contribute to the TC intensification. Next we investigate (i) which component(s) of the roll-induced fluxes is (are) important in affecting the TC intensity evolution and (ii) whether the rolls formed at different radii all have positive contributions to the TC intensity. Figure 11 shows the time series of maximum \( V \) at \( z = 5 \) km (well above the TC BL) and the minimum surface pressure in groups A and B experiments. Interestingly, only the TC in ROLL-V has a stronger intensification rate than that in CTRL. By contrast, the TC intensification rates in the other three experiments in group A are similar to that in CTRL (Figs. 11a,b). This suggests that the roll-induced tangential momentum flux is primarily responsible for the enhanced TC intensification. All the TCs in group B experiments have stronger intensification rates than the TC in CTRL, indicating that rolls at different radii (within the range considered in this study) all have positive contributions to the TC intensity (Figs. 11c,d). The TCs in the group B experiments are weaker than the TC in ROLL, suggesting the enhanced TC intensity in ROLL is very likely as a result of the collective contributions of rolls at different radii.

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footnote: Traditionally, the maximum surface wind speed \( (z = 10 \text{ m}) \) or the maximum tangential wind speed in the TC BL is used to represent the TC intensity. However, Fig. 10 indicates the changes of wind in the TC BL may occur only because of the adjustment of the TC BL wind to the roll-induced mixing (3–5 h). Considering the focus of this study is the response of the entire TC vortex, the maximum tangential wind at a level well above the TC BL (such as \( z = 5 \) km) is a more suitable indicator of the roll-induced TC intensity change.
It is interesting that, even though the magnitudes of roll-induced potential temperature and moisture fluxes are considerably large (as shown in Figs. 8c and 8d), their contribution to the TC intensity changes is insignificant during the time period we considered. This is because the mean potential temperature and moisture profiles are not significantly altered by the roll-induced mixing (not shown).

Fig. 9. (top) Height–radius distributions of the changes (ROLL minus CTRL) in the azimuthally averaged (a) radial, (b) tangential, and (c) vertical wind fields, time averaged during 4–5 h (colors). (middle) As in (top), but time averaged during 5–6 h. (bottom) As in (top), but time averaged during 6–7 h. The contours represent the azimuthally averaged TC wind fields in experiment CTRL: (a), (d), (g) the solid (dashed) contours represent outflow (inflow) with an interval of 5 m s^{-1}; (b), (e), (h), the contours are 15, 25, 35, and 45 m s^{-1}; (c), (f), (i), the contours are 1 and 2 m s^{-1}.
6. Physical interpretation

In this section, we aim to elucidate the physical mechanism through which rolls affect the TC structure and intensity from the axisymmetric perspective. Considering the rolls only exert momentum forcing in the TC BL, the question of how rolls affect the entire TC vortex can be decomposed into two parts: (i) how the roll-induced vertical momentum fluxes, particularly the tangential momentum flux, affect the dynamical balances and wind structure in the TC BL and (ii) how the roll-induced changes in the TC BL affect the TC intensification process. Sections 6a and 6b address these two questions, respectively. We will mainly present the analyses based on the results from experiment ROLL-R45 in the following. The reason is that rolls in ROLL-R45 are generated in a limited radius range, making it easy to identify their local and nonlocal impacts. The physical mechanism revealed from the results in ROLL-R45 can also be applied to interpret the enhanced TC intensity due to rolls in other experiments (ROLL, ROLL-V, and other group B experiments).

a. Effect of rolls on the TC BL dynamics

To gain physical insight into the impact of the roll-induced momentum fluxes on the dynamical balance and wind structure in the TC BL, we analyze the azimuthally averaged momentum budgets, which are written as follows:

$$\frac{d\langle U \rangle}{dt} = -\left(\frac{1}{\rho} \frac{\partial P}{\partial r}\right) + \left(f + \frac{\langle V \rangle}{r}\right) \langle V \rangle$$

$$-\left(\frac{\partial \langle W U \rangle}{\partial z}\right) + \left(\frac{\partial}{\partial z} \left(K_m \frac{\partial U}{\partial z}\right)\right), \quad \text{and} \quad (11)$$

$$\frac{\partial \langle V \rangle}{\partial t} = -\left(f + \frac{\langle V \rangle}{r} + \frac{\partial \langle V \rangle}{\partial r}\right) \langle U \rangle$$

$$-\left(\frac{\partial \langle W V \rangle}{\partial z}\right) + \left(\frac{\partial}{\partial z} \left(K_m \frac{\partial V}{\partial z}\right)\right) - \langle W \rangle \frac{\partial \langle V \rangle}{\partial z}. \quad (12)$$

The physical meaning of the terms in (11) is as follows (from left to right): the net acceleration in the radial direction (that is, the material derivative of $\langle U \rangle$); the gradient wind imbalance (IMB), which is the imbalance between the pressure gradient force and the sum of Coriolis and centrifugal forces; the total subgrid (here “subgrid” means relative to the COAMPS-TC grid) momentum tendencies in the radial direction (UBL), which consists of the roll-induced tendency $\langle R_U \rangle$ and the parameterized turbulent tendency $\langle P_U \rangle$. The physical meaning of the terms in (12) is as follows (from left to right): the local time-changing rate of $\langle V \rangle$; the acceleration due to the radial advection of the absolute angular momentum [ANG; defined as $(1/2)f r^2 + \langle V \rangle r$]; the total subgrid momentum tendencies in the tangential direction (VBL), which consists of the roll-induced tendency $\langle R_V \rangle$ and the parameterized turbulent tendency $\langle P_V \rangle$; and the vertical advection.

We first consider the subgrid momentum tendencies in ROLL-R45. Figure 12 shows Hovmöller diagrams of the azimuthally averaged subgrid momentum tendencies at a radius of 45 km. The roll-induced tendency $\langle R_V \rangle$ is positive at lower levels (roughly below 0.3 km) and negative at upper levels (roughly 0.3–1 km). Such distribution of $\langle R_V \rangle$ suggests that rolls have a vertical redistribution effect on the tangential momentum in the TC BL (Gao and Ginis 2016). Particularly, $\langle R_V \rangle$ has the opposite sign to $\langle P_V \rangle$ at...
the lower levels \((z < 0.3 \text{ km})\), indicating that the vertical redistribution effect of rolls on the tangential momentum partially cancels the dissipation effect of the parameterized turbulence near surface.

To further explore the impact of the roll-induced tangential momentum tendency \(\delta V\) in the TC BL, we derive the changes of the momentum budget terms, which are calculated as the differences between ROLL-R45 and CTRL (denoted by \(\delta\)). Figure 13 shows the changes of four terms that are most significant in the lower boundary layer \((z < 1 \text{ km})\). The chain of responses in the TC BL to \(\delta V\) at the radius where rolls are generated is described as follows and schematically summarized in Fig. 14:

(i) The distribution of \(\delta V\) (Fig. 13d) is mostly determined by \(\delta V\) (Fig. 12b). The vertical distribution of \(\delta V\) suggests that rolls have a direct effect on the local \(\langle V\rangle\) profile: they tend to increase \(\langle V\rangle\) at lower levels (roughly below 0.3 km) and decrease \(\langle V\rangle\) at the upper levels (roughly 0.3–1 km) [see (12)].

(ii) The vertical distribution of \(\delta IMB\) (Fig. 13b) reflects the effect of rolls on the local \(\langle V\rangle\) profile: \(\delta IMB\) is positive near surface where rolls tend to increase \(\langle V\rangle\), and \(\delta IMB\) is negative at upper levels where rolls tend to decrease \(\langle V\rangle\).

(iii) The distribution of \(\delta d\langle U\rangle/dt\) (Fig. 13a) is similar to \(\delta IMB\), suggesting that the change in IMB directly affects the net radial acceleration and therefore affects the local \(\langle U\rangle\) profile [see (11)].

(iv) The changes in \(\langle U\rangle\) and \(\langle V\rangle\) result in a change in the ANG term (note that \(\delta ANG\) with a negative sign is shown in Fig. 13c), which nearly cancels \(\delta V\) (Fig. 13d). This suggests that, under the impact of rolls, the local mean wind profiles adjust to a state in which \(\delta ANG\) is nearly in balance with \(\delta V\). It should be noted to the leading order there is a balance between the frictional dissipation of angular momentum and its replenishment by radial transport in the TC BL (Kepert 2013). The above discussion suggests that rolls make adjustments to the leading-order TC BL angular momentum balance.

The effect of rolls on the mean wind in the TC BL is not limited to the region where the rolls are formed.

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12 The changes of the vertical advection term in (12) are found to be not as significant as the changes of the four terms shown in Fig. 13 below \(z < 1 \text{ km}\) and therefore are not discussed.

13 This suggests that the direct impact of rolls on the parameterized turbulent diffusivity is weak. We compared the azimuthally averaged TKE fields in experiments CTRL and ROLL and found that the direct impact of rolls on TKE field is negligible (not shown). Thus, rolls affect the total subgrid momentum tendencies mainly by introducing the additional roll-induced tendencies.
Figure 15 shows the height–radius distribution of the radial ($\delta\langle U \rangle$) and tangential ($\delta\langle V \rangle$) wind changes (ROLL-R45 – CTRL), averaged during 3–4 h. It should be noted that there are no changes in the upper-level TC structures ($z > 3$ km) during this period. Thus, the wind changes shown in Fig. 15 originate from the dynamical response of the TC BL to the roll-induced momentum fluxes. While the roll-induced momentum fluxes only exist in the vicinity of a 45-km radius in ROLL-R45, the wind changes are spread in the radial and vertical directions, which is as a result of the advection by the mean circulation in the TC BL.

b. Effect of rolls on the eyewall convection

We now explore how rolls contribute to the TC intensity change. The fact that the roll-induced tangential momentum flux matters most (Figs. 11a,b) implies that the rolls contribute to the TC intensity change by affecting the secondary flow in the TC BL. In a recent study investigating the role of BL dynamics in the eyewall replacement cycle, Kepert and Nolan (2014) indicated that the frictional convergence in the TC BL is important in localizing the eyewall convection and affecting its intensity. Here we hypothesize that rolls contribute to the TC intensity change through a similar mechanism: the rolls enhance the eyewall convection by enhancing the convergence in the TC BL, which then leads to enhanced TC intensity. The following analysis aims to validate the above hypothesis by using a diagnostic axisymmetric TC BL model, as in Gao and Ginis (2016).

In the following, we give a brief description of the diagnostic TC BL model. More details can be found in Gao and Ginis (2016). The diagnostic TC BL model is formulated based on the assumption that the BL wind fields are in a steady state under the given gradient wind and pressure fields. It derives the radial, tangential, and vertical winds ($\langle U_e \rangle$, $\langle V_e \rangle$, and $\langle W_e \rangle$, respectively; here, subscript $e$ denotes the diagnostic calculation by the TC BL model) based on the steady-state nonlinear dynamical equations that consider the BL subgrid momentum tendencies (both parameterized and roll induced). The diagnostic TC BL model is therefore a suitable tool to validate our hypothesis that the eyewall convection change observed in the full-physics TC simulations can be attributed to the roll-induced momentum tendencies. In the diagnostic axisymmetric TC BL model, the governing equations...
for $\langle U \rangle_e$ and $\langle U \rangle_e$ in the TC BL model are the same as (11) and (12); $\langle W \rangle_e$ is calculated based on the convergence of $\langle U \rangle_e$, as follows:

$$\langle W \rangle_e = \int_0^z \left( -\frac{1}{r} \frac{\partial \langle U \rangle_e}{\partial r} \right) dz.$$  (13)

The diagnostic TC BL model extends vertically from surface to 3 km with a 30-m vertical grid spacing. The radial extent is set to 500 km and the horizontal grid spacing is set to 5 km (same as in COAMPS-TC). The surface-layer parameterization is based on the Monin–Obukhov similarity theory with modified roughness length formulation that caps the drag coefficient at 0.003 at high wind speeds. There are three types of inputs provided to the TC BL model in this study: (i) the tangential wind $\langle V \rangle$ at 3-km height from COAMPS-TC, which is used as the gradient wind for the TC BL model, (ii) the parameterized turbulent diffusivity $\langle K_m \rangle$ from COAMPS-TC, and (iii) the roll-induced momentum tendencies from SRM. The pressure gradient force in the TC BL model is assumed vertically uniform and obtained by using gradient wind balance relation. We use the turbulent diffusivity $\langle K_m \rangle$ directly from COAMPS-TC calculations to ensure the parameterized turbulent momentum tendencies in the diagnostic model resemble those in COAMPS-TC.

Several groups of diagnostic runs are performed that only differ in the source of the roll-induced momentum tendencies. Table 2 summarizes the source of inputs for different groups of diagnostic runs. These inputs are averaged over every 30-min period and provided to the diagnostic TC BL on a 30-min interval (one diagnostic run corresponds to one set of inputs). Each diagnostic run lasts for 24 h to reach a quasi-steady state, and the wind fields at the end of the run are considered the diagnosed wind fields under given inputs.

Consistent with Kepert and Nolan (2014), we find the diagnostic TC BL model captures well the main features in the BL wind fields. To demonstrate this, we show the comparison between the actual and the diagnosed wind fields averaged between 3 and 3.5 h in Fig. 16. The good agreement suggests that BL winds simulated by the full-physics TC model (COAMPS-TC) can be considered in a nearly balanced state under the imposed upper TC vortex (Kepert and Nolan 2014). The magnitude of $\langle W \rangle_e$ is nearly 50% weaker than $\langle W \rangle$, which is likely because the latent heat release in the eyewall is unaccounted in the TC BL model.
We next compare the diagnosed vertical velocity change \( \delta W_e \) with the COAMPS-TC simulated change \( \delta W \). The diagnosed vertical velocity change is only caused by the roll-induced momentum tendencies. Figure 17 shows the evolution of \( \delta W_e \) (ROLL-R45 minus CTRL), as well as \( \delta W \) and \( \delta H \) (ROLL-R45 minus CTRL), which are all vertically averaged within the lowest 3 km. The results shown in Figs. 17b and 17c demonstrate that the eyewall convection in ROLL-R45 is enhanced relative to CTRL. As expected, \( \delta H \) has a similar distribution to \( \delta W \), suggesting that the change in the latent heat release is associated with the change of vertical velocities. The more active eyewall convection in ROLL-R45 is presumably responsible for the enhanced TC intensification rate. The evolutions of \( \delta W_e \) and \( \delta W \) are similar, confirming that the change in the TC BL convergence induced by rolls is at least partially responsible for the enhanced eyewall updraft. The magnitude of \( \delta W_e \) is apparently weaker than \( \delta W \) after ~6 h, which is likely because the change in the latent heat release (not considered in the diagnostic TC BL model) also contributes to \( \delta W \).

Similar diagnosed calculations confirm that the enhanced eyewall convection in group B experiments originates from the roll-induced momentum tendencies (not shown). The rolls at all radii (experiment ROLL) contribute to the TC intensification in a collective manner (Figs. 11c,d). To illustrate this, Fig. 18 shows Hovmöller diagrams of the diagnosed and actual eyewall convection changes in experiment ROLL. Before ~4.5 h, rolls are mostly generated at the horizontal grid points near a radius of 45 km (similar to ROLL-R45), and therefore \( \delta W_e, \delta W, \) and \( \delta H \) in Fig. 18 are very similar to those in Fig. 17. At later times, rolls forming at other locations (Fig. 4) additionally contribute to the convergence in the TC BL (\( \delta W_e \) in Fig. 18a is larger than in Fig. 17a), and further enhance the eyewall convection (\( \delta W \) and \( \delta H \) in Figs. 18b and 18c are larger than in Figs. 17b and 17c).

### 7. Summary

In this study, we conducted idealized numerical experiments to investigate the impact of rolls on the structure and intensity of an axisymmetric TC. The vertical fluxes of momentum, heat, and moisture induced by rolls are explicitly represented in a three-dimensional full-physics TC model (COAMPS-TC) based on the approach proposed by Ginis et al. (2004) and Gao and Ginis (2014, 2016). In this modeling
framework, a two-dimensional roll-resolving model (SRM) is embedded at multiple horizontal grid points in the TC model domain. The SRM was embedded within the inner-core region (radius \( \leq 50 \) km) of the modeled TC in the experiments performed in this study.

Consistent with previous studies, the simulated rolls are mostly generated by the inflection-point instability and gain their kinetic energy from the mean radial wind shear. The impact of rolls on the mesoscale TC vortex is analyzed from the axisymmetric perspective. By comparing the TCs from the experiments that include and do not include rolls, we find that the rolls first trigger wind changes in the TC BL, which then leads to a moderate (approximately 15\%) increase in the TC intensification rate. Additional experiments suggest that the rolls affect the TC intensification mainly via their vertical transport of the tangential momentum in the TC BL, and the rolls formed at different radii all have positive contributions to the TC intensification. Furthermore, we identified a pathway by which the BL rolls can affect the structure and the intensification of the entire TC vortex, summarized as follows. The rolls trigger a chain of dynamical responses in the TC BL via their vertical redistribution effect on the tangential momentum. Their impact on the radial wind enhances the BL convergence in the eyewall region and induces more active eyewall convection, which then positively contributes to the TC intensification.

To the best of our knowledge, this study is the first attempt to investigate the impact of rolls on TC

<table>
<thead>
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<th>Group name</th>
<th>( \langle V \rangle_{3\text{km}} )</th>
<th>( \langle K_m \rangle )</th>
<th>( \langle R_u \rangle ) and ( \langle R_v \rangle )</th>
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<tr>
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<td>ROLL(_e)</td>
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Fig. 16. Height–radius distributions of the azimuthally averaged (a) radial, (b) tangential, and (c) vertical velocities from COAMPS-TC simulation in experiment CTRL averaged during 3–3.5 h. (d)–(f) As in (a)–(c), but from the diagnostic TC BL model. The dashed contours in (a) and (d) represent the radial inflow, and the contour interval is 5 m s\(^{-1}\).
intensification. Even though rolls enhance the vertical exchange of momentum in the TC BL, their impact on the TC intensification may not be simply represented by increasing the turbulent diffusion coefficient (see results in appendix A). Since rolls are possibly prevalent in the TC BL, the misrepresentation of the roll-induced fluxes in current operational TC models may negatively affect the intensity prediction of real storms. This study should encourage future studies to quantify the contributions of organized large eddies (rolls) to the vertical momentum and entropy transports in the TC BL and develop new methods for their proper representation in TC models.

The provided explanation of how the rolls contribute to the TC intensification in this study remains tentative. Our modeling approach assumes explicit separation of the mesoscale TC flow and the BL rolls, and the total BL turbulent flux is a linear summation of the roll-induced and the parameterized flux. This approach serves well as a research tool for investigating how the simulated TC vortex responds to the roll-induced vertical fluxes. However, it cannot fully address the multiscale flow interactions (the interactions between mesoscale flow, rolls/large eddies, and smaller-scale turbulence) in TCs. Also, only the rolls generated in the inner core of the TC are simulated in this study because of the limited computational resources. Further studies are needed to understand the formation of rolls at larger radii and their impact on the TC development, as well as the effect of rolls on real TCs.

**FIG. 17.** Hovmöller diagrams of the changes (ROLL-R45 minus CTRL) in azimuthally and vertically (within the lowest 3 km) averaged (a) diagnosed vertical velocity from the TC BL model (ROLL-R45, minus CTRL), (b) actual vertical velocity from COAMPS-TC, and (c) diabatic heating rate. The contours represent (a) \( \langle W \rangle \), (b) \( \langle W \rangle \), and (c) \( \langle H \rangle \) in experiment CTRL: in (a) and (b) the thick contour is 0.1 m s\(^{-1}\), and the contour interval is 0.5 m s\(^{-1}\); in (c) the thick contour is 0.01 K s\(^{-1}\), and the contour interval is 0.03 K s\(^{-1}\).

**FIG. 18.** As in Fig. 17, but for (a) ROLL\(_x\) minus CTRL\(_x\) and (b),(c) ROLL minus CTRL.
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APPENDIX A

Sensitivity to the Asymptotic Mixing Length

In the 1.5-order turbulent diffusivity scheme (Mellor and Yamada 1982), the asymptotic mixing length $\lambda$ affects the magnitude of the turbulent diffusivity $K_{m,h}$. It is well known that the mean wind distribution in the TC BL is sensitive to the choice of $K_m$ (e.g., Kepert 2012). Generally, a larger $K_m$ results in a higher TC BL (defined as the height of the radial inflow) and less wind shear. In this study, in addition to affecting the parameterized turbulent fluxes in COAMPS-TC, $\lambda$ also affects the roll-induced fluxes resolved by the SRM. This is because rolls gain kinetic energy from the mean wind shear in the TC BL.

Here we examine the sensitivity of the model results to the choice of $\lambda$. In the CTRL and ROLL experiments discussed in the main text, $\lambda$ has been set to 40 m. Here we select three additional values: 30, 50, and 60 m. These values all fall in the range estimated by Zhang and Drennan (2012) based on observations. For each value of $\lambda$, we perform two parallel experiments, with and without rolls. The configurations of the additional experiments are the same as the ROLL and CTRL, except for the value of $\lambda$. The new experiments are labeled as ROLL-$\lambda$30m (CTRL-$\lambda$30m), ROLL-$\lambda$50m (CTRL-$\lambda$50m), and ROLL-$\lambda$60m (CTRL-$\lambda$60m), respectively.

The results show that the impact of rolls on the TC intensification is reduced as $\lambda$ increases (Fig. A1). Such results are expected. According to Gao and Ginis (2014), a larger $\lambda$ results in less wind shear in the TC BL and therefore weaker rolls. Moreover, as $\lambda$ increases the magnitude of the parameterized turbulent fluxes increases. The net effect of a larger $\lambda$ is that the contribution of the roll-induced mixing to the total mixing in the TC BL is reduced.

Fig. A1. Time series of the maximum azimuthally averaged tangential wind at $z = 5$ km in four pairs of experiments in which the asymptotic mixing length $\lambda$ is varied: (a) 30, (b) 40, (c) 50, and (d) 60 m.
The sensitivity experiments with different values of $\lambda$ can also help to address the question of whether the roll-induced mixing may be represented by simply increasing the value of $\lambda$ (or $K_{m,h}$). In Fig. A2, we compare the time series of the maximum $V$ at $z = 5$ km and the minimum surface pressure in three experiments: (i) CTRL (reference case), which has no roll-induced mixing and relative weak parameterized mixing; (ii) ROLL, which has enhanced mixing caused by rolls compared to CTRL; and (iii) CTRL-$\lambda_{60}$ m, which has no roll-induced mixing but enhanced parameterized mixing compared to CTRL. In agreement with previous studies, increasing the value of $\lambda$ (or $K_{m,h}$) from 40 to 60 m has led to a weaker TC. This is opposite to the effect of rolls (ROLL). The main reason is that the roll-induced tangential momentum flux (the main contributor to enhanced TC intensification) is nonlocal and countergradient (Gao and Ginis 2016) and thus cannot be properly represented by the BL scheme based on $K$ theory.

APPENDIX B

Sensitivity to the Initial TC Vortex

Here we present three additional pairs of experiments in which the initial TC vortex is varied. The objective is
to demonstrate that our main conclusion that the rolls positively contribute to the TC intensification process is robust and is not qualitatively affected by the choice of the initial vortex. In the experiments discussed in the main text (ROLL and CTRL), the initial TC vortex is obtained from a 70-h spinup run. In the additional experiments, the initial TC vortices are obtained by extending the length of the spinup run to 72, 74, and 76 h, respectively (longer spinup run results in a stronger initial TC vortex). These experiments with (without) the roll model embedded are labeled as ROLL-72h (CTRL-72h), ROLL-74h (CTRL-74h), and ROLL-76hr (CTRL-76h), correspondingly. The results (Fig. B1) suggest that the impact of rolls on the TC does depend on the initial TC vortex. However, in all the experiments the rolls cause enhanced TC intensification, demonstrating the robustness of the conclusions in the main text.

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