Outer Rainbands–Driven Secondary Eyewall Formation of Tropical Cyclones

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ABSTRACT

Secondary eyewall formation (SEF) could be considered as the aggregation of a convective-ring coupling with a tangential wind maximum outside the primary eyewall of a tropical cyclone (TC). The dynamics of SEF are investigated using idealized simulations based on a set of triplet experiments, whose differences are only in the initial outer-core wind speed. The triplet experiments indicate that the unbalanced boundary layer (BL) process driven by outer rainbands (ORBs) is essential for the canonical SEF. The developments of a secondary tangential wind maximum and a secondary convective ring are governed by two different pathways, which are well coupled in the canonical SEF. Compared with inner/suppressed rainbands, the downwind stratiform sectors of ORBs drive significant stronger BL convergence at its radially inward side, which fastens up the SEF region and links the two pathways. In the wind-maximum formation pathway, the positive feedback among the BL convergence, supergradient force, and relative vorticity within the BL dominates the spinup of a secondary tangential wind maximum. In the convective-ring formation pathway, the BL convergence contributes to the ascending motion through the frictional-forced updraft and accelerated outflow associated with the supergradient force above the BL. Driven only by inner rainbands, the simulated vortex develops a fake SEF with only the secondary convective ring since the rainband-driven BL convergence is less enhanced and thus fails to maintain the BL positive feedback in the wind-maximum pathway. Therefore, only ORBs can promote the canonical SEF. It also infers that any environmental/physical conditions favorable for the development of ORBs will ultimately contribute to SEF.

1. Introduction

Secondary eyewall formation (SEF) and the following eyewall replacement cycle (ERC) as common structural changes in intense tropical cyclones (TC) have long been documented and investigated in both observational and numerical studies (Willoughby et al. 1982; Houze et al. 2007; Tervey and Montgomery 2008; Rozoff et al. 2008; Kuo et al. 2009; Qiu et al. 2010; Huang et al. 2012; Qiu and Tan 2013; Yang et al. 2013). SEF and ERC could bring about intense structural changes, intensity fluctuations as well as temporal size expansion of TCs (Willoughby 1990; Houze et al. 2006; Kuo et al. 2009; Sitkowski et al. 2011). However, SEF forecasting and predication remain challenging in various environmental conditions (Kossin and Sitkowski 2009, 2012).

According to observational studies (e.g., Willoughby et al. 1982; Houze et al. 2007; Kossin and Sitkowski 2009), in general SEF is defined as the codevelopment of a convective ring beyond the primary eyewall and an associated secondary tangential wind maximum. The secondary convective ring is related to the rainband activities outside the primary eyewall yet 70% of rainbands outside the primary eyewall were without collocated the secondary wind maxima (Samsury and Zipser 1995), indicating that the formation of a secondary wind maximum and convective ring in SEF have different dynamical pathways. However, the two pathways have not been specified and hardly discussed in previous studies.

Though it has been widely recognized that the SEF is closely related to the activities of spiral rainbands especially the outer rainbands (ORBs) (e.g., Willoughby et al. 1982; Houze et al. 2007; Kossin and Sitkowski 2009; Qiu and Tan 2013; Yang et al. 2013), the specific role of ORBs in SEF remains controversial. From the perspective of the axisymmetric balanced process, Rozoff et al. (2012) suggest the sustained azimuthal-mean latent

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heating outside the primary eyewall will eventually lead to SEF. [Zhu and Zhu \(2014\)](#) further highlight the important role of low-level convection in accelerating the secondary tangential wind maximum. However, the axisymmetric balanced framework cannot explain the development of deep convection associated with the SEF and largely underestimate the spinup of the secondary tangential wind maximum within the boundary layer (BL) ([Abarca and Montgomery 2014](#); [Wang et al. 2016](#)). [Qiu and Tan \(2013\)](#) first focus on the role of asymmetric forcing of ORBs during the early stage of SEF. They pointed that ORBs featured by stratiform heating at the downwind end are capable of triggering asymmetric inflow descending into the BL, which reinforces BL convergence at the leading edge of the strong BL inflow, and thus enhanced convection at the radial inward side of ORBs and spinup of a secondary tangential wind maximum. The role of the asymmetric descending inflow in triggering/sustaining deep convection at the middle to downwind end of ORBs is supported by observations of Hurricane Earl (2010) ([Didlake et al. 2018](#)) and associated numerical simulation ([Yu and Didlake 2019](#)). [Wang et al. \(2019\)](#) shows a more detailed illustration of the top-down organization and asymmetric forcing of ORBs under this framework. Basically, these studies focus mainly on the development/enhancement of the convective feature of SEF. Though [Wang et al. \(2019\)](#) insist that the inward propagation and axisymmetrization of perturbation tangential wind of ORBs contribute to the spinup of the tangential wind within the BL, the axisymmetrization effect on SEF is limited ([Kuo et al. 2009](#)) and the BL response to such forcing is not discussed.

The spinup of a secondary tangential wind maximum is associated with the development of unbalanced BL process, which is widely considered crucial to the SEF (e.g., [Wu et al. 2012](#); [Huang et al. 2012](#); [Qiu and Tan 2013](#); [Wang et al. 2013](#); [Abarca and Montgomery 2014](#); [Wang et al. 2016](#)) yet the initiative process of the unbalanced BL response remains unclear. [Huang et al. \(2012\)](#) attributed the unbalanced BL response to the vortex-scale evolution of the wind field. In detail, increased BL inflow in response to the broadening wind field causes the supergradient flow at upper portion of the BL, which decelerates inflow and accelerates outflow across the SEF region, thus reinforcing BL convergence there. However, the vortex-scale expanding wind field cannot explain the local development of supergradient flow at certain radii and therefore cannot predict the location of SEF. [Kepert \(2013\)](#) proposed a positive feedback among the local enhancement of radial vorticity gradient above the BL, the frictional updrafts and convection leading up to SEF; however, the specific mechanism sustaining the radial vorticity gradient remains unclear and cannot

explain the spinup of the secondary BL tangential wind maximum since it only considers the one-way response in a steady-state BL model with specified vorticity forcing at the top of the BL.

Based on studies above, in the SEF with collocated secondary convective ring and associated secondary tangential wind maximum, the two-way feedback between the BL and rainbands process needs investigation. This study aims at two main questions: 1) Are the ORBs essential for SEF? Would the SEF happen in TCs with weakened or suppressed ORBs? 2) What is the specific dynamical process of the interactions between ORBs and the BL that leads up to the codevelopment of the secondary convective ring and tangential wind maximum associated with SEF?

To answer these questions, a set of experiments with different rainband activities is conducted in this study. Though many sensitivity experiments with interfered rainband activities are conducted in earlier studies, generally they investigated the variations of SEF by changing environmental conditions (e.g., [Nong and Emanuel 2003](#); [Fang and Zhang 2012](#); [Dai et al. 2017](#)) or exploiting the sensitivity of model physics (e.g., [Tyner et al. 2018](#); [Tang et al. 2017](#); [Chen et al. 2018](#); [Cheng and Wu 2018](#)), all of which share the same defect as inevitably changing other dynamical processes and/or the original vortex structure. To distinguish essential dynamics of SEF, how to design numerical experiments that can produce both the SEF and no-SEF events with a consistent model configuration and minimal differences in initial conditions worth investigating.

The reminder of this paper is organized as follows. A detailed model configuration and experiment design are described in [section 2](#). The results are exhibited in [section 3](#). [Section 4](#) compares rainband structures and resultant BL responses during the early stage of SEF. [Section 5](#) identifies key BL processes during the developing stage of SEF. Two pathways responsible for the SEF are discussed in [section 6](#). Main findings are summarized in [section 7](#).

2. Numerical model and triplet experiment

Idealized experiments are conducted using the Weather Research and Forecasting (WRF) Model (version 3.8.1) with three two-way nested domains. The outermost domain contains 301×301 grid points with horizontal spacing of 18 km. Symmetric lateral boundary conditions are applied onto the outermost domain. Grid points of two inner domains are 181×181 and 301×301 with horizontal spacing of 6 and 2 km, respectively, centered in the parent domain. The vortex-following innermost domain is capable of covering and recognizing most convective activities

FIG. 1. Radial profile of surface tangential wind of the initial vortex for all experiments. The triplet experiments (B02, B05, and B08) are marked out with bold solid lines.

of the simulated vortex. Vertically, there are 45 half-sigma levels, among which the lowest 10 levels are set below 1.5 km altitude.

To get rid of the possible differences resulting from subgrid processes, physical parameterization schemes are identical in all experiments, including the Thompson microphysical scheme (Thompson et al. 2004, 2008), the Mellor–Yamada–Janjić (MYJ) (Janjić 1996, 2002) BL scheme, the RRTM longwave radiative scheme (Mlawer et al. 1997) and Goddard shortwave radiative scheme (Chou and Suarez 1999). The Kain–Fritsch cumulus scheme (Kain 2004) is only applied in the outer two domains since the convections in the innermost domain can be precisely simulated.

All experiments are initialized with axisymmetric cyclonic vortices on an f plane at 20°N over a quiescent ocean with a constant SST of 28°C. The mean Caribbean sounding during hurricane seasons (Jordan 1958) is employed as the initial far-field temperature and humidity profile. Similar to Qiu and Tan (2013), the vortex profile chosen for this study as follows,

$$V(r) = v_{\max} \left(\frac{r}{r_{\max}} \right) \exp \left\{ \frac{1}{b} \left[1 - \left(\frac{r}{r_{\max}} \right)^b \right] \right\}, \quad (1)$$

where the radius of maximum wind (RMW) ($r_{\max}$) is 120 km, and the initial maximum tangential wind speed ($V_{\max}$) equals 20 m s^{−1}. Identical specifications of the RMW and $V_{\max}$ are applied in all experiments to minimize the distinctions in inner cores among all experiments. The lapse rate of initial horizontal wind beyond the RMW is controlled by exponent “ b ” parameter. Experiments are named B02, B03, B05, B06 and B08 with b specified at 0.2, 0.3, 0.5, 0.6, and 0.8, respectively. As shown in Fig. 1, a smaller b parameter promotes

slower decaying of the outer wind speed of the initial vortex, resulting in more wind-induced surface enthalpy fluxes and convective available potential energy in the outer region, thus favoring convective activities at larger radii (Xu and Wang 2010). Therefore, the strength and radial spans of spiral rainbands decrease from B02 to B08, resulting in variations of the SEF process. The experiments of B02, B05 and B08 are collected as the triplet experiments (bold lines in Fig. 1). The word “triplet” means these three experiments have identical model dynamics/physics and a similar initial vortex except for the minimal difference in the initial outer-core wind field, which produce vortices with different rainbands activities and eventually different structural changes.

3. Overview of SEF in the triplet experiments

a. Evolutions of size, intensity, and rainbands

Figure 2 shows the temporal evolutions of $V_{\max}$ and the RMW of simulated vortices at 1 km altitude. After 6 h spinup for BL physics and 12 h spinup for moist physics, the simulated storms intensify synchronously from 18 h and reaches maximum intensity of 90 m s^{−1}. B02, B03, and B05 undergo rapid intensification, reaching their maximum intensity at during 60–65 h, one after another. In B02 and B03, outer RMWs appear at 72 and 78 h, respectively, and replace the inner RMWs accompanied by transient decreases and re-intensifications of $V_{\max}$, consist with observations during ERC (Sitkowski et al. 2011). The jump of the RMW in B02 is earlier and larger than that in B03. In B05, there occurs a slight jump of the RMW at 90 h and much milder intensity oscillation compared to B02 and B03, showing an ambiguous SEF feature. B06 and B08 intensify slowly with a steadily expanding RMW. No significant oscillations of the RMW or $V_{\max}$ are captured. It can be concluded so far that the structural changes of inner-core wind fields are correlated to the convective activities outside the primary eyewall, which are modulated by the different initial outer-core sizes.

Figure 3 shows the evolution of simulated surface rain rate in the triplet experiments during 60–78 h. According to the locations relative to the rapid filamentation zone, the rainbands are divided into inner rainbands (IRBs) and ORBs with different dynamical characteristics (Guinn and Schubert 1993; Chen and Yau 2001; Li and Wang 2012). Here, the radial outer edge of the rapid filamentation zone before SEF is approximately 120 km, which is also consistent with “3-times RMW” criterion for dividing the ORBs and IRBs (Wang 2009). During this period, both B02 and

FIG. 2. Temporal evolutions of maximum tangential wind (gray lines; m s^{-1}) and the radius of maximum wind (black lines; km) between 1 and 2 km height during 0–120 h.

B05 exhibit a concentric convective ring though they possess different rainband activities. In B02, a brunch of ORBs has formed at the north of the TC center at 60 h and contracts inward to 80 km radius at 63 h (Figs. 3a,b). At this time, the wavenumber-1 asymmetry of the ORBs is evident, with broad stratiform precipitation concentrated at the downwind end. Afterward, the ORBs are elongated azimuthally, forming a quasi-closed ring at 80–120 km radii at 66 h (Fig. 3c), which is further enhanced and fully closed at 72 h (Fig. 3d). The primary eyewall begins to weaken with the inward contraction of the secondary eyewall at 78 h (Fig. 3e), followed by an eyewall replacement cycle (not shown).

During the 60–72 h period in B05, convection outside the primary eyewall exhibits IRBs features (Figs. 3f–h). By contrast, the ORBs are barely organized until 72 h

(Fig. 3i). Therefore, the outer convective ring in B05 is attributed to the symmetrical distribution of the active IRBs but the inner-core wind structure experiences no significant changes during this period (Fig. 2c), indicating that the convective-ring-like structure formed by IRBs in B05 is essentially different from the secondary eyewall in B02. Until 72 h, in B05 the organization and contraction of ORBs invigorate convective activities outside the primary eyewall, forming the secondary convective ring and associated RMW jump at 90 h (not shown). However, since the preexisting IRBs merges with the primary eyewall at 78 h (Fig. 3j), the moat region of the later-formed concentric eyewall is unclear. By sharp contrast, there is suppressed precipitation beyond 120 km radius in B08 due to its minimal initial outer-core size. The IRBs are distributed at smaller radii compared with B05 with little ORBs; therefore, no

FIG. 3. Simulated surface rain rate (mm h^{-1}) at indicated times in the triplet experiments: (top) B02, (middle) B05, and (bottom) B08. The plot domain is a $400 \text{ km} \times 400 \text{ km}$ square following the storm center. Circles are at every 40 km radius from storm center, and the 120 km radius is marked in black. (b), (g), (l) Sectors bounded by dashed lines are the downwind portion of rainbands for use in Fig. 7.

secondary convective ring formed in B08 (Figs. 3k–o) and no SEF.

b. Evolutions of axisymmetric storm structures

Figure 4 shows the time–radius evolutions of axisymmetric storm structures in the triplet experiments. In B02, the ORBs form at 54 h and contract to 120 km radius at 63 h indicated by midlevel upward motions ($>0.25 \text{ m s}^{-1}$) with associated BL convergence. During 66–78 h, the BL convergences and midlevel vertical motions outside the primary eyewall strengthen progressively with decaying convergence of the primary eyewall (Fig. 4a). Along with the contraction and enhancement of ORBs and BL convergence, the tangential wind accelerates and develops into a local wind maximum at 80 km radius around 72 h (Figs. 4a,b). On the well-developed secondary convective ring and associated tangential wind maximum, B02 exhibits a canonical SEF. On the contrary, B08 is dominated by suppressed rainbands with little BL convergence outside the primary eyewall (Fig. 4e). The heating of IRBs accelerates the BL inflow toward the primary eyewall (Li et al. 2014), causing the thickest primary eyewall among

the triplets. At 78 h, the IRBs are further suppressed, showing similarities to annular hurricanes (e.g., Knaff et al. 2003; Chu and Tan 2014).

Since the initial outer-core size of B05 is between B02 and B08, it experiences two-stage rainband activities. During 54–72 h, the convection beyond primary eyewall is dominated by IRBs at 80 km radius, forming the concentric convective ring in B05 (Fig. 4c). The BL convergence associated with IRBs is barely enhanced and the local acceleration of tangential wind is also trivial (Fig. 4d). Therefore, the concentric convective ring is not coupled with a secondary tangential wind maximum, forming a “fake SEF” during this period. During the second stage (72–90 h), with the development and contraction of ORBs from 72 h, the BL convergence and local acceleration of the tangential wind become evident, forming the secondary tangential wind maximum at 90 h (Fig. 4d, indicated by white dot line), which is weaker and later compared with that in B02. Therefore, B05 form a fake SEF at the first stage with a secondary convective ring but no associated tangential wind maximum; later on, with the development and inward-contraction of ORBs, B05 undergoes a canonical

FIG. 4. Time–radius Hovmöller diagrams of azimuthal-mean structural evolutions during 48–96 h of the triplet experiments. (a),(c),(e) Radial BL divergence (shading; -10^{-4} s^{-1}) averaged over $z = 0.2\text{--}1 \text{ km}$ overlaid by vertical velocity (contoured at 0.25, 0.5, 1.0, 2.0, 3.0, and 4.0 m s^{-1}) at $z = 5 \text{ km}$. (b),(d),(f) Tangential wind speed (shading; m s^{-1}) and its tendency (contoured at 0.5, 1.0, and $1.5 \text{ m s}^{-1} \text{ h}^{-1}$; values within 40 km are omitted) at $z = 1 \text{ km}$. Columns represent (left) B02, (center) B05, and (right) B08. The white dotted line in (c) and (d) indicates the location of secondary eyewall at the later stage in B05.

SEF similar to B02. The occurrence of the fake SEF and the canonical SEF in the two stages in B05 due to different rainbands activities also shows that the different pathways are involved in the formation of the secondary wind maximum and convective ring of the SEF.

Both the fake SEF during the first stage of B05 and no SEF in B08 confirm that a canonical secondary eyewall cannot form without the driving of ORBs. To investigate into specific process of ORBs leading up to SEF, comparisons among the triplet experiments are mainly conducted during 63–78 h period.

Radius–height cross sections of the azimuthal-mean diabatic heating rate and secondary circulation in the triplet experiments are shown in Fig. 5. In B02 the

secondary diabatic heating center associated with ORBs is situated at 120 km radius at 63 h (Fig. 5a). Radially inward, narrow regions of diabatic cooling are sandwiched between the primary eyewall and ORBs. Both the diabatic heating and secondary circulation of ORBs are weak at this moment since the ORBs are highly asymmetric and less enhanced. During 66–72 h, the BL radial inflow underneath the ORBs enhances significantly accompanied by intensified outflow above the BL (Figs. 5b,c), consistent with the strengthening BL convergence during this period (Fig. 4a). At 72 h, an ascending center atop the BL is located at the radial inside of inflow maximum of ORBs, similar with the low-level convection highlighted in Zhu and Zhu (2014).

FIG. 5. Radius–height cross sections of azimuthal-mean diabatic heating rate (shading; K h^{-1}), radial velocity (black contours; m s^{-1}), and vertical velocity (gray contours; m s^{-1}) at indicated times in the triplet experiments: (left) B02, (middle) B05, and (right) B08. The solid and dashed black lines represent radial outflow and inflow, respectively, with contours at ± 1 , ± 3 , ± 5 , ± 10 , ± 15 , and $\pm 20 \text{ m s}^{-1}$. Gray lines for the vertical velocity are plotted at 0.25, 0.5, 0.75, 1.0, 2.0, and 3.0 m s^{-1} .

Thereafter, the secondary eyewall is well developed at 80 km radius with intense diabatic heating and secondary circulation throughout the troposphere (Fig. 5d).

In B05 the radial location of the secondary diabatic heating maximum is closer to the inner-core region corresponding to the IRBs. During 63–66 h, the mean diabatic heating rate of IRBs is comparable to and even

stronger than that of the ORBs in B02 since the IRBs are more symmetrical distributed (Figs. 5e,f). However, the local enhancement of BL radial inflow of the IRBs in B05 is less obvious than that in B02 and fails to form a secondary BL inflow center (Figs. 5f,g). Therefore, the BL convergence and tangential wind in B05 are less enhanced (Figs. 4c,d). Above the BL, there is slightly

extended range of outflow and enhanced rainbands convection at midlevels between 60 and 90 km radii, forming the outer convective ring at 80 km radius (Figs. 4c and 5g). Meanwhile, the ORBs of B05 appear at 160 km radius at 72 h and mingles with the IRBs at 78 h (Fig. 5h), which maintain the outer convection associated with the canonical SEF at 90 h (not shown). Nevertheless, a portion of IRBs is merged the primary eyewall by the intense BL inflow, resulting in shallow convection in the moat region. During the fake SEF stage of B05, the most evident defect is the absence of secondary BL inflow maximum compared with that in B02. B08 is characterized by the suppressed rainbands and deepest BL inflow toward the primary eyewall. The outflow above BL associated with suppressed rainbands is much weaker and closer to the primary eyewall than B05, hence B08 have no even secondary convective-ring structure (Figs. 5i–l).

Synthesizing the evolutions of secondary eyewall in B02, three stages for the canonical SEF could be extracted. The 60–66 h period is taken as the early stage as in Qiu and Tan (2013), where asymmetric structures ORBs are focused. The 66–72 h time frame represents the developing stage for SEF since the BL radial inflow, radial convergence, and secondary wind maximum undergo rapid development during this period (Figs. 3a,b). It is worth noting that the secondary convective ring is further deepened at 72 h when the secondary tangential wind maximum is established. Afterward, the secondary eyewall enters its mature stage with the diabatic heating and secondary circulation comparable to the primary eyewall.

4. ORBs-driven boundary layer dynamics during the early stage of SEF

Since the asymmetric forcing of downwind ORBs is highlighted during the early stage of SEF (Qiu and Tan 2013; Didlake et al. 2018; Wang et al. 2019), to extract particular features of ORBs responsible for SEF, the mesoscale structures averaged over the downwind end of rainbands in the triplet experiments are compared at 63 h (Fig. 6).

In B02, the updraft core of ORBs is located between 120 and 150 km radii (Fig. 6a). Radially outward, the stratiform precipitation is remarkable over 120–180 km radii with evaporative cooling below the melting level (around height $z = 5.6$ km) (Fig. 6b). The heating structure is typical in downwind end of ORBs (e.g., Qiu and Tan 2013; Yu and Didlake 2019), which induces descending inflow intruding into the BL and sustains convection at the radial inward side. Therefore, the augmented radial gradient of diabatic heating over

120–160 km radii corresponds with a secondary radial inflow maximum within the BL (Fig. 6d). The two up-down-distributed patches of radial convergence are pronounced in the ORBs (Fig. 6c). One is located at the inner edge of secondary radial inflow maximum within BL due to the sharpened gradient of radial velocity as explained in Qiu and Tan (2013). Another is located at 1–4 km altitude between 120- and 150 km radii, which is associated with the stratiform heating structure (Didlake et al. 2018). The tangential wind jet in response to the stratiform heating is found between 1 and 3 km heights (Fig. 6e), consistent with previous studies (e.g., Moon and Nolan 2010; Didlake and Houze 2013).

While in B05, the most evident updraft and diabatic heating of the IRBs are located at 80 km radius (Figs. 6f,h). By comparison, the ORBs at 120 km are less evident thus the stratiform heating structure is much weaker compared with B02, hence the resultant descending inflow and the BL convergence are also weaker (Fig. 6h), approving the rainbands are dominated by IRBs. The radial gradient of diabatic heating around 80 km radius is much weaker than that associated with ORBs in B02, thus the corresponding BL inflow cannot form a local maximum, resulting in much weaker BL radial convergence than B02 (Figs. 6h,i). By contrast, in B08, the updraft and diabatic heating of IRBs are suppressed, resulting in minimal convergence outside the primary eyewall (Figs. 6k–o).

The distributions of BL radial inflow and radial convergence outside the primary eyewall are closely tied to different locations and structures of rainbands, which usually cause local deviation from gradient wind balance. Here, the deviation is measured by the agradient force (AGF), defined as the residuals between the radial pressure gradient force (PGF) and the Coriolis force and the centrifugal force (grouped as CFS) (Smith et al. 2009):

$$\text{AGF} = -\frac{1}{\rho} \frac{\partial P}{\partial r} + f v + \frac{v^2}{r}, \quad (2)$$

where ρ , P , and f indicate air density, pressure, and the Coriolis parameter, respectively; and v represents the tangential wind velocity. If the tangential wind is over (under) the necessary threshold for gradient wind balance, $\text{AGF} > 0$ (< 0) and the flow becomes supergradient (subgradient). The AGF as well as its PGF and CFS components are shown in Fig. 7. In B02, the positive AGF is distributed at the radial inward side along the downwind end of ORBs (Fig. 7a) while in B05 it is mainly collocated with IRBs between 60- and 80 km radii (Fig. 7d). In B08 little supergradient force is found in the outer-core region (Fig. 7g). It is worth noting that

FIG. 6. The mean mesoscale structures of downwind rainband averaged over marked sectors in Fig. 3 at 63 h in the triplet experiments: (left) B02, (center) B05, and (right) B08. (a),(f),(k) Modeled reflectivity (dBZ). (b),(g),(l) Diabatic heating rate (K h^{-1}). (c),(h),(m) Radial divergence (10^{-4} s^{-1}). (d),(i),(n) Radial wind speed (m s^{-1}). (e),(j),(o) Tangential wind speed (m s^{-1}). Black and gray contours represent positive (0.25, 0.5, 1 m s^{-1}) and negative values of vertical velocity (-0.1 , -0.2 , -0.5 m s^{-1}), respectively.

the AGF atop the BL of B05 is larger than B02 at this time, due to the radial location of IRBs being closer the primary eyewall. Taking a height–radius perspective, the positive AGF of B02 can extend to the middle portion of the BL (Fig. 7b) while the middle to lower parts

of the BL of B05 are dominated by the subgradient forces (Fig. 7e). Decomposing the AGF into individual components, the inward-pointing PGF ($-PGF$) is weakest in B02 since concentrated heating of ORBs attenuates the horizontal pressure gradient at the

FIG. 7. (top) Plan view of the agradient force (AGF; 10^{-3} m s^{-2}) at $z = 1$ km. Circles are at every 40 km radius from the storm center, with the 200 km radius is marked in black. (middle) Radius–height view of AGF (shading; 10^{-3} m s^{-2}) overlaid by the radial pressure gradient force (PGF) (blue contours; 10^{-3} m s^{-2}) area-averaged over marked sector in the top row. (bottom) As in the middle row, but overlaid by the sum of the Coriolis force and centrifugal force (CFS) (red contours; 10^{-3} m s^{-2}). Values of ± 20 and ± 60 for PGF and CFS are highlighted by bolded lines. Column are presented for (left) B02, (center) B05, and (right) B08 at 63 h. Sectors bounded by dashed lines in the top row are consistent with Fig. 3.

radially inward side (Wang 2009) (Fig. 7b). Moreover, there is elevated CFS within BL between 80 and 120 km radii associated with the tangential wind jet of ORBs (Fig. 7c). Therefore, there is net positive AGF at the upper to middle BL at the radially inward side of ORBs. Whereas in B05, the contours of CFS protrude slightly outward atop the BL of IRBs, which is related to the vertical momentum transport there (Figs. 7f and 6j). Therefore, the positive AGF in B05 is closer to the primary eyewall and confined to the upper

BL. Owing to the large PGF in the inner-core region, the flow within the BL is subgradient (Figs. 7e,f), which accelerates the BL inflow toward the primary eyewall.

In brief, during the early stage of SEF, the asymmetric forcing of ORBs arouse locally enhanced BL convergence and supergradient force at the radial inward side of ORBs, which initially fastens up the SEF region, consistent with Qiu and Tan (2013). The configuration of BL supergradient force weakens the BL radial inflow toward the primary eyewall, causing relative stagnated

rainbands radially. Instead, the convection is extended farther downwind by the tangential flow, facilitating the projection onto the azimuthal-mean state. After the supergradient force appears from 63 h, the ORBs in B02 are soon azimuthally elongated during 63–72 h (Figs. 3b–d). Therefore, the following analyses regarding the developing stage of SEF are conducted under the symmetric view.

5. Boundary layer response during the developing stage of SEF

a. Spinup of tangential wind within and above BL driven by different rainbands

As shown in Fig. 4, B02 is characterized by reinforced BL convergence and tangential wind acceleration at the radial inward side of ORBs during 66–72 h, which is absent during the IRB period in B05, forming the essential difference between the canonical SEF and fake SEF. To determine specific processes of ORBs accelerating the outer tangential wind, the tendency of tangential wind is diagnosed. The budget equations is presented as

$$\frac{\partial \bar{v}}{\partial t} = -\overline{u(\zeta + f)} - \overline{w \frac{\partial v}{\partial z}} + \overline{F_\lambda}, \quad (3)$$

$$= -\overline{u(\zeta + f)} - \overline{u'\zeta'} - \overline{w \frac{\partial v}{\partial z}} - \overline{w' \frac{\partial v'}{\partial z}} + \overline{F_\lambda}, \quad (4)$$

where u , v , and w represent radial, tangential, and vertical velocities, respectively; ζ is the vertical component of relative vorticity; and F_λ stands for the radial and tangential components of diffusion due to friction and vertical mixing. The overbar denotes the azimuthal mean and the prime denotes the asymmetric parts. Though Zhu and Zhu (2014) and Wang et al. (2019) have disputes on the relative contributions of asymmetric and symmetric parts, it is mentioned above that the supergradient force at the radially inward side of ORBs facilitates the azimuthal-mean state projection of the asymmetric forcing at the early stage. Their conflicts are much due to the different stage of SEF they focused. Here, the asymmetric and azimuthal parts are summed up since the ORBs are highly symmetric during this period.

As shown in Fig. 8, different processes are involved in the spinup of tangential wind within and above the BL, consistent with Huang et al. (2018). Within the BL, the net results between radial inward advection of absolute vorticity and BL friction dominates while above the BL, the spinup of tangential wind relies on the upward transportation of large momentum from the BL. In B02

the radial advection term peaks between 80 and 100 km radii (Fig. 8a), which corresponds to the radial inward side of the mean location of the secondary inflow center during this period. Near the surface, the radial advection term is balanced to first order by the BL diffusion as calculated in Kepert (2013) (Figs. 8c,d). In the upper part of BL where diffusion diminishes, the acceleration of tangential wind is most evident and is extended farther upward by vertical transportation (Fig. 8b). Therefore, in B02, the tangential winds increase both within and above the BL at the radially inward side of the ORBs with the maximum acceleration at 1 km height (Fig. 8d). In B05, the spinup of the tangential wind above the BL is between 60 and 80 km radii due to the vertical advection term by IRBs (Fig. 8f), which is similar with that in B02. However, the radial advection of absolute vorticity within the BL driven by IRBs in B05 fails to form the local maximum (Fig. 8e). With the evidently larger BL diffusion at smaller radii, the radial advection is persistently offset (Fig. 8g); therefore, the spinup of tangential wind within the BL is inhibited in B05 (Fig. 8h). By comparison, in B08 with suppressed rainbands, even at the top of BL there is little spinup of tangential wind outside the primary eyewall (Figs. 8i–l).

Obviously, only the ORBs promote the acceleration of tangential wind within the BL. It is principally because the ORBs fastened the SEF region away from the inner-core region where stronger BL diffusion region exists, together with the locally enhanced radial influx of absolute vorticity, the net effects accelerate the tangential wind in the middle to upper part of the BL. By comparison, the radial advection associated with IRBs in B05 is offset by BL diffusion since it situates at inner-core region.

Since the diffusion term changes slowly with time, the temporal evolutions of radial influx of absolute vorticity are compared in Fig. 9 to determine detailed processes. In B02, there is increasing inflow over the 120 km radius during the 60–66 h period (Fig. 9a). Meanwhile, the reinforced radial convergence stretches the relative vorticity at the inner edge of inflow maximum, forcing a vorticity maximum at 66 h (Fig. 9b). Thereafter, the radial influx of absolute vorticity increases nonlinearly at the inner edge of the secondary BL inflow maximum, overtaking the BL diffusion term during the inward contraction, which causes progressively spinup of the tangential wind hence the CFS at the radial inward side of ORBs (Figs. 9c,d).

In B05, the radial gradient of BL inflow associated with IRBs is much weaker than that of the ORBs in B02 (Figs. 9a,e). Although the inflow increases slightly, the relative vorticity increases little due to the BL convergence is less enhanced (Fig. 9f). Consequently, the radial

FIG. 8. Tangential velocity tendency (10^{-3} m s^{-2}) averaged over 66–72 h due to the (top) radial advection (10^{-3} m s^{-2}), (second row) vertical transportation (10^{-3} m s^{-2}), (third row) diffusion (10^{-3} m s^{-2}), and (bottom) the sum of the first three rows (10^{-3} m s^{-2}). Positive and negative values are shown in red and blue, respectively. Column correspond to (left) B02, (center) B05, and (right) B08.

advection of absolute vorticity is continuously balanced by the BL diffusion. The enhancement of tangential wind and the CFS within the BL are thus inhibited (Figs. 9g,h). The evolutions in B08 are similar to that of B05 except there is no locally enhanced BL inflow outside the primary eyewall, which represents typical single eyewall (Figs. 9i–l).

b. Increasing AGF within and above BL

Since the spinup of tangential wind in the BL results in increased CFS, the increased AGF favors the BL convergence in return. The time–height evolutions of AGF within SEF region are presented in Fig. 10. The 60–100 km radii are chosen as the SEF region for a radial average, since most of the distribution of positive AGF as well as its radial movements can be covered for the triplets.

In B02, the supergradient force appears at the top of BL from 60 h when the ORBs starting to organize. Afterward, there is significant increasing of the AGF

both atop and within the BL when the ORBs are fully developed, consistent with the spinup of tangential wind both above and within the BL in the SEF region during the developing stage (Figs. 8d and 10a). The maximum supergradient force is at the top of the BL, which is enhanced and vertically extended with time. Especially at 69 h, the supergradient force penetrates into middle to lower parts within the BL, and extends upward to 1 km height above the BL. The supergradient force within the BL decelerates the radial inflow toward the primary eyewall while the supergradient force above the BL accelerates the outflow there, reinforcing the convergence above the BL at the radially outward side (Figs. 11b,c). By comparison, in B05 the evolution of the AGF also shows two-stage feature consistent with the rainbands evolution. During 66–72 h, the supergradient force in B05 is associated with IRBs, which is confined at the upper BL and increases much slower with time compared with B02. In the middle to lower parts of the BL, the AGF maintains subgradient and

FIG. 9. Radial profiles of (a) radial velocity (m s^{-1}), (b) relative vorticity (10^{-4} s^{-1}), (c) radial advection of absolute vorticity (10^{-3} m s^{-2}), and (d) the sum of the Coriolis force and centrifugal force (CFS) (10^{-3} m s^{-2}) averaged within boundary layer ($z = 0.2\text{--}1 \text{ km}$) at different time in B02. (e)–(h), (i)–(l) As in (a)–(d), but for B05 and B08, respectively. Quantities during 60–72 h are displayed at 3 h intervals.

even decrease slightly due to the spinup of the tangential wind within the BL is inhibited under the forcing of IRBs (Figs. 8h and 10b). However, after 78 h, the AGF in B05 shows remarkable enhancement under the driven of ORBs, showing similarities with the 66–72 h period in B02. It evident that the increase of AGF near the top of the BL is related to the spiral inward propagation of ORBs. In B08 with suppressed rainbands outside the primary eyewall, the supergradient forcing is similar with the first stage in B05 but at much smaller magnitudes, thus the acceleration of the outflow above the BL is negligible (Fig. 10c). Meanwhile, B08 possesses the strongest subgradient force ($-AGF$) due to the increasing inward-pointing PGF toward the primary eyewall. Therefore, the different evolutions of AGF among the triplet during 66–72 h are largely attributed to different rainband activities, that is, ORBs, IRBs and suppressed rainbands, respectively,

certifying that the unbalanced BL response associated with the SEF is driven by ORBs instead of the overall expanding wind field.

c. Enhancement of the BL convergence and establishment of deep convection

According to above analysis, the locally reinforced BL convergence at the radially inward side of ORBs plays crucial roles during the developing stage of the SEF, for it locally stretches the BL relative vorticity thus promotes the spinup of the BL tangential wind. In return, the spinup of tangential wind causes supergradient force at the inner-side of ORBs, facilitating the BL convergence further. The systematic evolutions of them are displayed in Fig. 11.

In B02, the strengthening of BL inflow over 120 km radii during 63–66 h is associated with the inward propagation of ORBs, which reinforces the BL convergence at

FIG. 10. Height–time evolutions of agradient force (AGF) (m s^{-2}) averaged over SEF region (between the radii of 60–100 km) during 48–90 h for (a) B02, (b) B05, and (c) B08.

its radially inward side (Fig. 11a). As shown in Fig. 9 the reinforced convergence persistently stretches the relative vorticity, forming a local vorticity maximum. Afterward, the tangential wind spin up rapidly at the inward side of the inflow maximum, facilitating the supergradient force within the BL and reinforcing the BL radial convergence in return (Figs. 10a and 11b). Therefore, there is a positive feedback within the BL among enhanced supergradient force, reinforced BL radial convergence, and elevated BL vorticity, which further accelerates the BL tangential wind into the secondary wind maximum at 72 h (Fig. 11c). Meanwhile, the vertical transportation term extends the secondary tangential wind maximum farther upward, accelerating the outflow above the BL, thus augmenting the convergence above the BL at its radially outward side, which contributes to the ascending motion of the secondary convective ring (Fig. 5c). Meanwhile, the frictional-forced updraft atop the BL also contributes to the ascending motion. At 78 h, the two patches of

enhanced radial convergence are well connected throughout lowest 3 km height, accompanied by the weakened inflow and convergence of the primary eyewall, indicating the secondary eyewall matures and starts to replace the primary eyewall (Fig. 11d).

As for B05, the BL convergence associated with IRBs is located at smaller radii than B02 during the early stage (Figs. 11e,f), where the larger BL diffusion retards the spinup of the BL tangential wind as illustrated in the tangential wind budget. Therefore, the BL convergence is not further enhanced since there is no evident supergradient force within the BL. Consequently, there are no further elevated relative vorticity and local acceleration of the tangential wind, and thus the secondary tangential wind maximum fails to form. At 72 h, and the BL convergence of IRBs merges with that of the primary eyewall due to the accelerated BL inflow, making a single-eyewall structure within the BL (Fig. 11g). However, above the BL, the outflow over the connected regions of the primary eyewall and IRBs maintains the low-level convergence radially outward, forming the secondary convective ring at 80 km radius (Fig. 11h), which exhibits a fake SEF. Moreover, the occurrence of the fake SEF in B05 indicates that the formation of the secondary convective ring is different from that of the tangential wind maximum in the SEF. By comparison, in B08 there is little outflow above the BL outside the eyewall region since the upward transportation of its minimal IRBs is insufficient to produce evident supergradient force above the BL (Figs. 11i–l).

Figure 12 further shows the buildup of deep convection in SEF region. During 66–72 h in B02, the enhancement of BL convergence is accompanied by a convergence of high-equivalent potential temperature (θ_e) air between 60 and 80 km radii, which extends upward from the BL at 72 h as the BL convergence and low-level convergence connect up (Figs. 12a,b). A low-level diabatic heating between 1 and 2 km height similar with the low-level convection stressed in Zhu and Zhu (2014) is found at 80 km radius, which is related to the condensation of the high- θ_e air passing the lifting condensation level from the BL. Therefore, the development of low-level convection in SEF region is associated with the unbalanced BL process at the radial inward side of ORBs. Accumulated high- θ_e air at low-levels amplifies convective instability in SEF region. As results, the enhanced ascending motion in convective favorable environment promotes the deep convection throughout the troposphere at 78 h (Figs. 12c and 5h). While at the IRBs stage in B05, the low-level heating center outside the primary eyewall is absent since the eruption of high- θ_e air from the BL is less evident (Figs. 12d,e). Instead, the high- θ_e air is advected radially outward from the primary eyewall by the connected

FIG. 11. Radius–height distributions of azimuthal-mean divergence (shading; 10^{-4} s^{-1}), radial velocities (red and blue contours; m s^{-1}), and tangential winds (black contours in 5 m s^{-1} intervals) at the indicated time. Curves in the top section of each panel represent the radial profile of tangential wind (m s^{-1}) at 1 km height. Columns are (left) B02, (center) B05, and (right) B08.

FIG. 12. Radius–height cross sections of azimuthal-mean diabatic heating rate (shading; K h^{-1}), θ_e (colored contours; K), and wind field (vectors; m s^{-1}) at the indicated times in the triplet experiments: (left) B02, (center) B05, and (right) B08.

outflow, which enhances convective instability around 80 km radius thus maintains the secondary convective ring at 78 h (Fig. 12f). By contrast, in B08 where rainbands are suppressed, high- θ_e air is mostly trapped within primary eyewall. The sporadic developed convection beyond primary eyewall is soon filamented and moved into primary eyewall (Figs. 12h–j).

6. Discussion

A schematic diagram extracted for the canonical SEF in B02 is shown in Fig. 13. There are two main different pathways for the formation of the secondary tangential wind maximum (gray arrow, the wind-maximum pathway) and the secondary convective ring (black arrow, the convective-ring pathway), respectively, which are triggered by the downwind end of ORBs and well coupled in the canonical SEF. At the early stage of SEF, the BL radial inflow locally enhanced by the stratiform heating of ORBs reinforces BL convergence at its leading edge, which fastens up the SEF region at the

radially inward side of ORBs and initiates the two pathways. Within the BL, the BL convergence persistently stretches the BL relative vorticity, resulting in accelerated BL tangential wind as well as the supergradient force within the BL through amplified radial influx of absolute vorticity. The supergradient force within the BL sharpens the radial gradient of the BL inflow and thus reinforces the BL convergence in return. The positive feedback among the supergradient force, radial convergence, and relative vorticity within the BL leads to the pathway of the secondary tangential wind maximum. In the convective-ring pathway, the contribution of BL convergence to the ascending motion above the BL consists of two parts. Subpathway A represents the direct contribution from the frictional updraft associated with BL convergence to the ascending motion above the BL. Meanwhile, the enhanced supergradient force atop the BL through vertical advection of tangential momentum accelerates the outflow above the BL, thus reinforce the ascending motion at the radially outward side (indicated as subpathway B).

FIG. 13. Schematic diagram showing the essential dynamics of canonical SEF, which contains two basic features: the secondary convective ring (the convective-ring pathway; solid black arrow) and the secondary tangential wind maximum within the BL (the wind-maximum pathway; solid gray arrow). The pathways for each are different but well coupled in the canonical SEF, which is indicated by the two-way arrow. The process is initiated by the diabatic heating of ORBs (dashed black arrow), the locally enhanced BL inflow reinforcing BL convergence is initiated in both pathways (solid gray arrow with interior solid black arrow). In the wind-maximum pathway, the positive feedback among the BL convergence, supergradient force, and relative vorticity in the BL is crucial. In the convective-ring pathway, the contribution of the BL convergence to the ascending motion above the BL contains two parts, which are associated with the BL frictional updraft (subpathway A) and supergradient force above the BL (subpathway B). The dashed gray arrow means that the increase of positive AGF within the BL could reduce the radial inflow in the BL. A more detailed description can be found in [section 6](#).

In the canonical SEF, the development of the secondary tangential wind maximum and the enhanced secondary convective ring further strengthen the BL convergence in the SEF region, which is the jointing point of the coupling of the two pathways. Along with the two formation pathways, thermodynamics are well fitted since the spinup of BL tangential wind facilitates surface flux and the enhancing BL convergence favors the eruption of high- θ_e air, aggravating the convective instability in the SEF region.

In IRBs-driven case, the essential difference is that the BL convergence associated with IRBs is much weaker than that driven by ORBs and is situated at smaller radii with larger BL diffusion. The local increasing of relative vorticity within the BL is inconspicuous due to the weaker BL convergence. The positive feedback among the BL convergence, relative vorticity and supergradient force within the BL is thus impeded, cutting off the pathway for secondary tangential wind maximum as the radial

influx of absolute vorticity is persistently offset by the BL diffusion. However, the frictional updraft and supergradient force above the BL still promote the ascending motion above the BL, producing a fake SEF with only operation of the convective-ring pathway. The lack of unbalanced process within the BL is unfavorable for the maintenance of the BL convergence and attenuate the associated two subpathways, thus the secondary ascending motion is much weaker in the fake SEF where the two pathways are not well coupled.

It is demonstrated that the ORB-driven unbalanced BL dynamics are essential for the SEF, instead of the overall extending wind field (e.g., [Huang et al. 2012](#)), which cannot predict the location of SEF. Particularly, the ORBs fasten up the SEF region at the radially inward side of ORBs through locally enhanced BL convergence, which keeps the SEF region away from the primary eyewall, thereby ensuring that the radial influx of absolute vorticity overtakes the BL diffusion in the

middle to upper BL and accelerates the secondary tangential wind maximum. Comparing with Kepert (2013) that emphasize the one-way response in a steady-state BL model with specified vorticity forcing at the BL top, this study examines the two-way interaction between the BL and rainband processes based on the coupling of the two pathways. Furthermore, both the fictional-forced updraft associated with the BL convergence and supergradient force contribute to the ascending motion above the BL instead of an isolated mechanism.

7. Conclusions

In this study, the dynamical mechanisms of the canonical SEF are investigated. By altering the radial decaying rate of initial tangential wind only, a set of triplet experiments with different degrees of rainbands activities is conducted in an idealized full-physics simulation. It turns out that the canonical SEF with both the secondary convective ring and the secondary tangential wind maximum is driven by ORBs. On the contrary, in experiment with suppressed rainbands, neither of the two features occurred. As a transition phase, the simulation with medium initial outer-core wind speed develops a fake SEF driven by IRBs, which possesses a secondary convective ring without associated tangential wind maximum. These results demonstrate that only driven by ORBs can the canonical SEF occur. Besides, the mechanism responsible for the secondary convective ring and secondary tangential wind maximum are not equivalent, which are concluded as two pathways and are well coupled in the canonical SEF.

A key difference between the ORBs and IRBs is that the stratiform heating at the downwind end of ORBs causes locally accelerated BL inflow, which reinforces the radial convergence within the BL. The BL convergence contributes to the ascending motion above the BL through the frictional-forced updraft as well as facilitates the development of supergradient force atop the BL, which blaze the trail of the secondary convective-ring pathway. Meanwhile, the locally enhanced BL convergence persistently stretches the relative vorticity within the BL, which facilitates the development of the tangential wind and supergradient force within the BL. The supergradient force within the BL reinforces the BL convergence in return, forming a positive feedback among the supergradient force, BL convergence and relative vorticity within the BL, which is essential for the formation of the secondary tangential wind maximum. Through continuously enhanced BL convergence the two pathways are well coupled to promote a canonical SEF.

In the case of fake SEF, the BL convergence associated with IRBs is weaker and at smaller radii, which fails

to accelerate the secondary tangential wind maximum within the BL. The main cause is that the BL convergence is insufficient to stretch up the relative vorticity within the BL; therefore, the slowly increasing radial influx of absolute vorticity is overtaken by the larger diffusion term and the subgradient force within the BL is hostile to the further development of the BL convergence. Yet compared with the experiment with suppressed rainbands, the stronger supergradient force above the BL of IRBs promotes the pathway for the secondary convective ring. Therefore, in the case driven by IRBs, the two pathways are not well coupled.

In this study, the ORBs-driven unbalanced BL process based on the coupling of the two pathways that leading to SEF is emphasized. In other words, the ORB is the only driving force for the BL response associated with SEF, and fastens up the SEF region at the radially inward side of the ORBs to away from the inner-core region, where stronger BL friction region exists. Additionally, here the rainband activities are controlled by different initial wind speed beyond the RMW. It implies that TCs with larger outer-core size is favorable for SEF since larger TCs are conducive to generating stronger ORBs in outer radii. Considering the high sensitivity of ORBs activities to the environmental conditions, it can be viewed as the bridge connecting the external and internal dynamics of SEF. Exploring how external forces (e.g., vertical wind shear) affect the time and location of SEF through ORBs is the main target of further research.

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