Impacts of initial structure of tropical cyclone on secondary eyewall formation

Xuyang Ge,1,2,* Liang Guan1 and Shunwu Zhou1
1Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory of Meteorological Disaster, Nanjing University of Information Science and Technology, Nanjing, China
2Henan Key Laboratory of Agrometeorological Support and Applied Technique of China Meteorological Administration, Henan, China

Abstract
The secondary eyewall replacement cycle (ERC) is an important aspect for tropical cyclone (TC) intensity and structure forecasts. Both observational studies and idealized simulations are conducted to explore the sensitivity of secondary eyewall formation (SEF) to the initial structure of the tropical cyclone. It is found that a TC with a larger size (i.e., both the radial of maximum wind and outer size) is apt to SEF. Furthermore, a larger TC likely has a potential to form a larger outer eyewall and thus a wider moat region. The different SE structures may lead to different intensity fluctuations. This study motivates further research with respect to how initial structure influences the storm intensity and structure changes.

Keywords: secondary eyewall formation; initial structure; intensity and structure change

1. Introduction
Tropical cyclone intensity prediction is one of the most challenging problems in operational forecasting. Intense tropical cyclones often have secondary eyewalls (SE), and may experience significant intensity changes during the sequential eyewall replacement cycle (ERC) (Willoughby et al., 1982; Hawkins and Helveston, 2004; Kuo et al., 2009). Numerous studies focused on the mechanism of secondary eyewall formation (SEF) (Montgomery and Kallenbach, 1997; Nong and Emanuel, 2003; Kuo et al., 2004, 2008; Terwey and Montgomery, 2008; Zhou and Wang, 2011; Huang et al., 2012; Rozoff et al., 2012; Abarca and Montgomery, 2013; Sun et al., 2013; Wang et al., 2016). To summarize, both internal and external dynamics and thermodynamics play vital roles in the SEF: Nong and Emanuel (2003) found that finite-amplitude perturbations induced by external forcing may lead to a SEF through the wind-induced surface heat exchange (WISHE). Kuo et al. (2004, 2008) advocated that axisysmmetritzation of positive vorctity disturbances near a strong center vortex can result in SEF. Montgomery and Kallenbach (1997) addressed the role of the radially propagating vortex Rossby waves (VRW). Terwey and Montgomery (2008) put forward so-called β-skirt axisymmetriczation (BSA) mechanism. More recently, Huang et al. (2012) and Abarca and Montgomery (2013) indicated the significance of unbalanced response in the boundary layer on secondary eyewall genesis. The broadening of the tangential wind profile, with enhanced inflows and supergradient winds in the boundary layer, forces convection outside of the primary eyewall, leading to the formation of a concentric eyewall (CE). Furthermore, Sun et al. (2013) and Rozoff et al. (2012) emphasized the roles of an expanding wind field and inertial stability in SEF.

The size of SE is a fundamental factor determining the horizontal scale of the destructive winds and heavy rainfall in TCs with CEs. Recently, some studies started to examine TC intensity and structure changes during the ERC (Sitkowski et al., 2011; Zhou and Wang, 2011, 2013; Yang et al., 2013; Ge, 2015). Zhou and Wang (2013) found that the SE structures exhibit a large variability in terms of the moat size. The intensity fluctuation is closely related to the structure of SE as well. It is well realized that the TC intensification is highly sensitive to its initial wind profiles (Wang, 2009; Xu and Wang, 2010; Chen and Chan, 2014). It is pointed out that the TC size is sensitive to its initial size, mainly due to the different radial distribution of surface entropy fluxes or absolute angular momentum fluxes. However, the impact of the initial structure of TC on the sequential SEF is less apparent. Hence, this stimulates further studies on the impacts of initial structure on the SEF.

This paper is organized as follows: in Section 2, the relationship of TC initial size with SEF is examined. In Section 3, based on the observational results, a series of sensitivity experiments are designed to reveal the sensitivity of SEF to initial structure. Section 4 compares the evolution characteristics of the simulated CEs. Section 5 presents a short conclusion and discussion.
2. Observational results

A complete ERC comprises the period from the onset of SEF to the demise of the inner eyewall. Due to the lack of the conventional observations, satellite analyses are widely used to objectively identify ERC (Hawkins et al., 2006; Yang et al., 2013). In this study, the Morphed Integrated Microwave Imagery (MIMIC; 15-minute interval) at Cooperative Institute for Meteorological Satellite Studies/University of Wisconsin-Madison is used. The strong TCs over western North Pacific basin during 2005–2014 are examined, and 45 storms are identified with CEIs. Here, the SEF is defined as the deep convection of outer region covering at least two-thirds of a circle, and there is a clear moat between the inner and outer eyewall. Although this criterion is somehow subjective, the cases we found are consistent with previous studies (Yang et al., 2013; Zhou and Wang, 2013). The duration time of SEF is defined as the period from the warning time to the onset of SE. The warning duration time of SEF is defined as the period from the warning time to the onset of SE. The warning time represents the moment when the TC is given a best-track dataset from the Joint Typhoon Warning Center (JTWC).

Figure 1 displays the relationship between the formation time and initial TC structure parameters. The results show that there exists a negative correlation, which exceeds 90% significance level. In short, the larger initial TC size (both RMW and R34), the quicker SEF is. Figure 1(c) and (d) displays the bootstrapping distributions of samples. The mean value of initial RMW (R34) is about 65 (100) km, and the standard deviation is 17 (32) km, respectively. This reflects that both parameters have certain uncertainties. To validate the statistical results, idealized numerical simulations are conducted in the following sections.

3. Model and experiment designs

The version 3.3.1 of the WRF-ARW model is utilized to simulate SEF with different initial wind profiles. The model is quadruply nested with horizontal grid-spacings of 54, 18, 6 and 2 km, respectively. The Kain–Frisch convective parameterization scheme is applied to the two outermost domains, and the microphysics scheme is from Lin et al. (1983). All the simulations are on an f-plane (centered at 10°N) in a quiescent environment with a constant sea surface temperature of 29 °C. The mass and thermodynamic fields are obtained by solving the non-linear balance equation for the given wind field and sounding profile (Ge, 2015).

Provided that the SEF is sensitive to the initial wind profile of TC, two sets of idealized simulations are designed. In the first group, the modified Rankine-type vortices initially have a \( V_{\text{max}} \) of 25 m s\(^{-1}\), but with different RMWs. That is, the RMWs are specified to be 50, 70, 90, 110 and 130 km, respectively. It is worthwhile to mention that, these vortices with diverse initial RMWs have different outer sizes as well. To further reveal the impact of outer size, four storms with the same RMW but different outer sizes are designed. Specifically, in the second group, the vortices initially have the same RMW (100 km), but with different wind profiles beyond the RMW. Figure 2 shows the initial radial profiles of low-level tangential winds. These vortices are spun up for 10 days, and the model output will be compared to reveal the different evolution features.

4. Preliminary results

4.1. SEF and structure comparisons

In this section, the evolution characteristics of simulated storms are first examined. Figure 3 shows the radius-time diagrams of the azimuthally averaged tangential velocities at the height of \( z = 2 \text{km} \). In the first group, all of the storms experience SEF during the period of interest, since the tangential wind fields evolve into a configuration where a secondary maximum is evident at a certain radius. Once the outer eyewall forms, the storm does not significantly intensify and sometimes even weakens. Along with the inner eyewall’s demise, the outer eyewall becomes the primary one, thereby completing an ERC. Of particular interest, there appears to be significant differences in the timing of SEF. The SEF occurs the quickest in RMW130, and the slowest in RMW50. More specifically, the formation time is about 202 (107) hours in RMW50 (RMW130), respectively. The other three storms are in between. The result indicates that the onset of SE is closely related to the initial structure of TC, which is consistent with the aforementioned observational studies. Moreover, there exist salient differences in the SE structures. For instance, the SE is located at the radius of 100 km in RMW130, which is farther away from the center than that in RMW50 (about 80 km).

For the second group, the results generally bear many similarities to the first group. Interestingly, SEF occurs in the cases with larger outer size, but no SEF occurs in OUT4 in which the storm has the smallest outer size. Furthermore, the SEF is much delayed in the cases with smaller outer size. For instance, the SEF appears much earlier (i.e. \( t = 126 \text{h} \)) in OUT1, which is much shorter than that in OUT3 (i.e. \( t = 172 \text{h} \)).

Table 1 summarizes the associated intensity and structure changes during ERCs. It clearly shows that the initial larger TC has a potential to build up a larger SE. Accompanied with marked differences in both onset and structure of SEs, the intensity changes and duration of ERCs show some variations. The duration of ERCs ranges between 6 and 14 hours. In RMW130,
Figure 1. Relationships of SEF timing with initial RMW (a) and initial R34 (b). The numbers represent the correlation coefficients. (c) and (d) correspond respectively to the bootstrap distributions.

4.2. Possible physical mechanisms
Numerous studies (Huang et al., 2012; Abarca and Montgomery, 2013) found that the broadening of the tangential wind field and radial pressure gradient force at the top of the boundary layer play important roles in the SEF. The unbalanced response in the boundary layer leads to a narrow supergradient wind zone outside the primary eyewall, which helps build up an outer eyewall. Following these previous studies, the boundary layer mechanism is measured by the imbalance between the local radial pressure gradient and the sum of the centrifugal and Coriolis forces in the radial
Figure 2. Initial wind profiles in the first group with different initial RMWs (left panel) and the second group with different outer size (right panel).

Figure 3. The radius-time cross-section of the azimuthally averaged tangential velocities (m s$^{-1}$) at $z = 2$ km in all the experiments.

The radius-time cross-section of the azimuthally averaged tangential velocities (m s$^{-1}$) at $z = 2$ km in all the experiments.

The momentum equation, i.e.

$$AF = -\frac{1}{\rho} \frac{\partial p}{\partial r} + f \overline{v} + \frac{v^2}{r}$$

where $p$ is the pressure, $\rho$ is the air density, $f$ is the Coriolis parameter, $r$ is the radial distance and $v$ is the tangential velocity. The overbar represents the azimuthal mean. When the agradient force (AF) = 0, the tangential flow is in exact gradient wind balance. Around the top of the boundary layer, a positive supergradient flow (AF > 0) indicates an enhancement of the outflow away from the vortex center. On the contrary,
the subgradient flow (AF < 0) implies that there exists a tendency to enhance the inflows towards the vortex center.

For brevity, RMW50 and RMW130 are selected as examples. Figure 4 presents the sequences of structural changes and the associated boundary layer imbalances. In general, the radially outward AF (positive value) emerges in the boundary layer. Within this region, this positive AF strengthens with time. Meanwhile, a region of convergence is associated with the development of supergradient winds, a rapid deceleration of the inflow, and an eruption of air out of the boundary layer to support deep convection. These properties agree well with the spatial distribution and evolution of supergradient winds (Huang et al., 2012). The analysis confirms that the unbalanced boundary layer and its coupling to the interior flow are important processes for the SEF. For other cases with SEF, they show similar evolution characteristics, except for different radial locations of the supergradient zone (not shown). Notice the different behaviors of supergradient forces in RMW50 and RMW130. It is obvious that the onset of positive AF in RMW130 is much earlier than that in RMW50. In short, for a TC with a larger initial RMW and outer size, it is quicker to build up a radially outward AF region and thus a SEF.

As pointed out by Xu and Wang (2010), surface entropy fluxes outside the eyewall favor the large convective available potential energy (CAPE) and thus outer convection such as spiral rainbands. In turn, the latent heating released in the outer region plays a key role in increasing the low-level radial inflow and accelerating the tangential winds outside the eyewall, leading to outward expansion of tangential wind fields. In conjunction with the acceleration of the tangential winds, the inertial stability parameter will be enhanced gradually. As a result, it further helps the conversion from diabatic heating to kinetic energy, and then leads to a secondary maximum wind (Rozoff et al., 2012). To this end, the time evolution of diabatic heating and inertial stability is examined. As anticipated, for the cases with larger RMW, large inertial stability emanates more quickly at the outer region coincided with the outer diabatic heating (not shown). It is reasonable to expect that, SEF ultimately arises from the

---

**Table 1. Comparisons of intensity and structure changes during the ERCs.**

| Experiment symbols | SEF timing (hour) | duration time (hour) | Moat size (km) | Intensity change (m s⁻¹) |
|--------------------|------------------|----------------------|----------------|-------------------------|
| RMW50             | 202              | 6                    | 38             | −12.8                  |
| RMW70             | 156              | 8                    | 40             | −13.3                  |
| RMW90             | 133              | 9                    | 50             | −13.9                  |
| RMW110            | 121              | 12                   | 54             | −14.2                  |
| RMW130            | 107              | 14                   | 58             | −14.9                  |
| OUT1              | 126              | 11                   | 53             | −13.9                  |
| OUT2              | 144              | 10                   | 40             | −13.5                  |
| OUT3              | 172              | 8                    | 33             | −10.8                  |

---

**Figure 4.** The sequences of structural changes and boundary layer imbalances in RMW50 (top panels) and RMW130 (bottom panels). The contours are the axisymmetric component of tangential wind velocity (m s⁻¹), positive AFs are shaded, and vectors are radial circulation.
convective heating released from the outer rainbands, the balanced response in the transverse circulation, and the unbalanced dynamics in the atmospheric boundary layer, along with the positive feedback among these processes (Sun et al., 2013; Wang et al., 2016).

5. Conclusion and discussion

In this study, the impacts of the initial structure of a TC on the SEF are examined by using both observational comparisons and idealized numerical simulations. It is found that the SEF is highly sensitive to the initial structure of a TC. When a TC has a larger initial RMW and outer size, it has a greater potential to establish an SE. Meanwhile, the SE tends to be located at a larger radius, and thus the TC has a wider moat region. The idealized simulations reveal that the TC with a larger outer eyewall usually experiences more significant intensity changes, which is consistent with previous results (Zhou and Wang, 2013; Ge, 2015). It is expected that different wind profiles lead to dissimilar inertial stability and thus affect the development of outer convection. The broadening of the tangential wind field and the unbalanced boundary layer process play vital roles in the SEF. Admittedly, the numerical experiments are performed under highly idealized environmental conditions. In the future, examination of complicated environmental flows should be conducted to more completely understand how initial structure influences the storm dynamics and thermodynamics.

Acknowledgements

This work is jointly sponsored by the National Science Foundation of China (Grant No. 41575056), Key Basic Research Program of China (Grant No. 2015CB452803), China Meteorological Administration Henan Key Laboratory of Agrometeorological Support and Applied Technique (Grant No. AMF201403), the Key University Science Research Project of Jiangsu Province (Grant No.14KJA170005) and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

References

Abarca SF, Montgomery MT. 2013. Essential dynamics of secondary eyewall formation. Journal of the Atmospheric Sciences 70: 3216–3230.
Chan TF, Chan CL. 2014. Impacts of initial vortex size and planetary vorticity on tropical cyclone size. Quarterly Journal of the Royal Meteorological Society 140: 2235–2248.
Ge X. 2015. Impacts of environmental humidity on concentric eyewall structure. Atmospheric Science Letters 16: 273–278, doi: 10.1002/asl2.553
Hawkins JD, Helveston M. Tropical cyclone multiple eyewall characteristics. 26th Conf. on Hurricane and Tropical Meteorology, Miami, FL, Amer. Meteor. Soc. 2004.
Hawkins JD, Helveston M, Lee TF, Turk FJ, Richardson K, Sampson C, Kent J, Wade R. 2006. Tropical cyclone multiple eyewall configurations. Preprints. 27th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society: Monterey, CA.
Huang Y-H, Montgomery MT, Wu C-C. 2012. Concentric eyewall formation in Typhoon Sinlaku (2008). Part II: axisymmetric dynamical processes. Journal of the Atmospheric Sciences 69: 662–674.
Kuo H-C, Lin L-Y, Chang C-P, Williams RT. 2004. The formation of concentric vorticity structures in typhoons. Journal of the Atmospheric Sciences 61: 2722–2734.
Kuo H-C, Schubert WH, Tsai C-L, Kuo Y-F. 2008. Vortex interactions and barotropic aspects of concentric eyewall formation. Monthly Weather Review 136: 5183–5198.
Kuo H-C, Chang C-P, Yang Y-T, Jiang H-J. 2009. Western North Pacific typhoons with concentric eyewalls. Monthly Weather Review 137: 3758–3770.
Lin YL, Rarley RD, Orville HD. 1983. Bulk parameterization of the snow field in a cloud model. Journal of Applied Meteorology 22: 1065–1092.
Montgomery MT, Kallenbach RJ. 1997. A theory for vortex Rossby waves and its application to spiral bands and intensity changes in hurricanes. Quarterly Journal of the Royal Meteorological Society 123: 435–465.
Nong S, Emanuel K. 2003. A numerical study of the genesis of concentric eyewalls in hurricanes. Quarterly Journal of the Royal Meteorological Society 129: 3323–3338.
Rozoff CM, Nolan DS, Kossin JP, Zhang FQ, Fang J. 2012. The roles of an expanding wind field and inertial stability in tropical cyclone secondary eyewall formation. Journal of the Atmospheric Sciences 69: 2621–2643.
Sitkowski M, Kossin JP, Rozoff CM. 2011. Intensity and structure changes during hurricane eyewall replacement cycles. Monthly Weather Review 139: 3829–3847.
Sun YQ, Jiang Y, Tan B, Zhang FQ. 2013. The governing dynamics of the secondary eyewall formation of typhoon Sinlaku (2008). Journal of the Atmospheric Sciences 70: 3818–3837.
Terwey WD, Montgomery MT. 2008. Secondary eyewall formation in two idealized, full-physics modeled hurricanes. Journal of Geophysical Research 113: D12112, doi: 10.1029/2007JD008897.
Wang Y. 2009. How do outer spiral rainbands affect tropical cyclone structure and intensity? Journal of the Atmospheric Sciences 66: 1250–1273.
Wang H, Wu C-C, Wang Y. 2016. Secondary eyewall formation in an idealized tropical cyclone simulation - Balanced and unbalanced dynamics. Journal of the Atmospheric Sciences in press.
Willoughby HE, Clos JA, Shoreibah MG. 1982. Concentric eyewalls, secondary wind maxima, and the evolution of the hurricane vortex. Journal of the Atmospheric Sciences 39: 395–411.
Xu J, Wang Y. 2010. Sensitivity of the simulated tropical cyclone inner-core size to the initial vortex size. Monthly Weather Review 138: 4135–4157.
Yang YT, Kuo HC, Hendricks EA, Peng MS. 2013. Structural and intensity changes of concentric eyewall typhoons in the Western North Pacific Basin. Monthly Weather Review 141: 2632–2648.
Zhou X, Wang B. 2011. Mechanism of Concentric eyewall replacement cycles and associated intensity change. Journal of the Atmospheric Sciences 68: 972–988.
Zhou X, Wang B. 2013. Large-scale influences on secondary eyewall size. Journal of Geophysical Research 118: 11088–11097.