The Role of Boundary Layer Dynamics in Tropical Cyclone Intensification. Part II: Sensitivity to Initial Vortex Structure

Tsung-Han LI

*Department of Atmospheric Sciences and International Pacific Research Center,
University of Hawai'i, Hawai'i, USA*

and

Yuqing WANG

*Department of Atmospheric Sciences and International Pacific Research Center,
University of Hawai'i, Hawai'i, USA
State Key Laboratory of Severe Weather (LaSW), Chinese Academy of Meteorological Sciences,
China Meteorological Administration, China*

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Abstract

In Part I of this series of studies, we demonstrated that the intensification rate of a numerically simulated tropical cyclone (TC) during the primary intensification stage is insensitive to the surface drag coefficient. This leads to the question of what is the role of the boundary layer in determining the TC intensification rate given sea surface temperature and favorable environmental conditions. This part attempts to answer this question based on a boundary layer model and a full-physics model as used in Part I. Results from a boundary layer model suggest that TCs with a smaller radius of maximum wind (RMW) or of lower strength (i.e., more rapid radial decay of tangential wind outside the RMW) can induce stronger boundary layer inflow and stronger upward motion at the top of the boundary layer. This leads to stronger condensational heating inside the RMW with higher inertial stability and is thus favorable for a higher intensification rate. Results from full-physics model simulations indicate that the TC vortex initially with a smaller RMW or of lower strength has a shorter initial spinup stage due to faster moistening of the inner core and intensifies more rapidly during the primary intensification stage. This is because the positive indirect effect of boundary layer dynamics depends strongly on vortex structure, but the dissipation effect of surface friction depends little on the vortex structure. As a result, the intensification rate of the simulated TC is very sensitive to the initial TC structure.

Keywords tropical cyclone; typhoon; intensity change; boundary layer dynamics; tropical cyclone structure

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Corresponding author: Yuqing Wang, Department of Atmospheric Sciences and International Pacific Research Center, University of Hawai'i, Room 404A, IPRC/SOEST, 1680 East-West Road, Honolulu, HI 96822, USA
E-mail: yuqing@hawaii.edu
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1. Introduction

In Part I of this series, two models were used to examine how boundary layer dynamics affect the amplitude and radial location of eyewall updraft/convection to control tropical cyclone (TC) intensification (Li and Wang 2021). Results from a boundary layer model suggest a possible pathway by which the boundary layer dynamics contribute to eyewall contraction and TC intensification, which we referred to as a positive indirect effect¹ of boundary layer dynamics on TC intensification. There are four sequential interactive processes: (1) The frictional boundary layer inflow responds to the radial distribution of gradient wind above the boundary layer; (2) the boundary layer inflow, as a function of surface drag coefficient (C_D) and radial distribution of gradient wind above the boundary layer, determines the amplitude and radial location of the frictional eyewall updraft; (3) the frictional updraft at the top of the boundary layer affects both the amplitude and radial location of condensational heating in the eyewall; and (4) condensational heating in the eyewall in response of the boundary layer dynamics to the gradient wind distribution above the boundary layer changes contraction of the radius of maximum wind (RMW) and intensification of the TC.

Results from a boundary layer model demonstrate that the storm with a larger C_D (thus larger surface friction) corresponds to the stronger and more inwardly penetrated boundary layer inflow and upward motion at the top of the boundary layer inside RMW. Results from a full-physics model support the indirect effect of surface friction where a larger C_D together with the associated boundary layer dynamics induces stronger and more inwardly penetrated boundary layer inflow and eyewall convection inside the RMW with higher inertial stability. This contributes positively to the TC intensification as inferred from the balanced vortex dynamics (e.g., Schubert and Hack 1982; Vigh and Schubert 2009). However, the enhanced positive indirect effect due to an increased C_D is often largely offset by the enhanced negative dissipation effect of surface friction, resulting in insensitivity of the simulated TC intensification rate to C_D . Based on the results in Part I, the amplitude and radial location of frictional eyewall updraft can be largely determined

by boundary layer dynamics given the radial distribution of gradient wind above the boundary layer (see also Kepert 2013, 2017). However, because the main objective in Part I is to address why the simulated TC intensification rate is insensitive to C_D , the question remains how the initial structure of the TC vortex may affect the amplitude and radial location of the frictional eyewall updraft in response to boundary layer dynamics and, thus, the TC intensification rate, which we address here.

The impact of the vortex structure on TC intensification has received considerable attention in previous studies (Rotunno and Emanuel 1987; Chen et al. 2011; Rogers et al. 2013; Carrasco et al. 2014; Xu and Wang 2015, 2018a, b). Based on the best-track data for the western North Pacific, Chen et al. (2011) found that higher intensification rates are favored for compact TCs (small RMW, small average 34-kt wind radius, or both). They found that the compact TCs with strong convection concentrated near their centers had a higher occurrence of rapid intensification relative to the less compact TCs. Similar to the results in Chen et al. (2011), Carrasco et al. (2014) found that the rapid intensification depends significantly on the initial size (including the RMW and average 34-kt wind radius) of the TC in the North Atlantic. A comparison between rapid and non-rapid intensification TCs suggests that TCs that undergo rapid intensification tend to be initially smaller than TCs that intensify non-rapidly. Based on the same database, Xu and Wang (2015) found that the intensification rate of TCs increases with decreasing RMW because of the higher inner-core inertial stability for TCs with smaller RMW. They also demonstrated that storms with a larger radius of gale force wind are unfavorable for rapid intensification. Similar results are also found for western North Pacific TCs (Xu and Wang 2018a).

To understand the physical processes responsible for an observed dependence of the TC intensification rate on TC structure, Xu and Wang (2018b) conducted idealized ensemble sensitivity experiments using the axisymmetric full-physics model (Bryan and Rotunno 2009) and examined the impact of the initial vortex structure on the initial spinup and the primary intensification of the simulated TC. They demonstrated that the initial spinup stage is shorter, and the intensification rate is higher during the primary intensification stage for a TC vortex with an initially smaller RMW or weaker winds outside the RMW. Xu and Wang (2018b) found that the weaker Ekman pumping in a vortex with a larger RMW, or of higher strength (i.e., slower radial decay of tangential wind outside the

¹ In Part I, we used “indirect effect” to represent this boundary layer dynamical control on updraft and condensational heating in the TC eyewall because the direct effect of surface friction is traditionally considered to be dissipation to kinetic energy of the TC system.

RMW) and thus higher inertial stability outside the RMW, slowed down the moistening of the inner core, leading to a longer initial spinup period. The lower inertial stability in the inner core in a vortex with a larger RMW, or the higher inertial stability outside the RMW in a vortex of higher strength, slowed down the intensification during the primary intensification stage. They explained these results mainly based on the quasi-balanced vortex dynamics (Schubert and Hack 1982; Pendergrass and Willoughby 2009).

In this study, we will give an alternative explanation for the dependence of the intensification rate of a simulated TC on the initial vortex structure based on the boundary layer dynamics as discussed in Part I. It is our hypothesis that the indirect effect of boundary layer dynamics on TC intensification depends considerably on the TC structure, whereas the dissipation effect of surface friction depends primarily on TC intensity but little on the TC structure. As a result, the intensification rate of a simulated TC during its primary intensification stage should be largely determined by the structure of the initial TC vortex through the indirect effect of surface friction. This hypothesis will be verified based on results from a series of numerical experiments using both the boundary layer model and the full-physics model already introduced in Part I. The experimental design is briefly given in Section 2. Results from the boundary layer model and full-physics model are discussed in Sections 3 and 4, respectively. Our main conclusions from this study are summarized in Section 5.

2. Experimental design

2.1 Experiments with the multi-level boundary layer model

The multi-level axisymmetric TC boundary layer model was introduced in detail in Part I (Li and Wang 2021). The model can be used to examine the boundary layer response to a prescribed pressure gradient force that represents the gradient wind distribution at the model top. The modified parametric TC tangential wind profile (Wood and White 2011; Wood et al. 2013), which was given in Eqs. (2) and (3) in Li and Wang (2021), was used for all experiments in the boundary layer model. Because we attempt to understand how the simulated TC intensification rate depends on the initial vortex structure, different values of the RMW and the decaying parameter b for the tangential wind speed outside the RMW were used in the boundary layer model. Two groups of sensitivity experiments were conducted. In the first group, the R_m varied from 20 km to 100 km with an interval of 1 km

Fig. 1. Radial profiles of the initial tangential wind speed used in sensitivity experiments in the boundary layer model for (a) storm strength [$b = 1$ (black) and $b = 0.4$ (gray)] and (b) storm RMW ($R_m = 20$ km, black, and $R_m = 100$ km, gray).

(81 cases in total) and $b = 1.0$. In the second group, b varied from 0.4 to 1.0 with an interval of 0.05 (13 cases in total) and $R_m = 40$ km. A smaller decaying parameter b indicates a slower radial decay rate of tangential wind outside the RMW, which indicates higher strength. All experiments were integrated for 12 hours when a steady-state was reached. Several examples of the radial distribution of the tangential wind speed specified at the model top in the boundary layer model experiments are provided in Fig. 1.

2.2 Experiments with the TC model version 4

The full-physics TC model version 4 (TCM4), developed by Wang (2007), was used to conduct a series of sensitivity experiments. A brief description of the model was given in Part I (Li and Wang 2021), and a more complete description and the application

Table 1. Summary of numerical experiments for the initial TC structure performed using TCM4.

Experiment	b	Maximum tangential wind speed (m s^{-1})	RMW (km)
R041	1.0	20	40
R061	1.0	20	60
R101	1.0	20	100
b055	0.5	25	75
b075	0.7	25	75
b105	1.0	25	75

of TCM4 to TC studies can be found in the literature (e.g., Wang 2007, 2008a, b, 2009; Wang and Xu 2010; Xu and Wang 2010a, b; Wang and Heng 2016; Heng and Wang 2016; Heng et al. 2017). The model was initialized with an idealized axisymmetric cyclonic vortex, which has a surface radial profile of tangential wind given in (7) in Li and Wang (2021).

To address how the structure of the initial TC vortex may affect the intensification rate of a simulated storm through condensational heating largely controlled by boundary layer dynamics, similar to the sensitivity experiments using the boundary layer model, we ran two groups of sensitivity experiments. The experiments were conducted by varying either the RMW or the decaying parameter of tangential wind outside the RMW in the initial conditions (Table 1). In the sensitivity experiments to the RMW, the initial vortex had the maximum tangential wind speed $V_m = 20.0 \text{ m s}^{-1}$ at $R_m = 40$ (R041) km, 60 (R061) km, and 100 (R101) km with $b = 1.0$. In the sensitivity experiments to the vortex strength, the radial decaying parameter b in (14) in Li and Wang (2021) was set to be 0.5 (b055), 0.7 (b075), and 1.0 (b105), with the maximum tangential wind speed $V_m = 25.0 \text{ m s}^{-1}$ at $R_m = 75$ km. A smaller decaying parameter b indicates a lower radial decay rate of tangential wind outside the RMW, which corresponds to a TC vortex of higher strength. Figure 2 compares the radial distributions of the initial tangential wind speed and inertial stability of the two groups of TC vortices with different RMWs and strengths. The storm with a smaller RMW (Fig. 2a) has higher inertial stability in the inner-core region but has lower inertial stability outside the RMW (Fig. 2b). A storm of lower strength (larger b , Fig. 2c) has lower inertial stability outside the RMW and has the same inertial stability in the inner-core region inside the RMW (Fig. 2d). All experiments were integrated for 180 h, but the following analyses will focus on the initial spinup stage and the primary intensification stage. Here, the initial spinup stage refers to the initial period prior to

the primary intensification stage; refer to Part I in Li and Wang (2021) for a brief definition.

Note that some parameters such as C_D and radial tangential wind distribution used in the boundary layer model and TCM4 are not the same. Although the comparison could be straightforward if the same wind distribution and C_D were used, any direct comparison between the two models would be impossible because of the interactive nature of the full-physics model, in which the TC structure and intensity evolve with time. The main purpose of using the boundary layer model is to highlight the dynamical processes in a qualitative manner rather than to make a side-to-side quantitative comparison with the full-physics model simulations. Nevertheless, some extra experiments using the boundary layer model forced by the azimuthal mean pressure gradient force from the full-physics model experiments, similar to those conducted by Kepert and Nolan (2014), Zhang et al. (2017), and Stern et al. (2020), were also conducted and are discussed in Section 4.

3. Results from the boundary layer model

Figure 3 illustrates the radius-height cross sections of tangential and radial winds, vertical relative vorticity, and vertical motion for a storm in response to the prescribed radial distribution of gradient wind with default $R_m = 40$ km and $b = 1.0$, a lower radial decay rate of tangential wind outside the RMW ($b = 0.4$, higher strength), and a larger RMW ($R_m = 60$ km) at the model top, respectively. Comparing Figs. 3a and 3c, we can see that the boundary layer inflow near the RMW is weaker and shallower in the higher-strength vortex than in the lower-strength vortex. This is because the former has relatively larger inertial stability outside the RMW and thus receives greater resistance to the frictionally induced inflow. As a result, the boundary layer inflow in the higher-strength TC vortex is weaker and extends more broadly to outer radii (Fig. 3c). This leads to the reduction of the radial gradient of both tangential and radial winds and thus weaker vertical relative vorticity and vertical motion (Figs. 3b, d). These results are generally consistent with those of Kepert and Wang (2001). Note that the vertical relative vorticity in the higher-strength vortex is more broadly distributed, and the pattern is closer to a monopole than to a ring structure in the boundary layer (Fig. 3d). The weaker vertical motion in the higher-strength vortex may be less favorable for rapid intensification because of less condensational heating in the eyewall. This is consistent with the results of Rogers et al. (2013), who compared the intensifying

Fig. 2. Radial distribution of (a), (b) initial tangential wind speed (m s^{-1}) and inertial stability (10^{-4} s^{-2}) in R041 ($R_m = 40 \text{ km}$, red), R061 ($R_m = 60 \text{ km}$, blue), and R101 ($R_m = 100 \text{ km}$, magenta), and (c), (d) initial tangential wind speed (m s^{-1}) and inertial stability (10^{-4} s^{-2}) in b055 ($b = 0.5$, magenta), b075 ($b = 0.7$, blue), and b105 ($b = 1$, red).

TC group with the steady-state TC group and found that intensifying TCs often indicated a lower-strength structure with stronger convection inside the RMW.

Similar to a storm of higher strength, the boundary layer inflow, the vertical motion, and vertical relative vorticity are weaker in the vortex with a larger RMW (Figs. 3e, f) than in the vortex with a smaller RMW (Figs. 3a, b). An interesting result is the more inwardly displaced upward motion and relative vorticity ring relative to the RMW in the vortex with the larger RMW than in the vortex with the smaller RMW (Figs. 3b, f). This result is consistent with the finding of Kepert (2017), who hypothesized that this may explain why TCs with a larger RMW may contract more rapidly during their early intensification stage and that the contraction of the RMW often slows down in the later intensification stage after the RMW becomes small. Kepert (2017) also found that the frictional eyewall updraft displaced to the inward side of the

RMW by a distance scaled by $-u_{10}/I$ (where u_{10} is 10 m height radial wind, and I is the inertial stability parameter in the inner core).

To give an overall description of the dependences of the boundary layer response on both the RMW and the vortex strength, Fig. 4 presents the minimum radial wind speed (maximum inflow), the maximum vertical motion at the top of the inflow boundary layer, and the inward displacement of the eyewall updraft relative to the initial RMW from all sensitivity experiments using the boundary layer model. A storm of lower strength corresponds to a stronger boundary layer inflow along with stronger and more inwardly displaced frictional updraft inside the RMW at the top of the inflow boundary layer. By contrast, a storm with a smaller RMW also corresponds to a stronger boundary layer inflow and stronger frictional eyewall updraft, although the inward displacement is smaller with the storm with a smaller RMW. A storm with a

Fig. 3. Radius-height cross sections of (a, c, e) tangential (shaded; m s^{-1}) and radial wind speeds (contours; m s^{-1}) and (b, d, f) vertical vorticity (shaded; 10^{-4} s^{-1}) and vertical velocity (contours; with a contour interval of 2 m s^{-1}) for (a, b) default vortex, (c, d) higher strength ($b = 0.4$), and (e, f) a larger RMW ($R_m = 60 \text{ km}$) in the steady-state response in the boundary layer model.

smaller RMW has a smaller inward displacement due to its higher inertial stability near and inside the RMW (see Fig. 2b). Note that the greater inward displacement does not imply a more rapid intensification of the storm with an initially larger RMW because of the

lower inertial stability inside the RMW and weaker frictional eyewall updraft. Therefore, based on the results of Li and Wang (2021), a storm of lower strength or with a smaller RMW favors stronger eyewall convection inside the RMW and thus may intensify more

Fig. 4. Dependence of the maximum radial wind speed (solid, left ordinate, m s^{-1}) and the maximum vertical velocity (dashed, right ordinate, m s^{-1}) near the top of the boundary layer (at the 866 m height) and dependence of the inward displacement of the frictional eyewall updraft (km) at the same height relative to the initial RMW on (a, c) the initial vortex strength inferred from the decaying parameter b and (b, d) the initial RMW (km) in the steady-state response in the boundary layer model. Positive values of Δr indicate an inward displacement.

rapidly as inferred from the balanced vortex dynamics (Schubert and Hack 1982; Vigh and Schubert 2009). This will be further demonstrated with results from the full-physics model TCM4 in the next section.

4. Results from the full-physics model TCM4

4.1 Sensitivity to the initial RMW

Figure 5 compares the time evolutions of maximum azimuthal mean 10 m height tangential wind speed, RMW, and the intensification rate in all three sensitivity experiments with varying RMW of the initial TC vortex. It took approximately 12 h for the storm with an initially smaller RMW in R041 to spin up, whereas storms with an initially larger RMW had a longer spinup period of approximately 18 h in R061 and of 24 h in R101. After the initial spinup stage, the storm

with a smaller RMW intensified more rapidly during the primary intensification stage. The RMWs in all three experiments experienced a contraction during the spinup stage and primary intensification stage but did not change much during the quasi-steady stage. Note that the TC structure changed with time in the simulations (Fig. 5b), whereas the overall structural difference among these three storms was still distinct. In Fig. 5c, the storm with the smallest initial RMW in R041 had a substantially higher intensification rate [approximately $50 \text{ m s}^{-1} (24 \text{ h})^{-1}$] than the storms in either R061 or R101 [approximately $30 \text{ m s}^{-1} (24 \text{ h})^{-1}$ and $20 \text{ m s}^{-1} (24 \text{ h})^{-1}$, respectively]. The storm with the largest initial RMW in R101 took approximately 60 h to reach its maximum intensification rate, whereas storms in R061 and R041 took only approximately

Fig. 5. Time evolution of (a) the maximum azimuthal mean 10-m height tangential wind speed (m s^{-1}), (b) the RMW (km), and (c) the intensification rate [$\text{m s}^{-1} (24 \text{ h})^{-1}$] with a 5 h running mean in R041 ($R_m = 40 \text{ km}$, red), R061 ($R_m = 60 \text{ km}$, blue), and R101 ($R_m = 100 \text{ km}$, magenta).

36 h and 30 h, respectively. These results suggest that a TC vortex with the initially smaller RMW corresponds to the shorter initial spinup stage and higher intensification rate during the primary intensification stage. The faster initial moistening/saturation of the inner core in R041 is associated with stronger upward motion primarily due to stronger boundary layer inflow and larger moisture convergence and Ekman pumping (Fig. 6). In addition, the storm with an initially smaller RMW had a smaller volume in the inner core, which could be moistened in a shorter time period, and established convection in the inner-core region earlier. These are consistent with many previous studies using both axisymmetric and three-dimensional models (e.g., Rotunno and Emanuel 1987; Emanuel 1989, 1995; Kilroy and Smith 2017; Miyamoto and Nolan 2018; Xu and Wang 2018b).

After the initial spinup stage, the storms started their primary intensification stage after the averaged relative humidity in their inner-core region reached approximately 90 % in all three experiments, which is consistent with the results in Part I. During the primary intensification stage, the averaged vertical motion in the inner-core region was the fastest (approximately 50 cm s^{-1}) in R041, compared with approximately 30 cm s^{-1} in R061 and 20 cm s^{-1} in R101. Unlike the effect of boundary layer dynamics on the initial spinup stage, which can accelerate moistening in the inner-core region, the boundary layer dynamics during the primary intensification stage primarily enhanced condensational heating in the region with higher inertial stability inside the RMW.

Figure 7 compares the radial inflow and condensational heating rate together with the inertial stability averaged in 3 hours prior to the primary intensification stage in all three RMW experiments. As expected, the storm with an initially smaller RMW induced stronger inflow and upward motion inside the RMW (Fig. 7a) and had a higher condensational heating rate in the region with higher inertial stability (Fig. 7b). However, both the condensational heating rate and inertial stability were lower inside the RMW in R101 (Fig. 7f). These are consistent with the results in Section 3, which suggest that a storm with an initially smaller RMW could induce stronger frictional eyewall updraft inside the RMW through the boundary layer dynamics (cf. Figs. 3b, f). Stronger condensational heating in the higher inertial stability region implies higher dynamical efficiency to spin up the low-level tangential wind and thus a higher intensification rate of the storm (Schubert and Hack 1982; Pendergrass and Willoughby 2009; Xu and Wang 2018b). Note that the eyewall

Fig. 6. Time-height cross sections of relative humidity (shaded, %) and vertical velocity (contours, cm s^{-1}), both averaged within the radius of 1.5 times of the RMW in (a) R041 ($R_m = 40$ km), (b) R061 ($R_m = 60$ km), and (c) R101 ($R_m = 100$ km). The vertical green dashed line in each panel shows the time when the initial spinup stage ends in the corresponding experiment.

updraft and absolute angular momentum surface were more upright in a smaller RMW storm (R041) than in a larger RMW storm (R101), which is consistent with the observational results (Stern and Nolan 2009; Stern et al. 2014) (not presented). Similarly, the eyewall convection (condensational heating) is located inside the RMW in both R041 and R101.

4.2 Sensitivity to the initial vortex strength

The vortex strength is another important parameter that may affect the intensification rate of a TC, as

discussed in Section 3 and studied by Xu and Wang (2018a, b). Figure 8 compares the time evolutions of maximum azimuthal mean 10 m height tangential wind speed, RMW, and the intensification rate in the three sensitivity experiments for different initial vortex strengths. Similar to the evolution of the initially smaller RMW TC, the storm in b105 intensified a few hours earlier; that is the initial spinup stage was shorter than the other two TCs of initially higher strength. The storm with an initially lower strength in b105 had a slightly higher intensification rate during the primary

Fig. 7. Radius-height cross sections of the azimuthal mean radial wind speed (left shaded, m s^{-1}) and vertical velocity (left contours, m s^{-1}), and condensational heating rate (right shaded, K h^{-1}) and inertial stability (right contours, 10^{-4} s^{-1}) for R041 [(a, b) $R_m = 40 \text{ km}$], R061 [(c, d) $R_m = 60 \text{ km}$], and R101 [(e, f) $R_m = 100 \text{ km}$]; all variables are averaged in 3 hours prior to the corresponding primary intensification stage. The red solid curve indicates the RMW in the corresponding experiment.

Fig. 8. Time evolution of (a) the maximum azimuthal mean 10-m height tangential wind speed (m s^{-1}), (b) the RMW (km), and (c) the intensification rate [$\text{m s}^{-1} (24 \text{ h})^{-1}$] with a 5 h running mean in b055 ($b = 0.5$, magenta), b075 ($b = 0.7$, blue), and b105 ($b = 1$, red).

intensification stage than that with an initially higher strength in b055. The storm in b105 behaved similarly to the TC with the initially smaller RMW discussed in Section 4a. In Fig. 8c, the maximum intensification rate was higher in b105 during the early primary intensification stage (24–36 h), but the difference was very small. The difference in the intensification rate for the vortices with initially different strength is smaller than that presented by Xu and Wang (2018b, see their Fig. 2). This is mainly because different radial profiles of tangential wind were used in their study (their Fig. 1) and in this study (Fig. 2). As we can see, the three vortices with different b parameters (0.5, 0.7, and 1.0) in this study show little difference in inertial stability outside the inner core between the RMW and a radius of 150 km from the storm center. By contrast, Xu and Wang (2018b) found the difference in inertial stability in the initial vortex to be large in the inner core (i.e., inside the RMW) but small outside the inner core (see Fig. 1b in Xu and Wang 2018b and Fig. 2d in this study). This suggests that the TC intensification rate is more sensitive to the inertial stability in the inner core but less sensitive to the inertial stability outside the inner core. Also note that since different models and wind profiles of the initial vortex were used in the study by Xu and Wang (2018b) and in this study, a direct comparison of the intensification rate is impossible. Nevertheless, the dependence of the intensification rate on the wind profile outside the RMW in the initial vortex is qualitatively consistent in the two studies.

Figure 9 illustrates the time evolutions of relative humidity and vertical motion averaged within a radius of 1.5 RMW in all three experiments. Based on results in Section 3, the storm of higher strength would induce a weaker boundary layer inflow and upward motion (Ekman pumping) inside the RMW through the boundary layer dynamics. This explains the initially slower moistening of the inner core in b055 compared to those in b075 and b101. These results are consistent with those recently reported by Xu and Wang (2018b), who also found that a TC vortex with an initially higher strength had a longer initial spinup stage and intensified less rapidly than that with an initially lower strength because the higher inertial stability outside the RMW in the former imposed higher resistance to boundary layer inflow.

The azimuthal mean radial wind, vertical motion, condensational heating rate, and inertial stability averaged in 3 hours prior to the corresponding primary intensification stage in the three experiments are compared in Fig. 10. We can see that the TC

Fig. 9. Same as Fig. 6 but for (a) b105 ($b = 1$), (b) b075 ($b = 0.7$), and (c) b055 ($b = 0.5$).

with initially lower strength developed stronger and deeper boundary layer inflow in the inner-core region within a radius of 75 km, leading to stronger and more inwardly penetrated inflow and upward motion in the early primary intensification stage. Meanwhile, the condensational heating rate in b105 was higher inside the RMW where inertial stability was also high; thus, the condensational heating intensified the TC more efficiently. These results are consistent with those implied by the boundary layer model discussed in Section 3.

4.3 Direct and indirect effects of surface friction

Figure 11 illustrates the vertically integrated energy

gain from condensational heating and the energy loss due to surface wind stress, both averaged between 0.5 times and 1.5 times of the RMW in the simulated TCs in all six experiments during their corresponding primary intensification stage in Part I (Li and Wang 2021). The storm with an initially smaller RMW or lower strength gained more energy from condensational heating (indirect effect of surface friction) near the RMW than the storm with a larger RMW or higher strength, even though those storms had similar intensities (Figs. 11a, b). The difference among the storms increased as the TC intensified. However, the energy loss due to surface wind stress (direct dissipation effect of surface friction) near the RMW was almost

Fig. 10. Same as Fig. 7 but for (a) and (b) b105 ($b = 1$), (c) and (d) b075 ($b = 0.7$), and (e) and (f) b055 ($b = 0.5$).

the same in all six experiments (Figs. 11c, d) because they had the same dependence of C_D on a 10-m height wind speed. The difference in energy gain from condensational heating is responsible for the different intensification rates of the storms because energy losses due to surface wind stress during the primary

intensification stage are similar in all six experiments. These results support the hypothesis mentioned in the introduction, that the indirect effect of boundary layer dynamics in the presence of surface friction on TC intensification depends considerably on storm structure, whereas the direct dissipation effect of surface friction

Fig. 11. Dependence of (a, b) the vertically integrated energy gain rate from condensational heating ($\text{J kg}^{-1} \text{s}^{-1}$) and (c, d) the rate of kinetic energy loss due to surface friction ($\text{J kg}^{-1} \text{s}^{-1}$) on the maximum 10-m tangential wind speed (m s^{-1}), both averaged in the area between 0.5 and 1.5 times the RMW with a 5 h running mean during the corresponding primary intensification stage. The left (right) panel is for the sensitivity to the initial RMW (initial vortex strength).

depends primarily on the TC intensity but little on the storm structure.

The difference in both the duration of the initial spinup stage and the subsequent intensification rate among the vortex strength sensitivity experiments is much smaller (Fig. 8) than that among the experiments on sensitivity to the initial RMW (Fig. 5), although the lower-strength storm can induce a higher condensational heating rate inside the RMW through boundary layer dynamics presented in Section 3 (cf. Figs. 3b, d) and Section 4b (cf. Figs. 10a, e). This

could be explained by the fact that the inner-core inertial stability was very similar in the vortex strength experiments and the difference in inertial stability outside the RMW was moderate (Fig. 2d). Another reason is that the vortex structures in vortex strength experiments changed during the model integration. We found that the storm with initially lower strength contracted more rapidly than the storm with initially higher strength, leading to a smaller RMW, whereas the RMW difference in vortex strength experiments is smaller than that in vortex RMW experiments (not

presented). Nevertheless, the overall feature is still visible; that is, the storm with initially lower strength had a shorter duration of the initial spinup stage and a higher intensification rate during the primary intensification stage.

To further confirm the dependence of the indirect effect of boundary layer dynamics on the initial vortex structure in determining the storm intensification rate during the primary intensification stage, we performed six extra experiments using the boundary layer model forced with the azimuthal mean pressure gradient force averaged in 3 hours prior to the corresponding primary intensification stages in the six TCM4 experiments (three RMW experiments and three strength experiments). These experiments can help with understanding of how the indirect effect of surface friction depends on the initial vortex structure through boundary layer dynamics. Figure 12 illustrates the steady-state response of radial wind and vertical motion to the azimuthal mean pressure gradient force averaged in the 3 hours prior to the primary intensification stage from the corresponding TCM4 experiments using the boundary layer model, similar to that conducted by Stern et al. (2020). We can see that the overall structure and differences among the experiments are quite similar to those directly from TCM4 (Figs. 7, 10). This further demonstrates that it is the vortex structure that determines the magnitude and radial location of condensational heating rate in the eyewall through boundary layer dynamics and, thus, the intensification of the simulated TC (indirect effect of surface friction).

In addition, the relationship between the inward displacement of the maximum eyewall updraft relative to the RMW (Δr) and $-u_{10}/I$, as identified by Kepert (2017), are examined for all experiments in Part I and Part II, with the results illustrated in Fig. 13. First, the inward displacement of the maximum eyewall updraft relative to the RMW and $-u_{10}/I$ in the sensitivity experiments to C_D (black) from both the boundary layer model and TCM4 indicate a nearly linear relationship when C_D is multiplied by a factor between 0.5 and 2.0. Second, the experiments with a storm with an initially lower strength ($b = 1.0$) (blue) or with a larger C_D (black) indicate a larger Δr and stronger radial inflow, in good agreement with Fig. 8 of Kepert (2017). Third, the storms with a larger RMW (red) have a larger Δr , and those with a smaller RMW have a stronger radial inflow but higher inertial stability. This is consistent with the results in Fig. 4 and those of Kepert (2017), which indicate that both $-u_{10}/I$ and inward displacement are larger when the RMW is larger. Finally, the results from the full-physics model are very similar

to those from the boundary layer model in that Δr is almost linearly proportional to the scale of $-u_{10}/I$, indicating that results from the boundary layer model can capture the indirect effect of surface friction through boundary layer dynamics.

In all, the storm with an initially smaller RMW or lower strength can produce stronger convergence in the boundary layer, more inwardly displaced eyewall updraft and, thus, a higher condensational heating rate inside the RMW through boundary layer dynamics than those of a storm with a larger RMW or higher strength. This would shorten the duration of the initial spinup stage and increase the intensification rate during the primary intensification stage for the storm with a smaller RMW or lower strength. Note that the differences in the azimuthal mean radial wind, vertical motion, and condensational heating rate between R041 and R101 (b105 and b055) are very similar to those between CT20R and CT05R with different C_D s (cf. Fig. 7 in Li and Wang 2021). However, the positive effect of the higher condensational heating rate in CT20-R with a larger C_D was largely offset by the negative effect of a greater surface frictional dissipation effect (Fig. 8 in Li and Wang 2021), resulting in little net contribution to the TC intensification rate. By sharp contrast, because the two storms during their primary intensification stages in R041 and R101 (b105 and b055) had a similar intensity and thus similar surface frictional dissipation effects (Figs. 11c, d), the greater energy gain from condensational heating in R041 (b105) directly contributed to the higher intensification rate of the simulated storm. These results demonstrate that the structure (such as the RMW and strength) of the initial TC vortex is key to both the duration of the initial spinup stage and the subsequent intensification rate during the primary intensification stage of a TC.

5. Summary

In this study, the indirect and (direct) dissipation effects of surface friction on TC intensification have been studied using both a boundary layer model and a full-physics model. We demonstrate that the positive indirect effect of surface friction on TC intensification involves an interaction between the boundary layer response and the radial distribution of gradient wind above the boundary layer (red arrow in Fig. 14). By contrast, surface friction has a negative dissipation effect on TC intensification through surface wind stress on boundary layer winds (green arrow in Fig. 14). Results in Part I indicate that the intensification rate of the simulated TC during the primary intensifi-

Fig. 12. Radius-height cross sections of radial wind speeds (shaded; m s^{-1}) and vertical velocity (contours, with a contour interval of 0.1 m s^{-1}) for (a) R041 ($R_m = 40$ km), (c) R061 ($R_m = 60$ km), and (e) R101 ($R_m = 100$ km) and for (b) b105 ($b = 1$), (d) b075 ($b = 0.7$), and (f) b055 ($b = 0.5$) in the steady-state response in the boundary layer model. The azimuthal radial gradient wind distribution, averaged in 3 hours prior to the corresponding primary intensification stage, from the outputs of TCM4 were used as the initial inputs of the boundary layer model.

cation stage is insensitive to C_D because the changes of the positive and negative effects of surface friction due to the change in C_D largely offset each other. Results in Part II demonstrate that the intensification rate of the simulated TC is sensitive to the initial vortex structure. This is because the indirect effect of surface

friction as a boundary layer response to gradient wind above the boundary layer depends strongly on the vortex structure (yellow arrow in Fig. 14), whereas the negative dissipation effect of surface friction depends primarily on the TC intensity but little on the storm structure.

Fig. 13. Dependence of the inward displacement (km) of the maximum eyewall updraft relative to the RMW near the top of the boundary layer (at the 654 m height) on $-u_{10}/I$ (evaluated at the RMW at the same height) for all experiments in the steady-state response in (a) the boundary layer model and (b) that prior to the corresponding primary intensification stage in the full-physics model TCM4.

Fig. 14. Schematic diagram illustrating the indirect effect and the (direct) dissipation effect of boundary layer dynamics in the presence of surface friction on the TC intensification rate. The direction of the arrow represents the cause and effect. The upper gray (bottom yellow) dashed rectangle was concluded in Part I (and Part II).

The boundary layer process was first investigated as a forced response to the prescribed radial distribution of gradient wind above the boundary layer using a boundary layer model. The results demonstrate that a storm with an initially smaller RMW or lower strength corresponds to stronger boundary layer inflow and stronger upward motion inside the RMW. This implies stronger eyewall updraft/convection and higher condensational heating rate inside the RMW with higher inertial stability. This would be favorable for a higher intensification rate of the TC. This indirect effect of surface friction was confirmed by results from

full-physics model simulations. As expected, the faster moistening was in the inner core of the TC vortex with an initially smaller RMW or lower strength in experimental results of the full-physics model from stronger boundary layer moisture convergence and Ekman pumping. This can shorten the duration of the initial spinup stage of the simulated TC. The higher condensational heating rate inside the RMW with higher inertial stability (largely contributed by the indirect effect of surface friction) can lead to a larger positive contribution to the intensification of the simulated storm with an initially smaller RMW or lower strength. Note

that compared to the sensitivity to the initial RMW, the sensitivity of the TC intensification rate to the initial vortex strength is considerably weaker. This is because the initial vortices of different strengths examined in this study have relatively smaller differences in the boundary layer inflow and condensational heating rate through boundary layer dynamics. Note that the boundary layer process (namely the indirect effect of surface friction) discussed in this study is mainly controlled by the differences in inertial stability between the inner core and outer core regions of the TC vortex.

Results from this study strongly suggest that the initial structure of the TC vortex is critical to both the initial spinup stage or the onset of the intensification and the subsequent intensification rate of a TC through boundary layer dynamics. More attention should be given to the analysis of the TC structure in observations and accurate representation of the TC structure in the initial conditions of numerical prediction models used for TC forecasts. In addition, an issue arises as to whether the results from this study might be valid if a coupled ocean-atmospheric model were used because only the atmospheric model was used in this study. As already mentioned in Part I, with ocean coupling, a larger C_D would impose a larger surface stress curl and stirring on the upper ocean and induce stronger upwelling and mixing at the mixed layer base, leading to greater cooling in sea surface temperature. This extra negative effect has not been considered in this study. Similarly, the ocean response, such as upwelling and mixing, to the TC forcing also depends on the TC structure. Therefore, a more complete understanding of the role of boundary layer dynamics in determining the TC intensification rate could be further achieved through numerical experiments with a coupled ocean-atmosphere-wave model, which is a topic for a future study.

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