Characteristics of the convective bursts and their relationship with the rapid intensification of Super Typhoon Maria (2018)

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ABSTRACT
For Super Typhoon Maria (2018), the multi-intensity change stages are identified and reproduced by numerical simulation. It is rather difficult to perform a perfect simulation for such a repeatedly reinforced typhoon during its long life-cycle and remote path. In this study, the rapid intensification (RI) episode is focused on to investigate the convective burst (CB) characteristics and the relationship between the CBs and the RI of Maria. For Typhoon Maria, 1) the spatial pattern of the inner-core CBs in distinct shear-relative quadrants, instead of the overall inner-core CBs frequently used in previous studies, presents cyclonic rotation from downshear to upshear quadrants during RI, producing a higher efficiency for tropical cyclone (TC) spinup, which accelerates the RI process. 2) Dual meanings/relationships exist between CBs and RI for Maria, in contrast to the previous argument that CBs might be an indicator or a precursor to RI. The sudden growth of CBs prior to RI provides a precursor for the upcoming RI. Additionally, the appearance of the CB peak soon after RI indicates RI could lead to more intensive deep convections. The overlap of CBs with high inertial stability inside the radius of maximum wind plays a significant role in the RI of TCs. 3) The synoptic attributions to CBs are also explored for the entire troposphere, fitting in the bottom-up thinking of convection growth. The CBs might be associated with high convective available potential energy in the boundary layer, a strengthening of the deep-layer secondary circulation, and an enhanced upper-level eddy momentum flux convergence.

1. Introduction
As a famous super typhoon that occurred over the northwestern Pacific Ocean in 2018, Maria was the most intensive and longest-lived tropical cyclone (TC) of the year, causing a direct economic loss of nearly 3 billion Yuan and affecting 1.172 million people. It underwent multi-intensity changes (Figure 1), which increases the difficulty of simulation and prediction. Furthermore, the reasons and mechanisms responsible for the multi-intensity changes are interesting research topics, and we carry out a series of studies to address these issues based on high-resolution-modeled results. In this study, a numerical simulation of the super typhoon Maria is performed, and its rapid intensification (RI) stage is focused on first to understand the sudden and sharp intensity change because TC intensity forecasting faces great challenges relative to track prediction in the world, particularly for rapidly intensifying TCs (Chen, Xue, and Fang 2018).

Many favorable external factors for RI, such as a high ocean heat content and warm sea surface temperatures, a high atmospheric humidity, weak vertical wind shear (VWS), stronger easterly winds in the upper troposphere, and relatively strong forcing from the mid-latitude upper-level trough (UT) and/or an inverted trough (IT) near a TC, have been identified from observations, statistics, and simulations of TCs (Kaplan and DeMaria 2003;...
However, these environmental factors alone are insufficient to differentiate RI from non-RI TCs (Hendricks et al. 2010; Yang et al. 2019). Thus, the inner-process seems significant, and more attention should be paid to it.

Favorable internal processes, e.g. convective bursts (CBs) and associated microphysical latent heating, have a close relationship with the RI of TCs. At times, CBs can even serve as an indicator or a precursor for RI onset (e.g. Hazelton, Rogers, and Hart 2017). Based on observations, Guimond et al. (2016) illuminated that CBs often develop prior to or synchronously with the onset of RI in TCs. Wang and Wang (2014) thought that the RI onset for Typhoon Megi was triggered by CBs. Miller, Chen, and Zhang (2015) concluded that the development of more CBs inside (RMW) and the associated latent heating derived from updrafts promoted the RI of simulated Hurricane Wilma. Hazelton, Rogers, and Hart (2017) also emphasized the role of CBs on the structure of TCs and the intensity change for two Atlantic hurricanes and showed that wavenumber-1 asymmetric vorticity leads to the development of CBs. From a thermodynamics viewpoint, the convective available potential energy (CAPE) or the slantwise CAPE might trigger CBs (Wang and Wang 2014). The intense updrafts rooted inside the eyewall release a large amount of latent heating, which is helpful for the formation of an upper-level warm-core by radially sinking toward the center. Thus, this process induces hydrostatic surface pressure decreases, thereby accelerating the RI process (Montgomery et al. 2006; Yang et al. 2019).

Figure 1. (a) Model domain configuration, (b) the observed (black) and the simulated tracks (red) of Typhoon Maria from 0000 UTC 4 to 0000 UTC 11 July 2018, (c) MSLP (red) and MSW (blue), where the curves and dots represent simulations and observations, respectively (with I, II, III, IV, V representing the intensifying, RI, steady-Vmax, reintensifying, and weakening stages), and (d) Evolution of the vertical wind shear (VWS) averaged within a 600-km radius relative to the eye. The gray shading indicates the RI period.
For the unusual Super Typhoon Maria, which had multi-intensity changes, the RI stage is focused on to explore the CB characteristics by invoking high-resolution simulations of the case. We address the following questions: 1) What is the spatial pattern of CBs in the distinct shear-relative quadrants of TCs? 2) What is the relationship between the CBs and the RI of Typhoon Maria from the pre-RI to the RI stage? Specifically, can CBs serve as an indicator or precursor for RI? How do CBs link with RI? 3) What are the associated synoptic attributions to CBs? To solve these problems, the Maria case and model setup, and the large-scale synoptic background are described in Section 2. In Section 3, the inner-core CB characteristics are explored. Then, the relationship between CBs and RI for Typhoon Maria is illuminated in Section 4. The possible synoptic attributions to CBs are analyzed in Section 5. A summary is given in the final section.

2. Case description and numerical simulation

2.1. Overview of Maria case

Maria was identified as a tropical depression by the Joint Typhoon Warning Center (JTWC) and named Maria at 0500 UTC 3 July 2018. Later, it was upgraded to a tropical storm, a typhoon, and then a super typhoon as it moved northwesterly (Figure 1(a,b)). Maria kept its super typhoon intensity for several days, with a peak intensity MSW (maximum sustained 10-m wind speed) of 54 m·s⁻¹ and an MSLP (minimum sea-level pressure) of 915 hPa at 0000 UTC 9 July. At 0900 UTC 11 July, Typhoon Maria made landfall and weakened. The synoptic situation is described in Figure S1.

2.2. Numerical simulation

As a long-lived super typhoon, Maria underwent a complicated intensity evolution within 1 week (from 4 to 11 July 2018) (Figure 1(c)). We could divide this evolution into five distinct stages based on the varied MSW and MSLP values, including (i) slow intensification (SI), (ii) RI, (iii) steady-MSW but with continuously decreasing MSLP, (iv) re-intensification, and (v) weakening. Note that from 0600 UTC 5 July to 0600 UTC 6 July, the observed MSW increased from 28 to 49 m·s⁻¹, and the MSLP decreased from 985 to 935 hPa within 24 h (Figure 1(c)), which satisfied the condition of RI defined by Kaplan and DeMaria (2003). Thus, 0600 UTC 5 July is considered as the onset of the RI for Maria. Then, the MSW remained in a steady state nearly without variation in amplitude from 0600 UTC 6 July to 0000 UTC 8 July, while the MSLP continued to fall slowly. From 0000 UTC 8 July, the typhoon experienced re-intensification, despite not reaching the RI criterion, and attained its peak intensity (PI). Then, Maria weakened rapidly from 9 to 11 July and made landfall on the Fujian province of China on 11 July 2018.

The model setup is described in the supplementary text B. In general, the model basically reproduces the track and multi-intensity stages of the typhoon (Figure 1(b, c)). We perform the analyses as described below based on the simulation. In this study, we pay more attention to the RI stage to analyze the external and internal processes.

3. CB characteristics of Maria

3.1. Definition of CBs

Although there is a wide range of criteria for CBs (Wang and Wang 2014; Hazelton, Rogers, and Hart 2017; Wadler, Rogers, and Reasor 2018), the definition of a CB is usually based on the statistical distribution mode of vertical velocity (Rogers 2010; Wadler, Rogers, and Reasor 2018). Therefore, we examine the distribution pattern of updrafts/downdrafts for Typhoon Maria by using contoured frequency by altitude diagrams (CFADs) (Yuter and Houze 1995; Rogers 2010) from the pre-RI to RI stages (Figure 2).

Figure 2 shows the CFADs of the simulated vertical velocity binned every 0.1 m·s⁻¹ at each altitude within a radius of 99 km. By comparing the vertical velocity CFADs from the pre-RI to RI stages (Figure 2), the vertical velocity develops simultaneously at whole-layer heights and is characterized by broader modes, with peak-updraft (99.99th percentile) growth from 6 m·s⁻¹ (Figure 2(a)) to 7.5 m·s⁻¹ (Figure 2(b)) and then to >10 m·s⁻¹ (Figure 2(c)) at 5 km and 11 km (i.e. where the updraft maximum is located). In the meantime, the upper-troposphere downdrafts enhance from −2 m·s⁻¹ to −6 m·s⁻¹ (Figure 2(a,c)). In general, the updrafts undergo whole-layer growth, while the downdrafts experience deep-layer strengthening. It seems that the CB definitions derived from whole-layer convection and deep-layer convection statistics from Wang and Wang (2014) and Wadler, Rogers, and Reasor (2018) are suitable. Therefore, both methods are attempted and compared in the following subsection.

3.2. Spatial pattern

Figure 3 demonstrates the spatial pattern of the CBs, derived from the definition of Wang and Wang (2014),
superposed by reflectivity and RMW. From the pre-RI (Figure 3(a,b)) to RI stages (Figure 3(c,f)), eyewall convections (shaded), manifested by strong reflectivity signals, present a structure of semicircular asymmetry and then tend to symmetry and form closed spiral rain bands accompanied by eyewall shrinking. The RMW contracts drastically just prior to RI (cf. Figure 3(b,c)). The inner-core CB elements, located within the strong convective eyewall near the RMW, significantly increase during RI. Note that the distributions of CBs according to the criterion of Wadler, Rogers, and Reasor (2018) take on a similar pattern, but it is not displayed herein due to sparse and insufficient samples for the following shear-relative quadrant analyses.

We also examine the CB distributions in the distinct shear-relative quadrants (see the legend at the bottom-right corner of Figure 3) due to the close correlation between the CBs and the VWS. The environmental VWS basically maintains a certain direction, pointing toward the southeast from the typhoon center and decreasing in magnitude with RI, which is consistent with previous research (Wadler, Rogers, and Reasor 2018; Zagrodnik and Jiang 2014). Prior to RI, CBs dominate in the DSL (downshear-left) quadrant (Figure 3(a)), the initiation quadrant with a high occurrence of deep convection (Molinari and Vollaro 2010; Nguyen and Molinari 2012). From the onset time of RI (Figure 3(c)), peak CB locations experience cyclonic rotation and growth in number, from 10 elements at the DSR quadrant (Figure 3(c)) to 16 on the upshear side of the TC during RI (Figure 3(d,e)), similar to the results of Rogers et al. (2016). Because of the larger projection of convective heating onto the azimuthal-mean TC system (Wadler, Rogers, and Reasor 2018), the upshear distribution of CBs could produce a higher efficiency for TC spinup, which accelerates the RI process.

**4. Relationship with RI of Maria**

**4.1. Temporal evolution of CBs from pre-RI to RI stages**

Figure 4 shows the evolution of the inner-core CBs during various stages of Maria. In general, the majority of the CBs are mainly concentrated upon several intensifying stages of the TC until the PI of Maria at 0000 UTC 9 July (Figure 4). After that time, almost no deep convections are counted during the weakening period.

Around the RI stage, the number of CBs suddenly increased by more than two times approximately 3 h prior to RI (cf. the varied values from points A1 to B1 and from points A2 to B2). Thus, an abrupt growth of CBs might provide a meaningful clue for RI occurrence/initiation. Soon after the end of RI (approximately 6 h), the number of CBs reaches its peak (see points C1 and C2), implying that the RI of Maria results in more deep-layer updrafts. In the meantime, the two CB curves (plotted according to the two sets of definitions) evolve similarly, and the smaller number of CB grid points for the former (Figure 4(a)) is due to the stricter limitation of the whole layer relative to the deep convections.

**4.2. Linkage of CBs with RI**

To further reveal the impact of the spatial distribution of CBs on TC intensity changes, Figure 5 shows the configurations among vertical velocity, inertial stability, and RMW. At 1800 UTC 4 July (Figure 5(a2)), updrafts of 0.8 m·s⁻¹ span across the RMW located at R = 72 km. The eye is dominated by downdrafts with an intensity of −0.4 m·s⁻¹. From the pre-RI to RI stages (cf. Figure 5(a2,b2)), the deep-layer convections intensively develop, exceeding 2.5 m·s⁻¹, forming a strong convective eyewall within the RMW, and contracting inwards radially to R = 36 km. The eye-region sinking...
airflow reaches up to \(-1.0\, \text{m} \cdot \text{s}^{-1}\). The inertial stability (IS) enhances and stretches from the boundary layer upwards to a height of 6 km, and a high IS is maintained in the inner-core region.

This type of overlap configuration of strong updrafts and high IS inside the RMW is favorable for RI, which could be explained by two aspects. A high IS could effectively constrain the adiabatic heat release by strong updrafts to escape out of the inner-core region, producing a higher heating efficiency (Rogers et al. 2016). In addition, deep convection and related boundary-layer inflow convergence could move the angular momentum surfaces inwards and play a direct role in the RI of a TC (Kilroy, Smith, and Montgomery 2016). During the post-RI stage, although deep convections continue to increase, the RMW and high IS region spread radially outwards.

Figure 3. Horizontal structure of the reflectivity (shaded, dBZ) and horizontal wind vectors (m·s\(^{-1}\)) at \(Z = 1\, \text{km}\), along with the CB (black crosses) distributions relative to the 200–850-hPa environmental wind shear (red arrows) at (a) 1800 UTC 4 July, (b) 0000 UTC 5 July, (c) 0600 UTC 5 July, (d) 1200 UTC 5 July, (e) 1800 UTC 5 July, and (f) 0000 UTC 6 July 2018. The mean RMW at \(Z = 1\, \text{km}\) is also plotted, and the bottom-right corner of the panel indicates the shear-relative quadrants (with DSL, DSR, USL, and USR denoting the downshear left, downshear right, upshear left, and upshear right quadrants, respectively).
Until 1800 UTC 9 July, strong updrafts move outside of the RMW, the favorable collocations (of strong convection and IS within RMW) for TC intensification are broken, and Maria enters the weakening stage.

5. Possible synoptic attributions responsible for CBs

5.1. Boundary-layer CAPE

The Hovmöller plot of azimuthal-averaged CAPE at $z = 0.25$ km (Figure 6(a)) shows that the high CAPE is located within the RMW before 0000 UTC 9 July, i.e. during the intensifying stages. The high CAPE provides available energy for the growth of deep convections and typhoon enhancement (Wang and Wang 2014).

High CAPE within a radius of 72 km, with a value of more than 1000 J·kg$^{-1}$, appears 4 h prior to the onset of RI and coincides with the dramatic increase in CBs. Then, the high-energy region is contracted within a radius of 30 km with a decreased RMW and reaches its peak of $>2000$ J·kg$^{-1}$ at 0600 UTC 5 July. The boundary-layer high-CAPE air within the inner-core region enters the eyewall through a lateral mixing process between the eye and the eyewall (Xu and Wang 2010), triggering deep convection inside the RMW and leading to the beginning of RI. The CB peak values (points C1 and C2 in Figure 4) are associated with the refreshed CAPE accumulation and energy release after 0600 UTC 6 July.

5.2 Deep-layer secondary circulation

The secondary circulation, made up of lower-/upper-level inflow/outflow and CBs (in particular, the deep-layer updrafts), intensifies from the pre-RI to RI stages (see Figure 5). For example, the azimuthal-mean radial inflow in the boundary layer is no more than 12 m·s$^{-1}$, with wind-speed core located at $R$ (Radius) = 72 km. Then, the inflow reaches 19 m·s$^{-1}$ at $R = 36$ km. The RMW contracts inwards toward the eye of the TC. The deep-layer updrafts (including the CBs) grow intensively and tend to be upright. The upper-level outflow synchronously develops with inflow and deep convection.

The intensifying radially lower-level inflow and upper-level outflow move the absolute angular momentum surfaces inwards (Stern et al. 2015) and speed up the RMW contraction (Figure 3(a,b)), thereby accelerating RI. The accompanying upright developments of the updrafts lead to the vertical alignment of the TC center under moderately low VWS conditions, which are beneficial to RI (Munsell et al. 2017; Chen, Xue, and Fang 2018).

5.3. Upper-level EFC

From the synoptic charts of Maria, there is an upper-level trough at 200 hPa and low pressure to the left of the typhoon near Maria (Figure S1a,b). To examine whether these low-value systems act on the TC, the eddy momentum flux convergence (EFC) index (DeMaria, Kaplan, and Baik 1993) is calculated for Typhoon Maria (Figure 6(b,c)). Positive values of EFC commonly indicate the approach of a low-value system to the TC and ensure that azimuthal eddies are acting to increase the mean angular momentum in the outflow layer (DeMaria, Kaplan, and Baik 1993; Tang et al. 2018).

The 100–300-km EFC sharply increases at 0600 UTC 5 July, just at the onset time of RI (Figure 6(b,c)), embodying the positive effect of the adjacent low on the RI of the TC. Additionally, the 1300–1500-km EFC is also plotted to check the role of the upper-level trough on the TC (Figure 6(c)). The latter shows an advanced
peak, at approximately 6 h prior to RI, and it is weaker in magnitude relative to the 100–300-km EFC due to a remote upper-level trough (Figure S1(a, b)). It seems that the RI has a more significant correlation with the approaching low of the nearby TC. The RI intensifies the vortex by injecting eddy momentum flux into the TC.

**Figure 5.** Composite vertical structure of (a1) the azimuthal-mean radial wind (shading; m·s$^{-1}$) and vertical velocity (contours at 0.7, 0.8, 0.9, and 1.0 m·s$^{-1}$) at 1800 UTC 4 July 2018: (b1), (c1), and (d1) are the same as in (a1) except for 1800 UTC 5 July 1800 UTC 8 July, and 1800 UTC 9 July. Thick red lines in (a1)–(d1) denote the RMW. The radial vertical structure of (a2), the vertical wind (shading; m·s$^{-1}$), and inertial stability (contour, $10^{-6}$ s$^{-2}$) at 1800 UTC 4 July (b2), (c2), and (d2) are the same as in (a2) except for 1800 UTC 5 July 1800 UTC 8 July, and 1800 UTC 9 July. Thick black lines in (a2)–(d2) denote the RMW.
system, thereby enhancing the tangential wind, accelerating the upper-level outflow from the gradient wind imbalance (Wang and Zhang 2003), and further accelerating deep-layer convections (CBs) by pulling the second circulation from the upper level.

6. Summary

For Super Typhoon Maria, which underwent multi-intensity changes during its long life cycle, the RI episode is focused on, and the inner-core CB characteristics, their possible synoptic attributions, and their relationship with the RI of Maria are explored based on numerical simulations in this study. The main points are summarized as follows.

(1) The spatial pattern of inner-core CBs in the distinct shear-relative quadrants, based on the refreshed definition for Maria by utilizing CFAD, is demonstrated. It experiences cyclonic rotation from the downshear to upshear quadrants during RI, producing a higher efficiency for TC spinup, which accelerates the RI process.

(2) In contrast to the previous argument that CBs might be an indicator or precursor to RI, dual meanings exist for the CBs and RI for Typhoon Maria. The sudden growth of CBs prior to RI provides a precursor for the upcoming RI. In the meantime, the peak of CBs soon after RI indicates that RI could lead to more intensive deep convections. We explore the linkage between CBs and RI and succinctly clarify the mechanism responsible for the RI of Typhoon Maria. The overlapping configuration of CBs (strong updrafts) and high IS inside the RMW is favorable for RI. Once this type of favorable collocation (of strong convection and IS within the RMW) for TC intensification collapses, Maria moves into the weakening stage.

(3) The possible synoptic attributions responsible for CBs are investigated. The CBs might be associated with high boundary-layer CAPE, strengthening deep-layer secondary circulation, and enhanced upper-level EFC.

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