Convection, latent heating and potential temperature budget in the rapidly intensifying Typhoon Mujigae (2015)

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Abstract

Based on a 72-hr simulation of the rapidly intensifying Typhoon Mujigae (2015), the spatiotemporal evolutions of various inner-core convections and the associated latent heating (LH) features were investigated. Results showed two interesting turning points from the pre-rapid intensification (RI) stage to RI onset. One was a change from convective–stratiform mixed precipitation to a convective precipitation (CP)-dominant trend, while the other happened inside the CP. As the major contributor to LH, during the CP, the dramatic increase and radially inward movement of deep convection and associated LH release from −4 to −2 hr relative to RI, provided some useful clues for predicting the RI of a tropical cyclone (TC). But how do distinct convections act on the RI of a TC? From the potential temperature budget and flow vector intuitive display, there were upper- and lower-level warm cores, fed by the centripetal transport from deep-convection-related LH sources and lower-level radial inflow of weak-to-moderate convection-associated LH sources. The former brought about higher heating efficiency, embodied by a higher rate (2.5 times greater) of pressure decline during RI. Thus, by comparing the LH effects of diverse convections on warm-core formation, and the role of the warm core in the RI of a TC, the link between various convections and TC intensification can be established.

KEYWORDS

convective–stratiform precipitation, latent heating, rapid intensification

1 | INTRODUCTION

Significant progress has been made in the prediction of tropical cyclone (TC) tracks in recent years, but the growth rate with respect to forecasting accuracy of TC intensity remains at only 0.7% per year (DeMaria et al., 2014). Therefore, it is still a considerable challenge to achieve an in-depth understanding of the mechanism responsible for the strengthening of a TC, so as to further improve the simulation or prediction of TC intensity change, especially for the rapid intensification (RI) stage of a TC (Rappaport et al., 2009).

Both external environmental conditions and internal convective-scale processes might contribute to RI (Kaplan and DeMaria, 2003; Molinari and Vollaro, 2010; Nguyen
and Molinari, 2012). In fact, Kaplan and DeMaria (2003) identified several favorable environmental factors for RI, including warm sea surface temperature, weak vertical wind shear (VWS), stronger easterly winds in the upper troposphere and high relative humidity in the lower troposphere. Clearly, these environmental conditions are not distinct from those favoring normal TC intensification. For instance, rapidly intensifying TCs have previously been observed and simulated in high-VWS environments (Molinari and Vollaro, 2010; Kanada and Wada, 2015), implying that these favorable environments are neither necessary nor sufficient conditions for RI. And inner-core convective-scale processes might be the main reason for RI (Hendricks et al. 2010).

Indeed, observational studies have confirmed that convective-scale processes are closely associated with RI, via the latent heating (LH) release due to cloud microphysical transformation processes between abundant moisture and other water substance types within convection elements in the inner core (Kelley et al., 2004; Reasor et al., 2009; Rogers et al., 2013). Based on a composite analysis of airborne Doppler observations, Rogers et al. (2013) found that, during the RI of TCs, there are relatively large quantities of deep convection and LH inside the radius of maximum wind (RMW), as compared with steady-state TCs. Recently, numerical-model studies (Zhang and Chen, 2012; Chen and Zhang, 2013; Wang and Wang, 2014) have also shown that a sudden increase in deep convection elements (termed convective bursts) occurring inside the RMW may create extra LH, where the high inertial stability constrains this heat to dissipate outside. However, slightly different from these viewpoints emphasizing the importance of deep convection, Chang and Wu (2017) suggested that the LH substantially increases within the mid-to-upper troposphere inside the RMW, mostly caused by the weak-to-moderate (WM) convection therein, and makes a significant contribution to RI.

Therefore, it seems that both distinct convection types exert their respective functions and play some non-negligible roles in the RI of TCs. But which one is more important to RI? Furthermore, how do various convections act upon the RI of a TC? As far as we are aware, these are still unresolved questions, and it is therefore necessary to carry out an in-depth investigation through a real TC case. In Tang et al. (2018), we successfully reproduced the track and intensity of Typhoon Mujigae (2015) by using the WRF model (Figure 1 in Tang et al., 2018).

The methods are introduced only briefly here, with more details provided in Appendix F. A two-level classification method was utilized to differentiate the various convections from each other (Appendix B in File S1). Table 2 in Appendix C describes the microphysical processes in the Goddard GCE cloud microphysics scheme. LH was calculated based on the GCE scheme (Equation 1 in Appendix C). Meanwhile, the potential temperature budget was calculated according to the methods of Hendricks et al. (2004) and Stern and Zhang (2013).

2 | MODEL AND METHOD

The main run parameters of the numerical simulation are listed in Table 1 in Appendix A in support File S1. For more details, please refer to Tang et al. (2018), in which we successfully reproduced the track and intensity of Typhoon Mujigae (2015) by using the WRF model (Figure 1 in Tang et al., 2018).

The objectives of this study are (a) to examine the spatiotemporal evolutions of various convections and their associated LH features from the pre-RI to RI stages of the TC, and (b) to elucidate the heating effect of various convections on warm-core formation during the RI of the TC. The model and method used to achieve these aims are described in Section 2. Then, in Section 3, the spatiotemporal distribution characteristics of different convections are distinguished from each other and elaborated before and during RI. In Section 4, the related LHS released by various convections are calculated. In Section 5, the heating effect of various convections on warm-core formation and the role of the warm core in the RI of the TC are compared. The final section (Section 6) summarizes our findings.

3 | DISTRIBUTION CHARACTERISTICS OF VARIOUS CONVECTIONS

3.1 | General structure of the inner-core convections

Following Tang et al. (2018), 0600 UTC 3 Oct was considered in this study as the onset of the RI. Radius–height cross sections of azimuthally averaged variables before and during RI are shown in Figure 1. At 0000 UTC 3 Oct (i.e., 6 hr prior to RI, denoted as −6 hr, the same hereafter), the azimuthally averaged tangential wind shows a peak of 25 m/s at the top of the inflow layer (Figure 1a). The radial wind presents lower-level inflow with an intensity of 4 m/s below the altitude of 1 km and upper-level weak outflow above 12 km. Generally, the convections (c.f., the vertical velocity
shown in Figure 1d) are distributed between the radius of 16.5–82.5 km, with updrafts exceeding 0.2 m/s\(^1\).

After 6 hr, RI begins (Figure 1b,e) and cyclonic rotation increases, manifested as a broad area and large depth of tangential winds >30 m/s (Figure 1b) and increased vertical absolute vorticity (Figure 1e). Synchronously, convective develop sharply (Figure 1e), due to increased boundary-layer inflow coupled with high-troposphere outflow.

At +6 hr during RI, although the TC keeps intensifying, for example, with enhancing tangential and radial winds (Figure 1b,c) and vertical vorticity (Figure 1e,f), the convection does not continue to strengthen. The axisymmetric vertical motion reaches a peak of 1.4 m/s at the radius of 56.1 km and altitude of 9–13 km, above the tangential wind peak, at the onset time of RI. Even at the time of the most severe convection, the main body of most convection is located within the radius of 82.5 km (Figure 1d–f). So, the region within the radius of 82.5 km is considered as the inner-core region or named as target convective areas in the present study.

3.2 Spatial distributions of various convection types

3.2.1 Pattern

The spatial distribution patterns of various convections are further differentiated. From Figure D1 and the analyses in...
Appendix D of File S1, the inner-core precipitation evolved from a mix of convective–stratiform precipitation (SP) prior to RI to a predominance of convective precipitation (CP) as RI began.

Inside CP, deep convection dramatically increases and surmounts WM convection, tends to develop toward the inner core, and evolves from an asymmetrical to symmetrical pattern, indicative of the onset of RI. LH mainly results from CP, concentrated in the spiral rain belt of the TC. Please refer to Appendix D in support File S1 for more detail.

### 3.2.2 Percentage

To quantify the different proportions of various convection numbers from the pre-RI to RI stage of the TC, the radius-percentage distributions within the inner-core are examined (Figure 2). Prior to RI (Figure 2a), the no-rain area accounted for the largest proportion, followed by the SP and CP region. At the onset time of RI (Figure 2b), both the inner-core CP and SP numbers experienced significant growth between 44 and 90 km, accounting for the intense updrafts within the eyewall convective region shown in Figure 1e.

**FIGURE 2** Percentages of different types of convections within the inner core, with respect to radius. Among the figures, (d–f) show close-up snapshots of the CP and its components. The red, orange, blue, green, black and purple curves respectively denote “convective,” “stratiform,” “other” precipitation, “no rain,” “deep convection” and “weak to moderate” convection, at (a, d) −6 hr, (b, c) 0 hr, and (c, f) +6 hr, relative to the time of RI.
Within CP grid points (Figure 2d,e), the proportion of deep convection increases rapidly from 14.5 to 40% from the pre-RI stage to RI onset, between the radius of 39.6 and 56.1 km, while that of WM convection remains at about 20%. One possible reason is that the number of WM convections grows continuously, developing upwards and transforming into deep convection (Kanada and Wada, 2015).

During RI (Figure 2c,f), SP surpasses CP, accompanied by a more organized, symmetric, and wider eyewall structure near the radius of 33–99 km, with the maximum value exceeding 60%. The proportion of deep convection decreases with radius, while that of WM convection increases rapidly at the radius of 33–56.1 km, reaching 43%, and then gradually decreases.

Therefore, relative to the SP, the abrupt increase of the inner-core CP numbers seems to be an important indicator of the onset of the RI for Typhoon Mujigae. Meanwhile, inside the CP, although WM convection accounts for a large percentage of the total CP before and during RI, the abrupt increase and radially inward movement of deep convection is a turning point from the pre-RI stage to RI onset, providing some useful clues for predicting the RI of TCs.

4 | LATENT HEATING

4.1 | Vertical profiles

Time-averaged total LH inside the RMW contributed by various precipitation/convections and time series of deep convection and WM convection are presented in Figure 3. From −6 to 6 hr relative to RI onset (Figure 3a), the total LH was mainly contributed by CP, followed by SP. Other types released less heat, except below the height of 2 km. For the total LH inside the RMW, there were two peaks. One was
located at \( Z = 2 \) km, and the other was distributed at \( Z = 9 \) km. The contribution of WM convection exceeded deep convection within the height range of 0.25–9 km, which would have been conducive to the formation of a warming core in the middle troposphere [see Figure 4 in Tang et al., 2018]. Since we are more concerned with whether any predictive information is presented prior to RI, the stages before RI were further partitioned into two halves (from \(-6\) to \(-4\) hr in Figure 3b, and from \(-3\) to \(-1\) hr in Figure 3c). For the first half-period (Figure 3b), the total LH within the height range of 1–7 km maintains at about \( 20 \times 10^4 \) K/hr but rises rapidly to \( 52 \times 10^4 \) K/h above 8 km, mainly as a result of the contribution of WM convection and SP. For the second half-period before RI (Figure 3c), the total LH increases rapidly to about \( 40 \times 10^4 \) K/h within the whole layer ranging from the height of 0.25–9 km. The LH released from WM convection is more than that of deep convection at the height of 0.25–6 km. Above 6 km, the case is opposite. This indicates that the LH from deep convection was focused more at the higher level than that of the WM, which seems intuitive. Another interesting phenomenon is that Figure 3b,c embody the pathways of evolution from stratiform to WM convection, and then transforms into deep convection via upward growth. After RI onset (from 0 to

**FIGURE 4** Vertical structure of the azimuthal-mean microphysical LH rate for the total convection (a, d), deep convection (b, e) and WM convection (c, f) (shading; units: K/hr) perturbation temperature (black lines, interval = 0.4 K) during the period between 0000 UTC 3 Oct and 0600 UTC 3 Oct. Figure 5: Integrated local heat budget for this TC case in the radius–height domain. Heating tendencies are integrated from 0400 UTC 3 Oct to 0600 UTC 3 Oct: (a) actual in the WRF model; (b) microphysical LH; (c); (d); (e); (f); (g). Contour intervals: (a) 2 K; (b) 4 K; (c, d, f) 1 K; (e, g) 10 K. Negative values are denoted by dashed contours.
convection and WM convection. The temperature perturbations are also superposed (contours). At −6 hr of RI (Figure 4a–c), the LH release (shaded) is located at $R > 33$ km (scattered in both the inner-core and outer regions), below the level of 10 km and mostly originated from WM convection, as determined by comparing the magnitudes of deep and WM convections (c.f., Figure 4b,c). Meanwhile, the inner core is dominated by a broad warm anomaly (contoured) of temperature perturbation below 12 km, with a maximum of 3.2 K at the height of 2–4 km. The mid-to-lower level warm core forms first. At the upper level, a weaker warm core with an intensity of 1.6 K presents at 16 km. RI begins (Figure 4d,e), LH enhances and shifts towards the TC center ($R = 33–66$ km, concentrated within the inner-core region), and stretches vertically up to the height of 14 km, contributed by both deep and WM convections due to the rapidly increasing deep convection. Correspondingly, the warm anomaly shrinks centripetally, strengthens (2.4 K), and develops vertically up to 16 km. Accompanying the amplifying warm core, the RI onset period arrives.

To clarify the transport pathways of LH from various convections, we plot the vertical cross section of the flow vector (Figure E1 in Appendix E). It is worth noting that there are three main transport pathways for LH. One is the upward and then centripetal transport of LH from deep convection (Path I), closely related to the higher-level warm core. The second is the centripetal sinking of LH from deep convection (Path II), and the third is the lower-level radial inflow of LH from WM convection (Path III). The latter two are associated with the mid-to-lower level warm core.

5.2 | Potential temperature budget

To further clarify and quantify the transport pathways of LH from various convections, the potential temperature budget (cf. Equation 2 in Appendix F), including the MLH effect, is estimated. The results of the azimuthal-mean heat budgets are shown in Figure 5. Examining the heat budget for this case, we see that (Figure 5a, local tendency) two local warming cores present at the mid-to-lower level (approximately 6 K) and upper levels (4 K). From the orders of magnitude, the MLH (Figure 5b) and the azimuthal-mean vertical $\theta$ advection (VADVM, Figure 5e) are the largest source and sink terms, showing near opposite-phase patterns, and thus implying their offsetting of each other. The net effect of both attains a consistent order of magnitude with local tendency of potential temperature.

Examining Figure 5c,e in turn, Path I of the MLH from deep convection (Figure E1b), that is, the upward transport (by the positive eddy component of vertical $\theta$ advection, VADVE, at the 15-km level, Figure 5f) then...
centripetal transport (by the azimuthal-mean radial $\theta$ advection, RADVM, Figure 5c) of the MLH from deep convection, is completed. Paths II and III are implemented by the azimuthal-mean radial $\theta$ advection (RADVM, Figure 5c) of LH from deep convection, and the eddy component of radial $\theta$ advection (RADVE, Figure 5d) of MLH from WM convection. As the residual term, diabatic heating, except for MLH (Figure 5g), is balanced out by the equations. The positive anomaly of the upper-level eye (Figure 5g) might have been induced by the strong radiation effect from the cloudless eye region of the TC.

5.3 | Warm-core structure, heating efficiency and role in the RI of the TC

The above analyses provide the transport pathways of LH contributing to the warm cores of the TC (Figures E1 and 5).
By quantifying the hydrostatic pressure decline induced by these warm cores (Hirschberg and Fritsch, 1993; Zhang and Chen, 2012), we can build a link between the various convections and the RI of the TC (Figure 6). From Figure 6a, a double warm-core structure is clear, with the upper-level core (>9 K at 16 km) stronger than the lower one (about 7 K, below 10 km). However, the lower-level warming begins first, before the RI of the TC (> 3 K, below 8 km). Therefore, the total hydrostatic pressure decline (about −15 hPa, black curve in Figure 6b) is determined by the lower-level warm anomaly (of −10 hPa, blue curve in Figure 6b) before RI. Accompanying the onset of RI, the heating efficiency of the upper-level warm core rises swiftly (to −25 hPa at valley, red curve in Figure 6b), overruns that of the lower-level warm core (−20 hPa), dominating the total pressure decrease (−55 hPa), accounting for the RI of the TC, and thus might be a predictive signal of the onset of the maximal RI. Relatively, the lower-level warm core keeps acting on the TC’s intensification slowly, maintaining a smooth and steady wave of pressure change.

6 | CONCLUSION

Based on the refined 72-hr model output as presented by Tang et al. (2018), we studied the various inner-core structures, distribution features and associated LH effects of different convection types classified from the pre-RI to RI stage of Typhoon Mujigae. The main results can be summarized as follows:

1. By comparatively analyzing the patterns and percentages of various convections, it is shown that the inner-core precipitation evolved from a mix of convective–SP prior to RI to a predominance of CP as RI began. Inside CP, deep convection increased dramatically and surmounted WM convection, tended to develop towards the inner core, and evolved from an asymmetrical to symmetrical pattern, indicative of the onset of RI.

2. CP was the major contributor to LH. The associated LH from deep convection and WM convection showed that the total LH of WM convection was greater than that of deep convection during the overall period before and during RI. However, the sudden change in the LH of deep convection from −4 to −2 hr before RI can be used as an indicator for predicting the RI process of a TC. This abrupt outbreak of LH is attributable to two effects: one is deep convective bursts, shown as the intense increase in deep convection number, providing a larger weight to calculate the LH; and the other is the higher LH of unit deep convection than that of WM convection itself.

3. By comparing the heating effects of various convections on warm-core formation, and the role of the warm core in the RI of the TC, a link between the evolutions of the various convections and rapidly intensifying TCs was established. The MLH and warm core were found to be heating sources and sinks, as determined by calculating the potential temperature budget. Flow vectors intuitively showed the centripetal sinking from the LH source derived by various convections towards the warm core, while the potential temperature budget offered further proof of the source and transport pathways from the LH source to the warm core through quantitative analyses. Three main transport pathways responsible for the transportation towards the warm core of the TC from the
MLH source induced by various convections were elucidated. One was the upward then centripetal transport of LH from deep convection (Path I), closely related to the upper-level warm core. The second was the centrifugal sinking of LH from deep convection (Path II), and the third was the lower-level radial inflow of LH from WM convection (Path III). The latter two were found to be associated with the mid-to-lower-level warm core.

4. By quantifying the hydrostatic pressure decline induced by these warm cores, the heating efficiency and the action on RI were compared among the various convections. Before the RI of the TC, the lower-level warm core induced by the LH of WM convection played a primary role and had higher heating efficiency, determining the slow intensification of the TC. However, a sudden increase in the heating efficiency of the upper-level warm core led to a more rapid rate of pressure decline (from 0 to −25 hPa), about 2.5 times greater relative to the rate of decline (−10 to −20 hPa) derived from the lower-level warm-core, from 0600 UTC 3 to 0300 UTC 4 Oct 2015. This mainly came from the contribution of the explosive development of deep convections.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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