Relationship between convective bursts and the rapid intensification of Typhoon Mujigae (2015)

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Typhoon Mujigae was the strongest typhoon in 2015, and underwent an extreme rapid intensification (RI). The RI of Mujigae was reasonably reproduced by a 72-hr control simulation. By enhancing two updrafts in the eye wall, connective bursts (CBs) were found to have played an important role in the formation of the two warming cores in the middle and upper troposphere, respectively, which triggered and maintained the RI of Typhoon Mujigae. Meanwhile, CBs induced the upper-tropospheric potential vorticity anomaly and caused the downward transfer of momentum from the upper to the middle troposphere which was also conducive to the RI of the typhoon. Sensitivity tests confirmed our conclusion.

KEYWORDS
convective bursts, rapid intensification, Typhoon Mujigae

1 | INTRODUCTION

Significant progress has been made in the forecasting of both tropical cyclone (TC) tracks and intensity over the past two decades (DeMaria, Sampson, Knaff, & Musgrave, 2014). However, compared with the forecasting of TC tracks, the prediction of TC intensity change, especially that of TC rapid intensification (RI), faces a greater challenge (Rappaport et al., 2009). To improve the prediction of TCs undergoing RI, it is necessary for us to deepen our understanding of the physical processes that accompany this phenomenon. Along with statistical analyses of a large number of examples (Ventham & Wang, 2007), diagnostic analysis based on high-resolution numerical modeling is also helpful, as it helps us to uncover specific details for typical TC cases (Chen & Zhang, 2013; Rogers, 2010).

Typhoon Mujigae was the strongest typhoon in 2015, striking Guangdong Province in October of that year, and undergoing a process of RI. Mujigae was determined as having experienced RI based on the broadly accepted definition of this process, that is, a maximum sustained 10-m wind increase of more than 15 m s⁻¹ in 24 hr (Kaplan & DeMaria, 2003) and a minimum central pressure decrease of more than 42 hPa in 24 hr (Holliday & Thompson, 1979). It is therefore valuable to explore in detail the RI experienced by Mujigae, to reveal the possible physical mechanisms involved in this important TC-related phenomenon.

Although it is known that RI often occurs under several favorable environmental conditions, such as warm sea surface temperature (SST), high ocean heat content (OHC), weak vertical wind shear (VWS), strong upper-tropospheric outflow, and high relative humidity in the lower troposphere...
(Kaplan & DeMaria, 2003; Lin, Wu, Pun, & Ko, 2008), these environmental conditions are difficult to separate from those favoring TC genesis or “normal” TC intensification. Gray (1998) found that, when all favorable environmental factors are present, a TC is unlikely to undergo RI without the occurrence of convective bursts (CBs). Indeed, observational studies have linked RI with CBs in the inner core (Kelley, Stout, & Halverson, 2004; Reasor, Eastin, & Gamache, 2009). Rogers, Reasor, and Lorsolo (2013) found that RI is linked to a relatively large number of CBs inside the radius of maximum wind (RMW), as compared with steady state TCs. In Chen and Zhang (2013), the convective action of a series of CBs straddling the RMW was shown to contribute to warm-core development, which is favorable for RI. Rogers (2010) showed that the CBs are generally located near regions of enhanced positive potential vorticity (PV), suggesting these features of CBs are generating PV anomalies. A diabatically generated lower-tropospheric PV anomaly dominated the RI stage after initial triggering by a positive upper-tropospheric PV anomaly (Kotal, Tyagi, & Bhowmik, 2012).

The above studies show that CBs play an important role in the RI of TCs. But, how do CBs cause the RI of a TC? The physical mechanisms involved remain unclear, and still need to be further studied. The primary goal of this work is to address the importance of CBs in RI by examining (a) the spatial distribution and evolution of CBs and their role in the formation of the mid-upper troposphere warm cores during the pre-RI and RI stages from the thermodynamic perspective, and (b) an analysis of the PV budget to reveal that CBs played a critical role in the RI of Mujigae during the pre-RI and RI stages from the dynamic perspective. In doing so, we hope to shed light on the possible physical mechanisms involved in the causation of RI by CBs.

2 | CASE DESCRIPTION AND MODEL SIMULATION

2.1 | Case description

Typhoon Mujigae was the strongest storm in 2015, affecting the Philippines, southern China and northern Vietnam during early October of that year. Sadly, 27 people died during the event, and direct economic losses of more than US$3.66 billion were suffered (Member Report: China, 2015).

2.2 | Model configuration

In this study, the RI of Typhoon Mujigae was simulated using the Advanced Research Weather Research and Forecasting Model (WRF-ARW). It was run using a two-way nested setup, with one input file (10/3.3 km) grid, in the non-hydrostatic version of WRF-ARW (version 3.6.1). The model was initialized at 0000 UTC 2 Oct 2015, and integrated for 72 hr. The outermost 10 km contained 361 × 301 grids; the innermost 3.3 km contained 607 × 583 grids (Figure 1a); and there were 30 vertical levels. For the microphysics, we used the Goddard Cumulus Ensemble (GCE) scheme, while the cumulus parameterization scheme—only for the outermost domain—was the Kain–Fritsch NewEta convective parameterization scheme. No convective parameterization was used in the innermost domain. The model initial and lateral boundary conditions for the outermost domain during integration were from National Centers for Environmental Prediction’s (NCEP’s) Global Forecast System (GFS) analysis, and from National Oceanic and Atmospheric Administration’s (NOAA’s) SST.

2.3 | Simulation results

The simulation successfully reproduced the track and intensity, as compared to those from the best track databases of the China Meteorological Administration—Shanghai Typhoon Institute (CMA) using 2-min-averaged wind and the Japan Meteorological Agency (JMA) using 10-min-averaged wind (Figure 1b,c). Starting at 0600 UTC 3 Oct, the intensification rate of Typhoon Mujigae increased, with the minimum sea level pressure (MSLP) dropping from 982 to 940 hPa and the maximum sustained 10-m wind increasing from 35 to 51 m s\(^{-1}\) in 18 hr (note: a total 24-hr intensification, from 0600 UTC 3 Oct to 0600 UTC 4 Oct, of 18 m s\(^{-1}\) and 16 m s\(^{-1}\) was found in CMA and JMA, respectively) (Figure 1c). Both the simulation and observation satisfied the definition of RI (Holliday & Thompson, 1979; Kaplan & DeMaria, 2003), and 0600 UTC 3 Oct was considered in this study as the onset of the RI.

The time series of simulated 850–200-hPa VWS magnitude and direction (Figure 1d), calculated by the large-scale shear averaged within a 528-km box centered on the TC, shows that the shear magnitude for the whole simulation was less than 8.0 m s\(^{-1}\). Typhoon Mujigae intensified rapidly when the VWS magnitude decreased from 7.8 m s\(^{-1}\) to 1.8 m s\(^{-1}\). The VWS direction remained northwesterly for most of the simulation, including during the onset of RI at 0600 UTC 3 Oct. Research has shown that certain orientations of shear can support intensification (Molinari, Dodge, Vollaro, Corbosiero, & Marks, 2006).

To further verify the correlation between the convection distribution and the RI process Typhoon Mujigae (2015), the time series of Tropical Rainfall Measuring Mission (TRMM) images and the simulated reflectivity were compared. As shown in Figure A1 in File S1, the observed 85-GHz microwave image from the Naval Research Laboratory (NRL) showed an asymmetric structure of Typhoon Mujigae. The inner core convection mainly occurred in the north quadrant, while the outer core convection occurred in the south quadrant, at 1800 UTC 2 Oct 2015. A similar pattern of convection in the eye wall can be seen from the
simulated reflectivity (Figure A1a1 in File S1). At 0600 UTC 3 Oct, Typhoon Mujigae rapidly intensified. Multiple eye walls appeared in the TRMM images (Figure A1b in File S1), which could also be found in the simulated reflectivity fields (Figure A1b1 in File S1). At 1800 UTC 3 Oct, the typhoon structure evolved from asymmetric to symmetric and the spiral cloud band was mainly located in the southwest side of the typhoon center, according to both the observation (Figure A1c in File S1) and the simulation (Figure A1c1 in File S1).

In general, the simulation successfully reproduced the observed Typhoon Mujigae, including its track, intensity, RI process, and structure of radar reflectivity. Therefore, the simulation results could be used for the mechanistic analysis, as reported in the following parts.

3 | LARGE-SCALE ENVIRONMENT AND UPPER-TROPOSPHERIC PV ANOMALY

3.1 | Large-scale environment

Figures 2a–e show the 200-hPa and 850-hPa fields at 0000 UTC 3 Oct and 0000 UTC 4 Oct from the GFS analysis data. In the upper troposphere (200 hPa), two outflow channels—one poleward and one equatorward—were established (Figure 2a,d). The upper-tropospheric outflow channels can accelerate the removal of the mass field and strengthen the secondary circulation, enhancing the TC’s primary circulation (Chen, Wang, Zhao, & Wu, 2017). In the low-level troposphere, there was strong convergence and high relative humidity (>85%) near Mujigae (Figure 2b,e). Strong upper-tropospheric outflow and low-level convergence are conducive to the development of deep convection, which also can be the result of the development of CBs. These CBs carry warm and humid air into the upper troposphere, which are conductive for the formation of an upper-tropospheric warm core. Convective available potential energy (CAPE) was more than 2000 J kg$^{-1}$ around the center of the TC (Figure 2c,f), which contributed to the triggering of CBs (Wang & Wang, 2014). We also analyzed the SST and the profile of sea temperature in the area of Typhoon Mujigae (see Figure A2 in File S1). The SST was above 29°C and the ocean mixed layer depth (height of SST = 26°C) ranged from 60 to 77 m in the RI area of Typhoon Mujigae. The upper-tropospheric OHC was calculated, using the method from Lin et al. (2008), to have been about 67.8–104.59 kJ cm$^{-2}$, which is conducive to the development of the TC. It is apparent that the environmental conditions of the ocean were also favorable for deep convection and the RI of Typhoon Mujigae.

3.2 | Upper-tropospheric PV anomaly

In addition to the circulation background and large-scale thermodynamic conditions, the PV anomaly is also an effective environmental diagnostic for RI. Bosart, Velden, Bracken, Molinari, and Black (2000) depicted the PV anomalies of Hurricane Opal (1995), demonstrating that those nearby were influenced by synoptic-scale PV advection.

FIGURE 1  (a) Model domain configurations. (b) Plots of best track position according to the CMA (green line) and JMA (blue line), along with the position of Mujigae simulated by WRF at 6-hr intervals from 0000 UTC 2 Oct to 0000 UTC 5 Oct 2015. (c) Plots of MSLP (solid) and maximum sustained 10-m wind (dashed) from 0000 UTC 2 Oct to 0000 UTC 5 Oct 2015. (d) Times series of 850–200-hPa shear magnitude (red line) and direction (blue line) in a 528-km box centered on the TC. The black line denotes the onset of RI.
originated from the upper-tropospheric trough before and after the RI process (see figure 3 in their paper). However, our results are different from their findings. Specifically, we found that only an isolated upper-tropospheric positive PV anomaly center, instead of the upper-tropospheric trough, was located near Mujigae (Figure A3 in File S1). The differences between the two studies are likely reflective of the mechanism of environmental influence on the RI of Hurricane Opal (1995) being unsuitable in the context of Typhoon Mujigae’s RI. Such an isolated PV anomaly may provide useful clues and should therefore be carefully examined. To further explore the impact of the PV anomaly on the RI of Typhoon Mujigae, and to understand the origin of the PV, a high-resolution simulation was performed. The model output was utilized to diagnose the PV anomaly during the RI period, as reported in Section 4.2.

4 | CBs AND THE PV ANOMALY IN THE UPPER TROPOSPHERE

4.1 | Convective bursts

Previous studies have found that CBs are important to the RI of TCs (Chen & Zhang, 2013; Reasor et al., 2009; Rogers, 2010; Wang & Wang, 2014). Wang and Wang (2014) defined a burst as the vertical velocity at an altitude of 11 km being greater than 7.5 m s⁻¹, which was also used to define a CB in this study. Figure 3 shows the distribution characteristics of CBs at a few selected times during the pre-RI and RI stages. Prior to RI, most CBs were concentrated in the downshear-left side of the circulation, with embedded cores of high reflectivity (Figure 3a,b). At the onset of RI (Figure 3c), most CBs not only tended to be located in the downshear-left but also took place in the right-of-shear region as the typhoon size shrank and the eye wall became better organized, which corresponded more or less to a northwesterly VWS of about 3.0 m s⁻¹. During the RI (Figure 3d), a closed eye wall had almost developed, with the VWS magnitude being less than 2 m s⁻¹ and its direction almost northerly. During the following 12 hr (Figure 3e,f), the reflectivity field became better organized as the typhoon intensified. The VWS direction remained northwesterly, but slowly turned westerly. From Figure 3, we can see almost all the CBs occurred in the eye wall. Liu, Zhang, and Yau (1997) found air with high equivalent potential temperature and strong convergence located in the eye wall of Hurricane Andrew. Later, Chen and Zhang (2013) concluded that CBs played an important role in generating an intense upper-tropospheric warm core for the RI of Hurricane Wilma (2005). In the current study, we also found that the time at which the upper-tropospheric warm core of Typhoon Mujigae formed coincided with the onset of RI. Accordingly, how the CBs contributed to the formation of Mujigae’s warming center was examined next, using the data presented in Figure 3.

4.2 | PV anomaly in the upper troposphere

The previous section described the distribution of CBs during the RI process of Typhoon Mujigae. This section illustrates the relationship between the CBs and PV...
anomaly. According to Section 3.2, positive upper-tropospheric PV anomalies were located within Typhoon Mujigae during the pre-RI and RI stages. Kotal et al. (2012) concluded that a positive upper-tropospheric PV anomaly was able to trigger the RI of Typhoon Giri (2010). So, we analyzed the link between the upper-tropospheric PV and CBs (Appendix B in File S1).

To examine which term was responsible for the upper-tropospheric PV anomaly, we performed a budget analysis of the PV tendency equation. The azimuthal mean of the PV budget equation (Wu, Wu, & Wei, 2016) is:

$$\frac{\partial PV}{\partial t} = -V_h \nabla PV - \frac{\partial PV}{\partial p} + \frac{1}{\rho} (\xi + f) \cdot \nabla \theta \left( \frac{\partial}{\partial p} \right)_{VA} + \frac{1}{\rho} (\nabla \theta \times \mathbf{F}_r),$$  \tag{1}

where $V_h$ is horizontal wind speed, $\omega$ is vertical wind speed, $\rho$ is air density, $\xi + f$ is absolute vorticity, $\theta$ is potential temperature, $\mathbf{F}_r$ is the frictional force. Equation (1) suggests that the PV tendency results from horizontal advection (HA), vertical advection (VA), diabatic heating (DH), and friction (FR). The FR is relatively small and can be ignored.

From the azimuthal mean positive PV budget terms at 0000 UTC (prior to RI), 0600 UTC (at the onset of RI), and 1200 UTC (during RI) 3 Oct (Figure A4), we can see large variability between the pre-RI and RI periods. It is noteworthy that the DH and VA terms are always larger than the HA term. The DH term contributes to the positive PV tendency in the middle and lower levels, which is due to more heating being released from abundant hydrometeors, consistent with the result of Kotal et al. (2012), while the VA term contributes to the positive PV tendency in the middle and upper troposphere. Prior to RI, the VA and HA terms are smaller than the DH term, suggesting the DH term played a critical role in the PV anomaly within the asymmetric structure. During RI, and at the onset of RI, the HA term is still smaller than the DH term, but the VA term is greater than the DH term at $z = 9–13$ km, even more significant in Figure A4i in File S1. So, it can be concluded that the sudden increase (Figure A4b,c in File S1) in the upper-tropospheric PV anomaly (which was closely associated with RI) was mainly caused by the drastic growth of the VA term (Figure A4h,i in File S1). Meanwhile, based on the PV tendency equation, the VA term is closely related to the vertical upward motion. When a typhoon experiences RI (CBs occur), the vertical velocity will increase dramatically and cause growth of the VA term (a detailed analysis of CBs and the VA term is given in Appendix C in File S1). As a result, the upper-tropospheric PV anomaly was mainly caused by the CBs in the RI process of Typhoon Mujigae.

### 4.3 Probable mechanism of the RI of Typhoon Mujigae

Figure 4a,b show the CB vertical structures at the onset of, and during, the RI of Mujigae. At the onset of RI, a large amount of air with high equivalent potential temperature, located inside the RMW, was transported to the upper troposphere by the CBs. The warm air was flanked by divergent outflows or cloud detrainment, with the inward branch descending from an altitude of 16 km into the eye. The subsidence was able to extend radially to the eye center and down to an altitude of about 10 km, resulting in the formation of a warming center in the mid-upper troposphere (6–10 km) of the eye area. During the RI, two warming centers—one located above 14 km and the other at 6–10 km—were found in our study, whereas only one warming core (at 14 km) was reported by Chen and Zhang (2013). Due to the warming of the eye area, the eye’s surface pressure then dropped quickly, from 982 hPa to 970 hPa in 6 hr, through hydrostatic adjustment (Guimond, Heymsfield, & Turk, 2010). To adapt to the central pressure’s sudden change and maintain the gradient wind balance (Willoughby, 1998), the tangential wind speed up (from 34 to 40 m s$^{-1}$ in 6 hr [figure omitted]), and thus the TC’s intensity rapidly increased. In addition, a strong vertical downdraft occurred at the edge of the warming center located in the upper troposphere, whereas the vertical updraft was found to cover the regions of the warming center located in the upper troposphere in Chen and Zhang (2013).

Based on the above analysis, a new possible mechanism of the RI process of a typhoon is proposed. The CBs motivate a weak updraft and strong updraft in the eye wall of the typhoon. The weak updraft rises from the surface and outflows in the middle troposphere, while the strong updraft rises from the surface and outflows in the upper troposphere. The two outflows condense (or desublimate) in the middle (or upper) troposphere and release latent heat, and two warm centers are formed in the middle and upper troposphere, respectively. The two centers heat the environmental air and cause depression of the atmospheric pressure in the middle and upper troposphere according to the adiabatic warming. In addition, downdrafts occur in the upper troposphere and outflow in the middle troposphere. Due to the downward transfer of momentum, the wind speed in the middle troposphere increases rapidly and results in the RI process.

Section 4.2 revealed that the upper-tropospheric PV anomaly in this case was mainly caused by the CBs. Here, we analyze the relationship between the PV anomaly and the RI process and try to identify the probable mechanism through which the PV anomaly in the upper troposphere was conducive to the RI process of Typhoon Mujigae.

Figure 4c shows the time series of the averaged upper-tropospheric PV anomaly at $z = 9–13$ km and the number of CBs within 99 km of the typhoon center. At 0300 UTC 2 Oct, the peak value of the number of CBs reached 50. After 3 hr, the PV anomaly occurred and the PV increased.
FIGURE 3  Horizontal maps of the predicted radar reflectivity (shaded; units: dBZ) and TC-relative flow vectors at $z = 1$ km, and CBs (black cross), plotted at 6-hr intervals during the period from (a) 1800 UTC 2 Oct to (f) 0000 UTC 4 Oct 2015. The black arrows denote the 200–850-hPa large-scale VWS. The mean RMW at $z = 1$ km is also plotted. The red lines in (b), (c), and (d) denote the locations of the vertical cross section used in Figure 4.
rapidly. Most of the CBs preceded the PV anomaly, again indicating that the PV anomaly may have been caused by the CBs to some extent. Furthermore, the RI process mainly started at 0600 UTC 3 Oct and, given the timing of the PV anomaly was earlier, it likely caused the RI process.

In addition, we also analyzed the vertical structure of PV and meridional momentum tendency field (Figure 4d–f). The meridional momentum tendency was calculated by

$$\frac{\partial (\rho v)}{\partial t} = -\nabla \cdot (V\rho v) - f \rho u - \frac{\partial p}{\partial y},$$

(2)

where $\rho$ is air density, $v$ is meridional wind speed, $u$ is zonal wind speed, $f$ is the Coriolis parameter, $V$ is three-dimensional wind speed, and $p$ is pressure.

A PV anomaly center was located in the upper troposphere, which was mainly caused by the CBs, as discussed above, and a strong downdraft was found near the center of the PV anomaly in the upper troposphere. The effects of downward momentum upon the RI process were explored in different RI stages (before/during/after). On the one hand, the downward momentum was able to strengthen the wind speed of the outflow at the middle troposphere; while on the other hand, the downward momentum promoted coupling of the winds at different levels. Before the RI (Figure 4d), the downward momentum mainly occurred in the upper troposphere at 8–11 km, albeit not prominently. Also, a negative center of momentum tendency appeared in the upper troposphere while a positive center occurred in the middle troposphere, demonstrating that the momentum could have been transported from the upper troposphere to the middle
troposphere by the downdraft. During RI (Figure 4e), the downward momentum was clearer and the momentum could be transported from the upper troposphere at $z = 14$ km to the lower levels at $z = 2–3$ km. At this time, a strong and positive center of momentum tendency existed in the lower levels at $z = 2–3$ km and a strong PV center formed by the coupling of two PV centers that were located in the upper troposphere and lower levels, respectively (Figure 4d). In fact, the downward momentum strengthened the compensating subsidence movement and secondary circulation in the eye area of the typhoon, which promoted the strength of the primary circulation and was conducive to the RI process (Rogers, 2010). After the RI (Figure 4f), the downward momentum descended obviously and only occurred in the lower levels. At this time, a weak positive center of momentum tendency was located near the ground. This demonstrates that the effects of downward momentum upon the RI were weak and the RI process terminated.

4.4 Sensitivity tests of the upper-tropospheric PV anomaly

To further verify the mechanism that the upper-tropospheric PV anomaly caused the RI of the typhoon, sensitivity tests were carried out. Figure 5a shows the PV perturbation field at 1800 UTC 2 Oct 2015. The PV perturbation was obtained by subtracting the mean PV averaged during the period from 1800 UTC 23 Sep to 1800 UTC 1 Oct 2015. From the results, a strong PV anomaly center was located at around (18°N, 116°E) at that moment. According to the method proposed by Hoskins, McIntyre, and Robertson (1985), we removed the strong PV anomaly over the area (16°–19°N, 115°–117.5°E) and obtained the PV disturbance field to filter out the PV anomaly in the upper troposphere (Figure 5b). Then, the piecewise PV inversion method (Davis, 1992) was used to retrieve the disturbance field of wind and geopotential height without the PV anomaly in the upper troposphere (Figure 5c). The wind and geopotential height fields at 1800 UTC 2 Oct, retrieved by the PV inversion without the PV anomaly in the upper troposphere, were chosen as the initial conditions to simulate the evolution of the typhoon. The results (Figure 5d) show that the MSLP increased significantly and the maximum sustained 10-m wind decreased as the upper-tropospheric PV anomaly was removed. The RI process of Typhoon Mujigae was not apparent without the upper-tropospheric anomaly. Therefore, the upper-tropospheric PV anomaly played an important role in the RI process of Typhoon Mujigae.

5 CONCLUSION AND DISCUSSION

WRF-ARW was used to simulate the RI of Typhoon Mujigae. The track, intensity, and convection distribution of Mujigae were simulated well, especially in terms of the timing and rate of intensification during the RI process. The spatial distribution and evolution of CBs, and the environmental conditions conducive to CBs, during the pre-RI and RI stages, were then examined. The main findings can be summarized as follows:

An isolated upper-tropospheric positive PV anomaly center was located near Typhoon Mujigae during the pre-RI and RI stages. The upper-tropospheric PV anomaly was not influenced by synoptic-scale PV advection, but was caused by the CBs.
CBs were conducive to the formation of warming cores in the middle and upper troposphere at the onset of, and during, the RI of Mujigae. During the RI, CBs motivated a weak updraft and strong updraft in the eye wall, which outflowed in the middle and upper troposphere, respectively. The two outflows heated the environmental air by releasing latent heat, and two warm centers formed at 6–10 km and 16 km altitude, respectively. The formation and maintenance of the two warm centers led to the RI process of Typhoon Mujigae.

The PV budget results showed that the DH term contributed to the positive PV in the middle and lower levels, while the VA term contributed to that in the middle and upper troposphere. By giving rise to the upper-tropospheric PV anomaly, CBs caused the downward transfer of momentum from the upper to the middle troposphere. The downward momentum increased the wind speed in the middle troposphere and caused the RI process.

Sensitivity experiments showed the MSLP to increase significantly and the maximum sustained 10-m wind speed to decrease without the upper-tropospheric PV anomaly, while the VA term contributed to that in the middle and upper troposphere, respectively. The formation and maintenance of the two warm centers led to the RI process of Typhoon Mujigae.

Clearly, this study comprises only a single case, and more examples are needed to verify the applicability of the conclusions drawn. The effect of outer cloud systems on the RI process, as well as the evolution and development of microphysical processes during RI, and their potential influence on it, will be explored in future research.

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SUPPORTING INFORMATION

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