A simulation study on the rapid intensification of Typhoon Megi (2010) in vertical wind shear

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Abstract

The improved Weather Research and Forecasting model was used to simulate Typhoon Megi, which experienced rapid intensification (RI) and gradual intensification processes. The model reproduced the typhoon track and intensity in accordance with the best-track observations. Our study has shown that in small or moderate shear environments, the great latent heat released in the upper troposphere through the enhancement of convective bursts, which enhanced the upper-level warm core and caused the intensification of typhoon. During the onset of RI, strong convective cells were found gathering in downshear eyewall quadrant or the left side of shear. They also indicated an asymmetric structure in the eyewall. As Megi intensified rapidly, the strong convective activity occurred both in upshear and downshear quadrants, then the symmetrical structures developed well.

Keywords: rapid intensification; typhoon; vertical wind shear; convective burst

1. Introduction

Vertical wind shear (VWS) is regarded as an important factor in the genesis and development of a tropical cyclone (TC). Large VWS leads to inhibition of the generation and declination of the intensity of TC. DeMaria (1996) stated that the potential vorticity (PV) pattern with the vortex circulation becomes tilted in the large VWS environments, which reduces the convective activity and inhibits the storm development. Meanwhile, VWS can also modulate the track and structure of TC. Wu and Emanuel (1993) found that the Northern Hemisphere TCs move to the left of VWS. Frank and Ritchie (2001) hypothesized that shear causes the structure of the eyewall region to become highly asymmetric throughout the depth of the storm. Owing to its relationship with the intensity of TC, VWS is often regarded as a parameter in the intensity prediction of TC (DeMaria and Kaplan, 1994).

The detailed processes by which VWS affects the intensity and structure of TC are presented in recent observations. Using the animated satellite imagery and aircraft data of fifty TCs from 1983 to 1984, Zehr (1992) found that a shear of 12.5 m s\(^{-1}\) inhibited TC development in the western North Pacific (WNP). Several observationally based studies provided evidence of the shear-induced asymmetric structure (Black et al., 2002; Corbosiero and Molinari, 2002; DeHart et al., 2014). In general, updrafts appear downshear right, intensify downshear left, and weaken upshear. Using airborne Doppler radar observations, Reason et al. (2009) found that the greatest intensification of Hurricane Guillermo coincided with the strong convective bursts (CBs) through the left-of-shear semicircle of the eyewall. Hazelton et al. (2015) analyzed a dataset of merged Doppler radar composites. This study found shear-relative asymmetry of radial maximum wind slope was significant. The downshear slope was greater than upshear in most cases. The effect of VWS on TC had also been clearly demonstrated by simulations (Frank and Ritchie, 2001; He et al., 2015). High-resolution numerical simulations of hurricanes indicated that large VWS produced a wavenumber-1 asymmetry in the vertical motion with upward motion in the downtilt direction. In addition, the mesovortices triggered the deep convection as they moved into the downtilt side (Braun et al., 2006; Braun and Wu, 2007).

The venting theory (Simpson and Riehl, 1958; Gray, 1968; Tang and Emanuel, 2010) has been widely used to explain the impact of VWS on TC genesis and intensification. Simpson and Riehl (1958) hypothesized that the intrusion of the drier and cooler air from mid-high level resulted in the decrease of the equivalent potential temperature in the eyewall, thus inhibiting TC intensification. Gray (1968) showed that shear led to the loss of heat and moisture of the upper-level warm core, causing the increase of the central sea level pressure (SLP). Riemer et al. (2013) suggested that the inflow layer of the storm is persistently intruded upon by shear-induced downdrafts.

Although the aforementioned studies explored the impact of VWS on TC genesis and intensification, which have improved our understanding of the interactions between TC and VWS, the particulars of the impact processes and the associated mechanisms are not clear. In addition, recent research shows that the
rapid intensification (RI) of TC is related to CBs in the eyewall region (Reasor et al., 2009; Chen and Zhang, 2013; Chen and Gopalakrishnan, 2015). However, the spatio-temporal correlation and relative importance between VWS and the convective activity in the eyewall region are still not known. The probable mechanism by which VWS impacts the RI needs to be explored further. Therefore, pertinent investigations are required to evaluate the influences of VWS on the RI process of TC in a three-dimensional model to develop an overall picture of the impact of VWS on the inner-core convective activities of TCs.

In this study, Typhoon Megi is simulated for understanding the deep convection effect upon the RI process of TC under different VWS environments. Section 2 describes the experimental design and gives an overview of the simulated storm. The simulated results are analyzed in Section 3. The main findings are summarized in the last section.

2. Model configuration and overview of Typhoon Megi

2.1. Numerical model and experimental design

The Weather Research and Forecasting (WRF) model was used to conduct the simulation experiment. Based on the Community Gridpoint Statistical Interpolation (GSI) system and its three-dimensional variational data assimilation (3DVAR) method, the 6 hourly radiance data of Advanced Microwave Sounding Unit A (AMSU-A) and B (AMSU-B) datasets were assimilated into the improved WRF v3.6.1. The 6-hourly circulation assimilation was conducted in the full simulation. The model had 38 uneven vertical levels and two domains of 214 × 118 and 499 × 211 grid points, with resolutions of 15 and 5 km, respectively. We chose the WRF single-moment 6-class scheme (WSM6), the Yonsei University scheme (YSU) and the Kain-Fritsch scheme each for the parameterization of microphysical processes, planetary boundary layer and cumulus convection. The model run from 0000 UTC on 14 October 2010 to 0000 UTC on 24 October 2010 and the time step was 30 s. The 6-hourly Climate Forecast System Reanalysis (CFSR) data from the National Centers for Environmental Prediction (NCEP) was chosen as the initial and boundary condition with the resolution of 0.5°. The simulated track and intensity of Typhoon Megi were compared with the best-track data from Joint Typhoon Warning Center (JTWC).

2.2. Overview of Typhoon Megi

As one of the most intense TCs on record, Megi had a complex track and experienced two periods of intensification. It caused torrential rainfall with 24 h accumulated precipitation of 1182 mm in Yilan, Taiwan. In addition, 13 people died, 26 people were missing and the storm caused at least 67.74 million yuan in agricultural damage in Taiwan. As a very intense TC, which underwent a period of RI and caused death and damage, Typhoon Megi was chosen to simulate in our study.

Megi began as a tropical disturbance over the WNP on 10 October 2010. It became a tropical depression at 1200 UTC on 13 October and intensified to a tropical storm at 1200 UTC on 14 October, then was upgraded to a typhoon in the same day. As shown in Figure 1(a), Megi moved toward the west-northwest at first, then turned west-southwest and made landfall over Luzon Island, Philippines at 0400 UTC 18 October. Thereafter, it entered the South China Sea and moved northwestward. On 20 October, Megi turned to nearly northward suddenly. It made the second landfall over Zhanapu area in Fujian at around 0400 UTC on 23 October. Time series of the intensity shows that Megi intensified rapidly on 16 October and became a super typhoon at 0000 UTC on 17 October. After 12 h, Megi reached its peak with the lowest SLP of 903 hpa and the maximum wind speed of 80 m s⁻¹ near the eye area. During the first intensification period, the maximum winds increased from 45 m s⁻¹ at 0000 UTC 16 October to 70 m s⁻¹ at 0000 UTC 17 October, which can be classified as RI. The RI definition for all TCs in the WNP is an increase of maximum sustained winds of 30 kt in 24 h (Wang and Zhou, 2008). Megi weakened significantly after the first landfall. Owing to the high sea surface temperature (SST) and other favorable conditions, it reintensified to a super typhoon. Finally, it weakened and dissipated completely on 24 October.

3. The analysis of simulated results

3.1. Track and intensity

Figure 1 depicts the simulated track and intensity of Typhoon Megi. Compared to the observation, the track was well simulated although the simulation still exhibited some small deviations (Figure 1(a)). Two track deflections of Typhoon Megi were consistent with the observation. It can be seen that the simulated typhoon took a more southward path before its first landfall, then moved a bit northward. After turning northward, the simulated track was very close to the best-track data. During its life cycle, the averaged bias of track prediction was <50 km. The model accurately simulated the landfall time and location, with the first landfall over Luzon Island and the second landfall over Zhanapu district in Fujian Province.

Figure 1 also shows the modeled intensity. Two intensification periods were simulated, including the RI with an increase of 15.5 m s⁻¹ in 18 h from 1800 UTC 15 October and the gradual intensification with 14 m s⁻¹ in 24 h from 1200 UTC 18 October. Compared to the central SLP of observation, the simulation reproduces the intensity change of Typhoon Megi, especially showing the two periods of intensification. At 0000 UTC on 18 October, the simulated storm achieved its peak intensity with the SLP of 912 hpa, 9 hpa weaker than
the observation. Although there was a time lag for the peak intensity between simulation and observation, the simulated Megi rapidly weakened after its landfall over Luzon Island, consistent with the JTWC data. The second period of gradual intensification was also shown in simulation and was close to the observation. Owing to the lower SST and stronger VWS at the later stage of the integration, Megi weakened rapidly. During the whole simulation period, the modeled maximum surface wind was weaker than observation, but represented the correct trend (Figure 1(c)).

3.2. Vertical wind shear

Typically, the magnitude of VWS is defined as the difference of the averaged horizontal wind between 200 and 850 hpa in a specific given region. In this study, a 420×420 km² horizontal wind was used to calculate VWS. Time series of central SLP and VWS are plotted in Figure 2(a). The result of the 200–850 hpa VWS indicated that shear was <7.5 m s⁻¹ in the first 24 h at every moment, which allowed Megi to strengthen. After the first 24 h, typhoon weakened gradually due to the larger VWS. Shear decreased preceding RI and in the early RI stage. The averaged VWS was only 4.8 m s⁻¹ during the RI stage. Compared to the RI period, the VWS was comparable for the weakening period after Megi’s first landfall. It can be concluded that the decrease of surface heat and moisture fluxes controlled the intensity rather than VWS. Under the environment of the weak 5.2 m s⁻¹ VWS, Megi intensified gradually after 1200 UTC on 18 October and completed its second intensification until 1200 UTC on 20 October. Thereafter, the VWS was >6 m s⁻¹ at every moment. Typhoon Megi weakened and dissipated. The intensity evolution with respect to the shear is consistent with the previous studies (Zehr, 1992; He et al., 2015). Regarding the 500–850 hpa VWS, shear decreased gradually in the early RI stage. Small shear persisted until the later time of the second intensification period, with small fluctuations. It should be noted that the 500–850 hpa shear was bigger than the 200–850 hpa shear from 20 October to 23 October. Apparently, RI onset was related to the decreasing shear and the small shear was beneficial to the intensification of Typhoon Megi.

For the better understanding on the effect of VWS on Typhoon Megi in the intensification stages, the hodographs are provided to show the magnitude and direction of the horizontal wind. At 0000 UTC on 16 October, the VWS was 6.3 m s⁻¹ from the southwest (Figure 2(b)). The horizontal wind changed from about 5.4 m s⁻¹ at 850 hpa level from the southeast toward northwest to 9.5 m s⁻¹ with an approximately same direction at 200 hpa level. Later on, the shear decreased to only 2 m s⁻¹ and became westward (Figure 2(c)). From Figure 2(d), the northwesterly VWS was 2 m s⁻¹, which benefited the reorganization and intensification of Typhoon Megi. The hodograph at 1200 UTC on October 20 (Figure 2(e)) showed the VWS increased to >6 m s⁻¹.

3.3. Convective structure in the eyewall

The horizontal distributions of the low-level vertical velocity and the equivalent potential temperature are shown in Figure 3. In the early RI stage (Figure 3(a)), a strong ascending motion existed on the west side of the eyewall, which was situated on the left side of the shear. In addition, the second strong ascending motion was situated on the downshear side, whereas
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Figure 2. (a) Time series of modeled SLP (black line), 200–850 hpa VWS (red line) and 500–850 hpa VWS (green line). The vertical black dashed line indicates RI onset. The hodograph at (b) 0000 UTC 16 October, (c) 1800 UTC 17 October, (d) 1200 UTC 18 October and (e) 1200 UTC 20 October. SI indicates the second intensification.

(a)

(b)

(c)

(d)

(e)

The weak ascending motion was on the right side of VWS. At 1800 UTC 17 October (Figure 3(b)), the VWS decreased significantly and the vertical motion in the eyewall was nearly axisymmetric. Two small areas of upward motion with the velocity >3 m s$^{-1}$ appeared in the east and southwestern quadrant as the typhoon intensified. After Megi’s first landfall, a decrease in surface heat and moisture fluxes that subsequently reduced eyewall instability, weakened eyewall convection. The eyewall of Megi disappeared and typhoon structure became loose although the VWS was still only 2 m s$^{-1}$ at 1200 UTC on 18 October (Figure 3(c)). At the later stage of the second intensification period, the maximum ascending motion area occurred in the downshear semicircle and left-of-shear quadrant while the direction of the VWS changed (Figure 3(d)). In general, the maximum upward motion area in eyewall is accord with the shear direction, which is on the left side of shear or in the downshear quadrant.

In addition to the horizontal distribution of the convective structure in the eyewall, we also focus on the vertical structure (Figure 4). The left side of...
Figure 3. The vertical velocity (color shading, m s$^{-1}$) and equivalent potential temperature (black contours, K) averaged in the lowest 2 km at (a) 0000 UTC 16 October, (b) 1800 UTC 17 October, (c) 1200 UTC 18 October and (d) 1200 UTC 20 October. The VWS is depicted by the black arrow and the gray lines in Figure 3(c) indicate the topography (>1000 m).

each panel denotes the upshear direction and the downshear direction is given on the right side. The vertical cross sections show the shear-induced asymmetric structure, vigorous convection was on the downshear side while convection in upshear direction was suppressed. The first cross section (Figure 4(a)) demonstrates the convective asymmetry, in which convective activity enhanced along the VWS vector. Compared to the stronger shear case, the convection was distributed symmetrically when VWS reduced to 2 m s$^{-1}$ (Figure 4(b)). In both downshear and upshear directions, there was strong upward motion. Moreover, there was no obvious eye contraction during the RI stage, Wang and Wang (2014) showed that the lack of eye contraction was attributed to diabatic heating in active spiral rainbands. The convection was inhibited and the typhoon structure was destroyed at 1200 UTC on 18 October (Figure 4(c)). The figure also showed the convective asymmetry reappeared in Figure 4(d) with the increase of the VWS.

3.4. Latent heat effect

To examine the influence of latent heat associated with VWS upon the RI process of Typhoon Megi, the time series of CB numbers [the definition of a CB is that a
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Figure 4. Vertical cross sections along the VWS vector for radar reflectivity (color shading, dBZ), equivalent potential temperature (black contours, K) and storm-relative wind component (arrow, m s\(^{-1}\)) at the same time as Figure 3. The black shading in Figure 4(c) indicates the topography.

grid point with its maximum vertical motion >3 m s\(^{-1}\) in the column (Chen and Gopalakrishnan, 2015) in 150×150 km\(^2\) around the typhoon center are shown in Figure 5(a). The heating rates are averaged within the same area and its time-height cross section is plotted in Figure 5(b). The time-accumulated hydrometeor budget during the RI period demonstrated that the condensation of water vapor into cloud water and the accretion of rain by graupel were the main microphysical processes that contributed to warming effect (picture omitted). Figure 5(a) shows that CB numbers suddenly increased when RI started and the large number persisted until 0000 UTC 18 October. Note that, the increase in CB activity coincided with the onset of RI and did not...
precede the onset of RI. Rogers (2010) also showed a similar timing between the RI onset and an increase in convective rain. The CB elements of the slower intensification stage were less than RI. In terms of the heating rate (Figure 5(b)), two heating centers existed in RI stage with a maximum heating rate of $1.1 \times 10^{-2}$ Ks$^{-1}$ at the height of 4 km. After its first landfall, the strong center disappeared. Until 19 October, the heating center reappeared, with the rate of $0.6 \times 10^{-2}$ Ks$^{-1}$. The heating rate deceased gradually after 21 October. It appears that there is a relationship between CBs and latent heat release. In the small or moderate shear environments, Typhoon Megi intensified associated with CBs. The enhanced vertical motion drove the water vapor to be transported upward, so that a great deal of latent heating released in the upper troposphere, which was conducive to the maintenance of the upper-level warm core, causing the intensification of typhoon. In turn, the released latent heat caused the rise of warm air, triggering the convective activities. It also contributed to the instability of the troposphere, strengthening the convection accordingly. Early studies have proved that the increasing latent heat enhanced the convection (Danard, 1964; Wang and Wang, 2014; Miller et al., 2015). Overall, the CBs and latent heat contributed to the intensification of Typhoon Megi in small and moderate shear environments. The decrease of the heating rate after 21 October appears to be related to the increase of shear (Gray, 1968).

Figure 5(c) shows the area-averaged and time-accumulated heating rate profiles for the two intensification periods. It was accumulated from 0000 UTC 16 October to 0000 UTC 18 October during RI stage and from 1200 UTC 18 October to 1200 UTC 20 October for the second intensification. The trend of heating rate profiles was similar and strong heating effect appeared between 3 and 6 km altitude in the two stages, but the heating rate in RI stage was almost two times more than that in gradual intensification stage.

As mentioned earlier, there is a relationship between heating rate and CBs. It can be seen from the comparison between Figures 3 and 6 that the heating effect distribution was accord with the vertical velocity. The maximum heating rate occurred in the downshear quadrant or the left side of shear in moderate shear cases (Figures 6(a) and (d)), due to the CBs associated with eyewall asymmetry. It showed an axisymmetric heating structure under the weak shear environments (Figures 6(b) and (c)).
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Figure 6. The heating rate (color shading, $10^{-2}$ K s$^{-1}$) and the horizontal wind (vector, m s$^{-1}$) at the height of 3 km at the same time as Figure 3. The VWS is depicted by the black arrow.

4. Conclusions and discussions

The Typhoon Megi was simulated using the improved WRF model and the model reproduced the typhoon track and intensity that were consistent with the best-track observations, which were available for the later analysis. In this study, we had evaluated the inner-core convection associated with intensity in different sheared environments. The main conclusions were as follows.

1. Typhoon Megi experienced the RI process in relatively weak shear environments. It was associated with the burst of deep convection in its inner core.
2. The convection in the core area of Typhoon Megi had changed from an asymmetric to a symmetrical structure during the RI stage.
3. In small or moderate shear environments, the enhancement of vertical motion drove more latent heating to release in the upper troposphere, which effectively maintained the upper-level warm core, causing the intensification of typhoon. In turn, the released latent heating not only caused the rise of warm air but also enhanced the instability of the troposphere, further enhancing the convection activities. In addition, the asymmetric structure of latent heat is associated with convective asymmetry in the eyewall.

This article showing the insight of the deep convection effect upon the RI process of TC under different VWS environments needs to be further confirmed in simulation of more cases. Moreover, the potential relation or mechanism between the CB and VWS still needs to be explored further in the future.

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