Impacts of Horizontal and Vertical Resolutions on the Microphysical Structure and Boundary Layer Fluxes of Typhoon Hato (2017)

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Abstract: We set four sets of simulation experiments to explore the impacts of horizontal resolution (HR) and vertical resolution (VR) on the microphysical structure and boundary layer fluxes of tropical cyclone (TC) Hato (2017). The study shows that higher HR tends to strengthen TC. Increasing VR in the upper layers tends to weaken TC, while increasing VR in the lower layers tends to strengthen TC. Simulated amounts of all hydrometeors were larger with higher HR. Increasing VR at the upper level enhanced the mixing ratios of cloud ice and cloud snow, while increasing VR at the lower level elevated the mixing ratios of graupel and rainwater. HR has greater impact on the distributions of hydrometeors. Higher HR has a more complete ring structure of the eyewall and more concentrated hydrometeors along the cloud wall. Increasing VR at the lower level has little impact on the distribution of TC hydrometeors, while increasing VR at the upper level enhances the cloud thickness of the eyewall area. Surface latent heat flux (SLHF) is influenced greatly by resolution. Higher HR leads to larger water vapor fluxes and larger latent heat, which would result in a stronger TC. A large amount of false latent heat was generated when HR was too high, leading to an extremely strong TC, VR has a smaller impact on SLHF than HR. But increasing VR at the upper-level reduces the SLHF and weakens TC, and elevating VR at the lower-level increases the SLHF and strengthens TC. The changes in surface water vapor flux and SLHF were practically identical and the simulation results were improved when HR and VR were more coordinated. The friction velocity was greater with higher VR. Enhancing VR at the lower level increased the friction velocity, while increasing VR at the upper level reduced it.

Key words: tropical cyclone; horizontal resolution; vertical resolution; WRF

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1 INTRODUCTION

While numerical models play an increasingly important role in forecasting tropical cyclones (TC), there are still many uncertainties in numerical forecasting process and grid resolution is one of them (Lindzen and Fox-Rabinovitz [1]; Schwartz et al. [2]; Kevin and Gary [3], Jin et al. [4]). The horizontal resolution (HR) may have been found to be one of the main reasons to bring large difference between the simulated TC structure and the observation (Rogers et al. [5]; Fierro et al. [6]). Many studies have shown that HR has few impact on the simulated TC track while increasing HR can enhance TC (Zhang and Wang [7]; Davis et al. [8]; Gentry and Lackmann [9]; Fierro et al. [6]; Wang and Zeng [10]; Zhao et al. [11]; Wu et al. [12]). However, there is no linear relationship between HR and TC intensity. Sun et al. indicated that when HR changes from 3 km to 1 km, the TC intensity significantly increases [13]. However, in another similar case the outcome tends to be different; the TC intensity decreases and microstructure improves when HR increases to 1 km (Wen et al. [14]). When HR varies from 4 km to 1.3 km, the minimum sea level pressure is reduced by 20 hPa and the maximum wind velocity is increased by 13 m s⁻¹ (Davis et al. [8]).

Vertical resolution (VR) is another important factor affecting TC simulation (Zhang and Wang [7]; Bhaskar Rao et al. [15]; Ma et al. [16]; Wu et al. [12]). Zhang found out that VR had little impact on TC track while significant impact on TC intensity [7]. Increasing VR can enhance TC, which is especially efficient while increasing it at the lower level (Zhang and Wang [7]; Zhang et al. [17]). Meanwhile, TC intensity is not sensitive to the upper-level VR. Hence, there is no significant improvement when upper-level VR is increased (Zhang and Wang [7]; Ma et al. [16]). Besides,
Bhaskar Rao indicated that VR has an impact on TC track. Simulated TC track can be improved due to the increased VR at the lower-level or the entire troposphere \[15\].

However, there are different explanations for how VR influences TC. TC intensity may be determined by the sensitivity to VR at the boundary layer and cumulus processes. Increasing lower-level VR enhances lower-level water vapor convergence (Ma et al. \[18\]), resulting in higher latent heat release. Additionally, increasing VR brings better-formed TC eye and cloud wall structures, leading to stronger TC (Zhang and Wang \[7\]).

In recent years, HR in many operational numerical models has increased from 2 to 10 km (Davies et al. \[19\]; Hong and Dudhia \[19\]; Benjamin et al. \[20\]). At present, HR in some models has reached 1 km or even less. However, there are studies showing that HR and VR should meet a certain degree of coordination (Lindzen and Fox-Rabinovitz \[2\]; Liu et al. \[21\]). Persson and Warner proved that false gravitational waves occurred when HR was increased while VR was not, using a two-dimensional numerical model \[22\]. Therefore, while increasing the HR, the model is confronted with higher requirements of calculation. Various physical parameterization schemes need to be re-studied and requirements for how to design VR need to be put forth.

Previous studies mainly focused on the impact of HR on TC intensity; these are comparative analysis of the results from sensitivity experiments. Some of the studies merely explained the causes from the perspective of dynamic processes. The effect of VR on TC has not been studied thoroughly, especially when HR is becoming higher. Microphysical latent heat process and boundary layer fluxes are closely related to HR (Rogers et al. \[1\]; Davis et al. \[8\]; Li and Pu \[23\]; Kueh et al. \[24\]) as important factors affecting TC intensity and structure (Li et al. \[25\]-\[29\]; Green and Zhang \[27\]; Ding et al. \[28\]; Zhao et al. \[29\]; Li et al. \[30\]-\[31\]). The difference between the influences of HR and VR on microphysical structure and boundary layer flux remains unclear.

We previously explored the impacts of HR on TC intensity (Zhao et al. \[11\]). The results showed that simulated TCs were enhanced with increased HR, which was mainly due to that TC cloud wall became steeper with increased resolution. Based on this, this study added sensitivity experiments and combined the two factors, HR and VR, to further explore the impact of HR and VR on the microphysical structure and boundary layer fluxes of TC, aiming to better explain the physical process of the resolution inducing the change of TC intensity.

The next section briefly summarizes an overview of TC Hato. Section 3 describes the experimental design. Section 4 demonstrates the impact of HR and VR on the microphysical structure and boundary layer fluxes. In the end, conclusions and discussion are given.

2 AN OVERVIEW OF TC HATO

Super typhoon Hato formed on the surface of the Pacific Ocean at 06:00 on 20 August 2017, with a central pressure of 1000 hPa and a maximum wind velocity of 18 m s\(^{-1}\) near the center at its formation. From its formation until its entrance into the South China Sea, the intensity of Hato increased slowly and developed rapidly after it entered the South China Sea. In 24 hours, the intensity grade developed from tropical storm to strong TC. Hato landed in Zhuhai, Guangdong at approximately 05:00 on 23 August (one hour before its landing) with a central pressure of 940 hPa, a maximum wind velocity of 48 m s\(^{-1}\), and a movement speed of 30 km h\(^{-1}\). After its landing, Hato continued to move northwesterly with its intensity quickly weakening. Two hours after landing, it weakened to be TC and dissipated at 09:00 on 24 August. Hato exerted the greatest impact on Guangdong Province in 2017. In general, it has caused heavy losses to the Pearl River Delta region, resulting in 26 deaths and economic losses of US $4.31 billion.

3 EXPERIMENTAL DESIGN AND DATA

This study adopted non-hydrostatic mesoscale numerical model (WRF, Version 3.8.1) (Skamarock et al. \[32\]), with the Mercator chart for projection. HRs of nested master regions of the model were 27 km. The simulation durations were set at 112 hours and the simulation started at 00:00 on 20 August 2017. The top of the atmosphere was set at 50 hPa using the NOAH land surface process scheme (Chen and Dudhia \[33\]), Lin cloud microphysical scheme (Lin et al. \[34\]), YSU non-local closed boundary layer scheme (Hong et al. \[35\]), RRTM long wave radiation scheme (Mlawer et al. \[36\]), and the Dudhia shortwave radiation scheme (Dudhia \[37\]). Except for regions with a HR of 1 km, other regions adopted the FK convective parameterization scheme (Kain \[38\]).

Four Groups of experiments were designed (Table 1). Groups A had 27 levels in the vertical direction, and Group B had 30 levels in the vertical direction. Beside this, other experiment settings are the same. The number of two-way nesting levels was the same as the HR in Group C, while the VR was different. The hyperbolic tangent method was adopted in Group A, Group B, and Group C for vertical layering. In Group D, on the basis of 30 levels, 5 levels were added to the upper or lower layers.

NCEP/NCAR FNL data once every 6 hours are employed as the initial field. Corresponding horizontal resolution is 1 °×1 °. The observational data of TC track and intensity (http://tcdatanet.org.cn/) are from the China Meteorological Administration tropical cyclone database (Ying et al. \[39\]).
Table 1. Experimental design.

| Group  | 1-L27   | 2-L27   | 3-L27   | 4-L27   |
|--------|---------|---------|---------|---------|
| Group A| HR (nested grids km) | 27 | 27-9 | 27-9-3 | 27-9-3-1 |
|        | VR (levels)           | 27 | 27 | 27 | 27 |

| Group B| 1-L30   | 2-L30   | 3-L30   | 4-L30   |
|--------|---------|---------|---------|---------|
|        | HR (nested grids km) | 27 | 27-9 | 27-9-3 | 27-9-3-1 |
|        | VR (levels)           | 30 | 30 | 30 | 30 |

| Group C| 3-L27   | 3-L30   | 3-L33   | 3-L36   | 3-L39   |
|--------|---------|---------|---------|---------|---------|
|        | HR (nested grids km) | 27-9-3 | 27-9-3 | 27-9-3 | 27-9-3 | 27-9-3 |
|        | VR (levels)           | 39 | 30 | 33 | 36 | 39 |

| Group D| LOW3   | HUP3   | LOW4   | HUP4   | CTL    |
|--------|-------|-------|-------|-------|-------|
|        | VR (levels) | 27-9-3 | 27-9-3 | 27-9-3-1 | 27-9-3-1 |
|        | 35 (5 levels were added to the lower layers) | 35 (5 levels were added to the upper layers) | 35 (5 levels were added to the lower layers) | 35 (5 levels were added to the upper layers) | 30 |

4 RESULTS

4.1 TC intensity and track

Higher HR tended to strengthen the TC (Fig. 1a, 1b). Vertical levels were layered using hyperbolic tangent. The number of vertical levels increased (Fig. 1a, 1b, 1c), and higher HR weakened the TC (Zhao et al. [11]). Higher VR in upper layers tended to weaken TC (Fig. 1d) while higher VR in lower layers tended to strengthen TC. HR and VR affected the simulated TC tracks (figure omitted) to some extent for that their variations were closely related to the variations of TC intensity and structure (Ma et al. [16], Wang and Zeng [10], Zhao et al. [11]). From Fig. 1, we can see that scheme 3-L30 and 4-L30 performed the best. To save resources, VR is set to 30 levels and HR is set to 3 km.

Figure 1. The simulated minimum sea level pressure and the observations from 00:00 on 20 August to 16:00 on 24 August 2017.
4.2 The impact of HR and VR on microphysical structure

In previous study, it is found that the inclination of typhoon cloud wall would be steeper, and the intensity of the simulated vertical wind speed would be larger while increasing HR (Zhao et al. [13]). The maximum value of cloud ice occurs at an altitude of 14 km and the radial distribution of cloud ice is extensive (Fig. 2), which is related to the upper-level divergent air flow. In Group A, simulated cloud ice is the smallest in 3-L27 and the largest in 4-L27. Cloud ice in 4-L27 is extended down to a height of 5 km, much lower than others. In Group B, the amount of cloud ice increases with HR. Cloud water distribution in the lower-level region reached 8 km in height and the maximum height of cloud water gradually increases with increasing HR. The maximum cloud water height of the 4-L27 reached above 12 km, extending to the height of cloud ice formation. In two sets of experiments, the intensity of cloud water basically increases with resolution. The intensity of cloud water in the 4-L27 is smaller, which may be because that more cloud water transformed into cloud ice, thereby the amount of cloud water reduced and that of cloud ice increased.

Figure 2. The azimuth average (units: g kg⁻¹) of simulated cloud water (shadow) and cloud ice (solid line) at 01:00 on 23 August 2017 in Group A and B.
The snow is distributed above the graupel (Fig. 3). The graupel comes from rain, cloud water, cloud ice and snow (Lin et al. [31]). The amounts of graupel and snow gradually increase as HR increases, so does the maximum height of graupel. When HR is 27 km, graupel is distributed below 10 km. When HR is 1 km, the maximum height of graupel exceeds 15 km. Rainwater is mainly distributed below 6 km, right below the graupel. In two sets of experiments, the rain intensity simulated with the schemes with 1-km resolution is lower than those with 3-km resolution. The maximum radius of graupel, snow, and rainwater decreases with the increase of HR, while the TC eye narrows.

Figure 3. The azimuth average (units: g kg$^{-1}$) of simulated rainwater (shadow), graupel (dotted line) and snow (solid line) at 01:00 on 23 August 2017 in Group A and B.
More cloud ice is generated in the upper-level when the upper-level VR increases (Fig. 4). Meanwhile, the cloud ice is slightly reduced when lower-level VR increases. Increasing lower-level VR has little impact on cloud water. When the range of cloud water value and the upper-level resolution increase, the height of the high-value region of cloud water decreases and the range becomes smaller.

![Figure 4](image.png)

Figure 4. The azimuth average (units: g kg⁻¹) of simulated cloud water (shadow) and cloud ice (solid line) at 22:00 on 22 August 2017 in Group D.

The maximum snow amount in LOW3 is 0.4 g kg⁻¹ (Fig. 5). The range of snow is greater than 0.3 g kg⁻¹, slightly larger than that of the 3-L30 direction. The intensity and range of the snow in HUP3 is similar to that in the CTL test, just slightly weaker. Snow distribution in LOW4 is the same as that in the CTL; the range of snow is bigger than 0.3 g kg⁻¹ and small in the high-value region. The amount of graupel is higher in LOW3 and LOW4 than that in 3-L30 and CTL test, respectively; the amounts of snow in HUP3 and HUP4 are comparable while the amounts of graupel are significantly lower than that in 3-L30 and CTL test, indicating that the amount of snow transforming to graupel is reduced when the upper-level VR increases. Therefore, in spite of the increased upper-level resolution and weakened TC intensity, the amount of snow does not change significantly. As the lower-level VR increases, the amount of rainwater increases. When the upper-level VR increases, the amounts of rainwater and graupel decrease.

4.3 The impact of HR and VR on boundary layer flux

The high-value regions of the surface latent heat flux (SLHF) are concentrated on the east side of the cloud wall (Fig. 6) of the TC center. SLHF decreases gradually as the cloud wall extends outward. When VR is set to 27 levels with an increase in HR, the magnitude of the TC eye gradually shrinks and the intensity of SLHF gradually increases. The energy of the TC is stronger when the SLHF acquired by the TC is greater. SLHF value in the 4-L27 is the largest, so its simulated TC has the highest intensity. When VR is 30 levels, the intensity and distribution of SLHF in 4-L30 and 3-L30 are relatively close and the simulated TC intensities of the two schemes are similar.

The magnitude of the surface sensible heat flux (SSHF) is distinctly smaller than that (Fig. 7) of SLHF, which indicates that SLHF is an important source of TC energy. When the resolution is set to 27 km, SSHF is simulated very poorly with very low intensity. Compared with 2-L27, the simulated intensity and range of SSHF in 3-L27 scheme are reduced. When SLHF of the simulated environmental field of the TC in 4-L27 is reduced, the difference between the SLHF of the TC core region and the SLHF of the environmental field is greater and the energy obtained by TC from the environmental field increased. The spiral structure of the TC is clearer and high-value region of the SLHF draws close to the TC center. When VR is 30 levels, 3-L30 has the largest SSLH, and there is little difference between the SSH distributions of the 4-L30 and the 3-L30 scheme. Meanwhile, the SSHF of the simulated environmental field using 2-L30 scheme is larger.
Figure 5. The azimuth average (units: g kg$^{-1}$) of simulated rainwater (shadow), graupel (dotted line) and snow (solid line) at 22:00 on 22 August 2017 in Group D.

Figure 6. Simulated surface latent heat flux (units: W m$^{-2}$) of Group A and B at 01:00 on 23 August 2017.
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The experiment shows that HR has greater effect on the strength of surface water vapor flux (SWVF) than on the distribution of it. The distributions of SWVF simulated by different HR schemes are basically the same (Fig. 8), so are the distributions of SLHF. When the vertical layer is 27 levels, the high-value region of SWVF is mainly distributed along the east side of the TC’s eye and the SWVF in 4-L27 is the largest. When VR is set to 30 levels, simulations of 3-L30 and 4-L27 have similar SWVF.

SWVF is the largest in 4-L27 (Fig. 9a) and the smallest in 1-L27. The magnitude of SWVF is consistent with TC intensity. In Group B, the variations of SWVF in 3-L30 and 4-L30 are practically the same (Fig. 9b). SWVF in 1-L30 is the smallest. SWVF in Group B is generally less than that in Group A. As HR increases, TC intensity increases and the simulated SWVF also gradually increases.

The variations of SLHF and SWVF while using different schemes are basically the same (Fig. 10), indicating that SLHF and SWVF vary closely. SLHF increases accordingly as SWVF increases. The energy obtained by TC will be greater if SLHF is larger and the intensity of the simulated TC is stronger. SLHF in 4-L27 is 400 W m\(^{-2}\), which is more than those simulated by other schemes and results in a large amount of false SLHF and the strongest TC. Scheme 1-L27 simulated the lowest SLHF. SLHF in 2-L30 is larger than that in 3-L30. SWVF in Group B increases as the resolution increases and the SLHF curves of 3-L30 and 4-L30 are

**Figure 7.** Simulated surface sensible heat flux (units: W m\(^{-2}\)) of Group A and B at 01:00 on 23 August 2017.

**Figure 8.** The surface water vapor flux (units: 10\(^{3}\) kg m\(^{-2}\) s\(^{-1}\)) simulated in Group A and B at 01:00 on 23 August 2017.
strongly matched.

The surface friction velocity (SFV) reflects TC intensity. Stronger TC is related with higher SFV. Variation of the friction velocity in 2-L27 and that of the SFV in 3-L27 are similar (Fig. 11). Simulated TC intensities of two tests are close. SFV in 4-L27 reflects the maximum and its simulated TC is also the strongest.

Figure 9. The average surface water vapor flux (units: \(10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}\)) changes over time in the TC-centric region within 150 km in (a) Group A, and (b) Group B.

Figure 10. The average surface latent heat flux (units: W m\(^{-2}\)) changes over time in the TC-centric region within 150 km in (a) Group A, and (b) Group B.

The 1-L27 test exhibits the minimum frictional velocity. In Group B, the SFVs in 4-L30 and 3-L30 are basically the same while the SFV in 1-L27 is minimal. SFV of Group B is generally smaller than that of Group A, indicating that SFV is greater with higher VR and thus enhanced TC.

The magnitude of SLHF exhibits a strong influence
on TC intensity. As upper-level VR increases (Fig. 12b, 12e), the maximum of SLHF decreases. As the lower-level VR increases (Fig. 12a, 12d), the maximum of SLHF increases. Therefore, increasing upper-level VR will decrease TC intensity, while increasing the lower-level VR will increase TC intensity.

Figure 12. Simulated surface latent heat flux (units: W m$^{-2}$) of Group D at 22:00 on 22 August 2017.
When SSHF is positive (Fig. 13), the closer it is to the eyewall, the larger SSHF will be. The SSHF of TC is an important part of maintaining its warm core structure. An increased lower-level VR leads to a slight positional change in the high-value region of SSHF. When upper-level VR increases, the high-value region of SSHF occurs along the southwest side of the TC center and the maximum of SSHF becomes smaller.

The high-value regions of SWVF in HUP3 and HUP4 are mainly distributed in the southwest of the TC (Fig. 14), in contrast to simulations using other schemes, where the high-value regions are distributed in the southeast of the TC. The magnitudes of SWVF in LOW3 and HUP3 are close to that in 3-L30. The SWVFs in LOW4 and HUP4 are relatively close to that in the CTL test. Increasing upper-level VR has greater impact on the distribution of SWVF, while increasing the lower-level VR has smaller influence. According to the regional average SWVF (Fig. 15a), the maximum value will slightly increase when lower-level VR is increased and decrease when the upper-level VR is increased.

Figure 13. Simulated surface sensible heat flux (units: W m$^{-2}$) of Group D at 22:00 on 22 August 2017.

Figure 14. Simulated surface water vapor flux (units: 10$^{-3}$kg m$^{-2}$s$^{-1}$) of Group D at 22:00 on 22 August 2017.
Increasing lower-level VR will increase SFV (Fig. 15b) and TC momentum flux. Meanwhile, increasing upper-level VR will reduce them. SFV in HUP3 is smaller than that in HUP4, which shows that change in VR impacts SFV differently under different HR.

Figure 15. The average (a) surface water vapor flux (units: 10^7 kg m^-2 s^-1) and (b) friction velocity (units: m s^-1) changes over time in the TC-centric region within 150 km in Group D.

5 CONCLUSIONS AND DISCUSSION

This study conducted four groups of experiments to explore the impacts of different HR and VR on the microphysical structure and boundary layer flux of TC Hato (2017) using WRF model; the physical mechanism of these impacts and the potential of eventually leading to different TC intensities was also studied.

Higher HR will enhance the strength of TC. When using hyperbolic tangent to layer vertical levels, higher VR will weaken the strength of TC. The conclusion is different from other studies (Zhang and Wang [7]; Ma et al. [16]). Increasing VR in upper layers tends to weaken TC while increasing VR in lower layers tends to strengthen TC, which is consistent with previous studies (Zhang and Wang [7]; Bhaskar Rao et al. [13]; Ma et al. [16]).

HR has large impact on the hydrometeor concentration of the TC. As HR increases, the amount of cloud ice also increases. The upward momentum of the water vapor is larger when the vertical wind velocity is increased. Meanwhile, the amount of cloud ice formed at upper-level is increased as well. Snow is distributed above graupel as the graupel are generated due to the snow. Therefore, the changes in graupel and snow are similar. Rainwater is mainly distributed right below the height of graupel, indicating that the rainwater is mainly formed from graupel melting after dropping down to the zero-degree level. Hence, the distributions of rainwater and graupel are similar. The hydrometeor content increases when higher HR is applied.

When upper-level VR increases, more cloud ice and snow are generated at the upper-level. When lower-level VR increases, the amount of cloud ice slightly decreases. Increasing lower-level VR has little impact on the amount of cloud water. However, it has certain impact on the range of cloud water. The height of the high-value region of cloud water reduces within a smaller range due to a higher VR. As VR increases at the upper-level, the amount of snow turning into graupel decreases as well as the amount of it turning into rainwater. Correspondingly, as VR increases at the lower-level, the amounts of rain and graupel increase with the slight increase in the amounts of cloud ice and snow.

The TC’s energy mainly comes from the latent heat released by water vapor condensation. The resolution has a great impact on the SLHF. Higher HR leads to larger water vapor flux, larger SLHF release, enhanced TC energy, and strengthened TC. When the resolution is coordinated, increasing HR has little impact on the SLHF. When HR is too high, a large amount of false latent heat is generated, leading to an excessively strong TC. Compared with HR, VR has smaller impact on the SLHF. Increasing lower-level VR leads to decreased latent heat at the upper-level and increased latent heat at the lower-level.

The SLHF is the main source of TC energy. The variation of HR has greater impact on the SLHF. High-value region of SLHF is concentrated along the east side of the cloud wall of the TC center. SLHF decreases gradually as the cloud wall extends outward. The size of the TC eye in the SLHF chart gradually becomes smaller with an increase in HR and the intensity of SLHF is gradually enhanced. An excessively high HR will produce a strong false latent heat flux while the simulation of the SLHF is improved as HR and VR are more coordinated. Variations in the SWVF and SLHF were nearly identical. Increasing VR at the lower-level slightly increases the maximum values of the SWVF and SLHF. Increasing VR at the upper-level results in the
decreases in the SWVF and SLHF.

SFV is greater with higher VR. Increasing VR at the lower-level increases SFV and the TC momentum flux, whereas increasing VR at the upper-level reduces them. Variation in VR has different impacts on SFV with different HR.

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