The Uncertainty of Tropical Cyclone Intensity and Structure Based on Different Parameterization Schemes of Planetary Boundary Layer

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Abstract: Based on different parameterization schemes of planetary boundary layer (PBL), the uncertainty of intensity and structure of the Super-strong Typhoon Rammasun (1409) is investigated using the WRF model (v3.4) with six PBL parameterization schemes. Results indicate that PBL uncertainty leads to the uncertainty in tropical cyclone (TC) prediction, which increases with forecast time. The uncertainty in TC prediction is mainly reflected in the uncertainty in TC intensity, with significant differences in the TC intensity forecasts using various PBL schemes. The uncertainty in TC prediction is also reflected in the uncertainty in TC structures. Greater intensity is accompanied by smaller vortex width, tighter vortex structure, stronger wind in the near-surface layer and middle and lower troposphere, stronger inflow (outflow) wind at the lower (upper) levels, stronger vertical upward wind, smaller thickness of the eye wall, smaller outward extension of the eye wall, and warmer warm core at the upper levels of eye. PBL height, surface upward heat flux and water vapor flux are important factors that cause the uncertainty in TC intensity and structure. The more surface upward heat flux and water vapor flux and the lower PBL height, the faster TC development and the stronger TC intensity.

Key words: planetary boundary layer; uncertainty; tropical cyclone; intensity; structure

1 INTRODUCTION

Many studies have shown that the vertical transport of sensible heat, latent heat and momentum in the planetary boundary layer (PBL) plays an important role in the genesis and development of tropical cyclone (TC) (Chen and Ding [1]; Koyolev et al. [2]; Zhang et al. [3]; Schade and Emanuel [4]). The physical processes in the PBL are introduced into numerical models by the method of parameterization. The approximation of parameterization makes the model description of these processes uncertain. Besides, due to the lack of observational data, there is no PBL parameterization scheme for TC, further increasing the uncertainty of models describing TC PBL processes.

In the convective instability of the second kind (CISK) theory (Charney and Anthes [5]) and the wind-induced surface heat exchange (WISHE) theory (Emanuel [6]), which explain the TC genesis and development, the latent heat transport and frictional convergence in the PBL are both emphasized. PBL friction is also an important factor causing the rapid decline of the intensity of landing TCs (Chen and Ding [1]; Yuan et al. [7]). Some studies reveal that the PBL parameterization scheme has a significant impact on TC intensity prediction (Davis and Bosart [8]; Deng et al. [9]; Zhang et al. [10]; Li and Pu [11]; Hill and Lackmann [12]). Differences in TC structures simulated by different PBL parameterization schemes lead to different TC intensity (Deng et al. [9]). The maximum difference of hurricane intensity forecasted by different PBL parameterization schemes in the MM5 model can reach 15 m s⁻¹ for the maximum surface wind speed and 16 hPa for the minimum sea level pressure (Braun and Tao [13]). Using the observations of Powell et al. [14] and the new formula of roughness length of Makin [15], Zeng et al. [16] improved the YSU PBL parameterization scheme, and the improved model optimized the intensity prediction of Super Typhoon Saomai (2006).

Some recent studies further demonstrate that the physical processes in the PBL play an essential role in the maintenance and intensification of TC and TC intensity and structure are sensitive to PBL parameterization scheme (Smith and Thomsen [17]; Bryan [18]; Kepert [19]; Cione et al. [20]; Zhang et al. [21]; Ming and Zhang [22]; Zhang et al. [23]; Tang et al. [24]). Idealized numerical experiments (Smith and Thomsen [17]) show that the difference of vortex evolutions simulated by using different PBL parameterization schemes can be traced to the different eddy diffusivities determined by the PBL parameterization schemes, which further confirm the dependence of TC intensification on PBL.
parametrization. Kepert\textsuperscript{[19]} evaluated several PBL parameterization schemes, representative of those available in popular modeling systems, and recommended either the Louis or Mellor-Yamada schemes as suitable schemes for TC simulation. Tang et al.\textsuperscript{[24]} investigated the sensitivity of hurricane intensity and structure to two PBL parameterization schemes in idealized HWRF simulations.

In summary, there is a great deviation between the actual TC PBL processes and the simulated ones by the current PBL parameterization schemes. At present, none of those PBL parameterization schemes typically used for TC simulation is designed specifically for TC conditions. Even in the operational Hurricane Weather Research and Forecasting (HWRF) model, although the PBL physics upgrades have been made (Zhang et al.\textsuperscript{[23]}; Zhang et al.\textsuperscript{[23]}; Zhang and Rogers\textsuperscript{[25]}), the PBL parameterization scheme used is essentially the traditional medium-range forecast (MRF) scheme (Troen and Mahrt\textsuperscript{[26]}; Hong and Pan\textsuperscript{[27]}). Therefore, there is a great uncertainty in the model description for the TC PBL processes, which will inevitably lead to the uncertainty of TC prediction, especially TC intensity prediction. Although there have been some studies on the impact of PBL processes on TC genesis and development, it is necessary to continue research in this area.

At present, the widely used Weather Research and Forecasting (WRF) model includes a variety of PBL parameterization schemes. A survey of PBL parameterization methods (Kepert\textsuperscript{[19]}) shows that in the WRF, the Yonsei University (YSU) scheme is basically the most popular PBL scheme used for TC simulation. In the WRF, except for the YSU scheme and the Mellor-Yamada (MY) scheme, other PBL schemes are hardly used for TC simulation. In this paper, we use the WRF (V3.4) model as the experimental model and choose 6 PBL schemes to make experiments on the Super-strong Typhoon Ramiyasun (1409). Our study will focus on the uncertainty of TC intensity and structure based on different PBL parameterization schemes. Section 2 describes the experimental model, the data used as the initial conditions, and the data used to verify forecast results. In section 3, we present a brief introduction to the chosen 6 PBL schemes, and in section 4 we present an overview of Ramiyasun. Forecast results are given in section 5 and a summary is given in section 6.

2 MODEL AND DATA

We use the WRF model (v3.4) configured with three static and two-way nested domains and its center is at 17\textdegree N, 117\textdegree E. The horizontal grid spacing of the outer, middle, and inner domain is 27, 9, and 3 km, respectively, and the inner domain covers the region (7.3\textdegree N–26.4\textdegree N, 104.2\textdegree E–129\textdegree E). All forecast results shown are for the inner domain. Vertically, the model employs the terrain-following stationary pressure coordinate and there are 28 levels, with the pressure at the top level being 50 hPa.

Different experiment uses consistent physics parameterization schemes, except for the PBL scheme. The model’s three domains also use consistent physics parameterization schemes, except for the convection scheme. It is commonly thought that when the horizontal resolution reaches 4–5 km, models can resolve cumulus convection rather than relying on its parameterization. Therefore, no convection parameterization is applied in the inner domain, whereas the KF convection scheme is applied in the outer and middle domains. The other applied physics parameterization schemes include the WSM6 cloud microphysics scheme, the Dudhia shortwave radiation scheme, the RRTM longwave radiation scheme, and the Noah land surface scheme.

The data used as the initial conditions in the experiments are obtained from the initial fields of the National Centers for Environmental Prediction (NCEP) Global Ensemble Forecast System (GEFS) with a resolution of T190L28. This system consists of 21 members and the initial fields of member 11 are initialized to form the initial fields used in the experiments. The initialized data also provide the lateral boundary conditions for the outer domain of the model, and the lateral boundary conditions are updated every 6 h. Corresponding to the horizontal resolution of the three domains, the step length of integration is 90s, 30s, and 10s in the outer, middle, and inner domain, respectively, and the integration time is 48 h. The observational data used to verify the forecast results are from the TC best-track dataset compiled by the Shanghai Typhoon Institute of the China Meteorological Administration (CMA-STI) (Ying et al.\textsuperscript{[28]}).

3 PBL PARAMETERIZATION SCHEMES

We choose 6 PBL parameterization schemes in the WRF model to conduct 6 experiments. The 6 PBL schemes chosen are the YSU, the Mellor-Yamada-Janjic (MYJ), the Mellor-Yamada-Nakanishi-Niino, version 2 (MYNN2), the Asymmetric Convective Model, version 2 (ACM2), the Bougeault-Lacarrere (BouLac) and the University of Washington (UW) schemes.

The YSU scheme is a vertical diffusion package with a nonlocal turbulent mixing coefficient in the PBL (Hong et al.\textsuperscript{[26]}). It is a revised version of the Medium-Range Forecast (MRF) scheme, The major ingredient of the revision is the inclusion of an explicit treatment of entrainment processes at the top of the PBL. Compared with the MRF scheme, the YSU scheme increases boundary layer mixing in the thermally induced free convection regime and decreases it in the mechanically induced forced convection regime. The YSU scheme outperforms other schemes in reproducing the convective inhibition.

The MYJ scheme is developed from the Mellor-Yamada (MY) scheme (Janjic\textsuperscript{[10]}). In the MYJ scheme, a
new marine viscous sublayer scheme is designed and the MY level-2 and level-2.5 schemes are retuned. Two layers are introduced over the oceans: a viscous sublayer with the vertical transports determined entirely by the molecular diffusion, and a layer above it with the vertical transports determined only by the turbulence. The method used for calculating the MY level-2.5 master length scale is rectified. In this way, possible overestimation of the MY level-2 surface fluxes over water is also avoided.

The MYNN2 scheme is derived from the improved Mellor-Yamada (MY) level-3 model (Nakanishi and Niino [11]). In order to ensure the reliability of the improved MY level-3 model and its numerical stability, restrictions are imposed on computing stability functions, temperature and water-content variances, and their covariance. In a regional prediction, the MYNN2 scheme can reasonably reproduce the satellite-observed horizontal distribution of an advection fog (Nakanishi and Niino [11]).

The ACM2 scheme is a combined local and nonlocal closure PBL scheme, which is able to represent both the supergrid- and subgrid-scale components of turbulent transport in the convective boundary layer (Plemi [12]; Plemi [13]). The ACM2 scheme performs equally well for both meteorological parameters and trace chemical concentrations, and is designed to simulate the vertical mixing of any modeled quantity realistically for both meteorological models and air quality models.

The BouLac scheme applies the techniques for turbulence parameterization in the PBL to altitude, orography-induced turbulence events (Bougeault and Lacarrere [14]). It generalizes the specification method of the length scales without undermining the scheme performance in the PBL. The BouLac scheme can simulate the turbulence kinetic energy (TKE) accurately, which allows for an improvement of the mean flow simulation and is beneficial to a number of studies in applied meteorology.

The UW scheme is derived from the Grenier and Bretherton (GBM) scheme but has been modified markedly to improve its numerical stability and efficiency (Bretherton and Park [15]). The key features of the UW scheme include the use of moist-conserved variables, an explicit entrainment closure for the convective layers, the diagnosis of TKE for the computation of turbulent diffusivities, an efficient new formulation of TKE transport as a relaxation to layer-mean TKE, and the unified treatment of all turbulent layers in each atmospheric column. The UW scheme can provide a more physically realistic treatment of marine stratocumulus-topped boundary layers.

4 TC RAMMASUN

TC Rammasun formed over the ocean to the east of the Philippines at 06:00 UTC 12 July 2014, reaching the South China Sea on 16 July. It reached its strongest intensity at 06:00 UTC 18 July, when at its center the maximum wind velocity was 72 m s\(^{-1}\) and the lowest pressure was 888 hPa. Rammasun subsequently made landfall on the coast of China for three times. Based on the lowest recorded value of central pressure—which occurred when Rammasun made landfall in Wenchang, Hainan—Rammasun became the strongest TC to have made landfall in China in the past 50 years. Detailed information about TC Rammasun can be found in Wang and Zeng [16] and Wang and Zeng [17].

We focus on a forecast period from 00:00 UTC 16 July to 00:00 UTC 18 July, a total of 48 h, when Rammasun moved away from the Philippines over the South China Sea towards China, before making landfall in Wenchang, Hainan. Rammasun underwent a process of intensification from typhoon to strong typhoon and then to super-strong typhoon.

5 RESULTS

5.1 Forecast uncertainty

The uncertainty in the PBL processes may result in the TC forecast uncertainty. The root-mean difference in total energy (RM-DTE) is used to characterize the forecast uncertainty (Sippel and Zhang [18]). The larger the RM-DTE, the greater the forecast uncertainty. The RM-DTE is calculated as

\[
\text{RM-DTE} = \sqrt{\frac{1}{N_e} \sum_{k=1}^{N_e} \sum_{i,j,k,N} DTE_{i,j,k,N}^2}
\]

where DTE is a commonly used measure of ensemble spread and is calculated as

\[
DTE = 0.5(u'\cdot u' + v'\cdot v' + kT'\cdot T')
\]

where \(u, v\) and \(T\) denote the difference between an ensemble member and the ensemble mean of the \(u, v\) and \(T\), respectively, and \(k = C_p/T_m\), where \(C_p = 1004.9\) J kg\(^{-1}\) K\(^{-1}\) and \(T_m = 270\) K. In the RM-DTE equation, \(k_{max}\) is the maximum vertical level of the model domain, and \(N_e\) is the number of ensemble members. In our experiments, 6 PBL schemes are used. Each experiment can be regarded as one member, with the 6 experiments forming an ensemble forecast with 6 members.

Figure 1 shows the spatial distribution of the RM-DTE for the 12-h, 24-h, 36-h and 48-h forecasts. As shown in Fig. 1, the uncertainty of TC forecasts increases with the forecast time, with a more rapid and significant increase occurring after 36 h. The maximum RM-DTE increases from 8 m s\(^{-1}\) at 12 h to 8 m s\(^{-1}\) at 24 h, to >17 m s\(^{-1}\) at 36 h, and to >30 m s\(^{-1}\) at 48 h. The maximum RM-DTE is located to the southeast of the TC center. The RM-DTE decreases gradually from its maximum center to the periphery, and the maximum RM-DTE is closer to TC center after 24 h.

Figure 2 shows the observed and the forecasted track and intensity for Rammasun over the 48-h forecast period, including the sea-level pressure (SLP) and the 10-m horizontal wind speed (HWS10). As shown in
Fig. 2, the PBL processes have a large impact on the predicted TC intensity but little effect on the predicted TC track. In other words, the uncertainty of TC forecast due to the PBL uncertainty is mainly reflected in the uncertainty of TC intensity forecast. The intensities predicted by using various PBL schemes differ noticeably, and this difference increases with forecast time. At 48 h, the maximum difference reaches 15 m s$^{-1}$ (maximum HWS10) and 32 hPa (minimum SLP). However, the intensities predicted by using the 6 schemes are generally weaker than the observed intensity, and the intensity by using the YSU scheme is the closest to the observed.

\[ \text{Minimum sea surface pressure (hPa)} \]

The results in Fig. 2 are similar to those by Nolan et al.\(^{[9]}\), which evaluated and compared the high-resolution WRF simulations of Hurricane Isabel (2003) with two PBL parameterizations: the YSU scheme and MYJ scheme. The two schemes produce very similar tracks, which follow the retrospective “best track” very closely. However, the simulated intensities by the two schemes differ obviously, and compared with the best-track values, they are both low throughout the simulations. The only difference between the results in Fig. 2 and those by Nolan et al.\(^{[9]}\) is that in the latter, the simulated intensity by using the MYJ scheme is stronger than that by using the YSU scheme, which is exactly opposite to the result in Fig. 2.

\[ \text{Time (h)} \]

Figure 1. The spatial distribution of the RM-DTE (m s$^{-1}$) for the (a) 12-h, (b) 24-h, (c) 36-h and (d) 48-h forecasts. The typhoon symbol indicates Rammasun’s position.
5.2 Evolution of intensity and structure

Figure 3 shows the 12-h, 24-h, 36-h and 48-h forecasted HWS10 and SLP fields and Fig. 4 shows the evolution of the forecasted axisymmetric HWS10 for Rammassun by using the 6 PBL schemes. As shown in Fig. 3, although at 48 h the TC predicted by using the YSU scheme is the strongest among the 6 schemes, it is not the strongest before 24 h. After 24 h, it develops rapidly and becomes stronger and stronger. Before 24 h, the TC intensity by using the ACM2 scheme differs little from that by using other schemes. After 24 h, although its development has accelerated, the development is slower than that by using other schemes, which make its intensity the weakest among those predicted by using the 6 schemes at 48 h. However, at 48 h, the strong wind (> 20 m s\(^{-1}\)) region of the TC by the ACM2 scheme is the largest among those of the 6 schemes, which can also be found in Fig. 4.

As shown in Fig. 4, before 24 h, the TCs predicted by using the 6 schemes all develop slowly, and at 24 h, their axisymmetric maximum HWS10 are all between 20 and 25 m s\(^{-1}\). After 24 h, their developments all accelerate and the maximum HWS10 by using the YSU (ACM2) scheme first (finally) reaches 35 and 40 m s\(^{-1}\), respectively.
As the TCs strengthen, their maximum wind radii and eye wall thicknesses both gradually decrease, and their strong wind (>25, 30, and 35 m s⁻¹) regions gradually expand outward. The stronger the TC, the smaller the maximum wind radius and the narrower the eye wall thickness.

Figure 3. The 12-h (column 1), 24-h (column 2), 36-h (column 3) and 48-h (column 4) forecasted HWS10 (color shading; m s⁻¹) and SLP (contours; hPa) for Rammasun by the 6 PBL schemes: YSU (row 1), MYJ (row 2), MYNN2 (row 3), ACM2 (row 4), BouLac (row 5) and UW (row 6). The numbers in the lower left corner of each panel are the maximum HWS10 and the minimum SLP for the corresponding scheme at the corresponding forecast time.
5.3 Disparity of intensity and structure

For Rammasun by the 6 PBL schemes, Fig. 5 shows the forecasted HWS10 in the inner core region at 48 h, and Fig. 6 and Fig. 7 show the axisymmetric 1-hourly (47–48 h) time-averaged radius-height cross-sections of the forecasted horizontal tangential wind (Fig. 6) and horizontal radial wind and vertical wind (Fig. 7) respectively.

As shown in Fig. 5, different PBL scheme forecasts the TC with different horizontal structures and different maximum horizontal wind speed. The stronger the TC predicted by the PBL scheme, the smaller the vortex width and the typhoon eye, the larger the radial gradient of the horizontal wind, and the tighter the vortex structure. However, the TCs by using the MYJ and MYNN2 schemes differ a little from this pattern in that they are weaker than the TCs by using the YSU and UW schemes, but their vortex widths are slightly smaller than the vortex widths by the YSU and UW schemes. Because of their smaller vortex widths, at 48 h, their area-averaged intensities are weaker than those by the BouLac and ACM2 schemes, as shown in Fig. 2(d). For the predicted TC, the horizontal wind is distributed asymmetrically, and the wind to the right of TC forward direction is larger than the wind to the left.

![Figure 5](image-url)

*Figure 5.* The 48-h forecasted HWS10 (m s⁻¹) in the inner core region for Rammasun by using the 6 PBL schemes: (a) YSU, (b) MYJ, (c) MYNN2, (d) ACM2, (e) BouLac and (f) UW.

![Figure 6](image-url)

*Figure 6.* The axisymmetric 1-h (47–48 h) time-averaged radius-height cross-sections of the forecasted horizontal tangential wind (m s⁻¹) for Rammasun by using the 6 PBL schemes: (a) YSU, (b) MYJ, (c) MYNN2, (d) ACM2, (e) BouLac and (f) UW.
Apart from different horizontal structure, different PBL scheme forecasts the TC with different vertical structure. As shown in Fig. 6, horizontal tangential wind decreases with height. The stronger the predicted TC, the greater the wind in the near-surface layer and the middle and lower layers of the troposphere, the higher the height of the strong wind zone, the smaller the maximum wind radius, and the tighter the vortex structure. However, the height of the strong wind zone by using the UW (BouLac) scheme is higher than that by using the YSU (MYJ) scheme, although at 48 h, the TC by using the YSU (MYJ) scheme is 1 m s$^{-1}$ stronger than that by using the UW (BouLac) scheme as shown in Fig. 3 and Fig. 5. This inconsistency is due to that what is shown in Fig. 6 is a little different from what is shown in Fig. 3 and Fig. 5. In addition, as shown in Fig. 6, the vertical profile of the maximum wind radius extends outward with the height, particularly at the middle and upper levels. This effect increases with the decrease of TC intensity.

As shown in Fig. 7, air flows in at the lower levels, rises along the eye wall, and flows out at the upper levels. The heights of the inflow and outflow layers do not differ much among the various PBL schemes. The upper boundary of the inflow layer is at ~850 hPa and the most important outflow occurs in the upper troposphere, at ~300–100 hPa. However, the inflow, rising and outflow rates are different among the various schemes. In addition, the thickness of the eye wall and the outward extension of the eye wall with height are also different among those simulated by using the various schemes. The stronger the predicted TC, the greater the inflow and outflow velocity, the greater the vertical upward wind, and the smaller the thickness and outward extension of the eye wall.

![Figure 7](image)

Figure 7. The same as Fig. 6, but for the forecasted horizontal radial wind (contours; m s$^{-1}$) and vertical wind (color shading; m s$^{-1}$).

As shown in Fig. 5, Fig. 6 and Fig. 7, the simulated horizontal structure and vertical structure of Rammasun are both significantly different. We can find similar results in the studies by Nolan et al. [40]. Compared with the hurricane simulated by using the YSU scheme, the stronger hurricane by using the MYJ scheme is structurally expressed as smaller radius of maximum winds, stronger eye subsidence, stronger low-level inflow and upper-level outflow, and stronger mean updrafts in the eyewall.

5.4 Disparity and evolution of warm core structure

The changes in TC intensity are accompanied by the changes in the warm core at the upper levels. For Rammasun by the 6 PBL schemes, Fig. 8 shows the 48-h cross-sections of the forecasted temperature anomalies and specific humidity across the TC center, and Fig. 9 shows the evolution of the forecasted axisymmetric potential temperature at 300 hPa.

As shown in Fig. 8, different PBL scheme forecasts the TC with different warm-core structures including the maximum temperature anomaly, the temperature gradient in the eye wall, and the humidity in the eye wall and eye. Obviously, the stronger TC corresponds to the warmer warm core that exists at the upper levels of eye, the greater temperature gradient in the eye wall, and the greater humidity difference between the eye wall and eye. The smaller eye and the narrower eye wall also accompany the stronger TC. For the stronger TC, all these factors make the eye warmer and drier. In addition, the eye wall gradually extends outward from the lower to the upper levels, and stronger TC corresponds to the smaller outward extension of the eye wall.
Figure 8. The 48-h cross-sections of the forecasted temperature anomalies (color shading; K) and specific humidity (contours; g kg$^{-1}$) across the TC center for Rammasun by using the 6 PBL schemes: (a) YSU, (b) MYJ, (c) MYNN2, (d) ACM2, (e) BouLac and (f) UW. The typhoon symbol indicates the TC position.

Figure 9 shows the evolution of the warm core structure predicted by different PBL schemes, which is consistent with the evolution of the vortex structure as shown in Fig. 4. Before 24 h, the average potential temperatures predicted by the 6 schemes all increase slowly, and at 24 h, they are not much different. After 24 h, the increases of the potential temperatures all accelerate, and the stronger the predicted TC, the faster and higher the rise of the potential temperature. The potential temperature by using the YSU (ACM2) scheme first (finally) reaches 362 K. In addition, the stronger the predicted TC, the narrower the region with the high potential temperature, and the greater the potential temperature gradient.

Figure 9. The evolution of the forecasted axisymmetric potential temperature (K) at 300 hPa for Rammasun by using the 6 PBL schemes: (a) YSU, (b) MYJ, (c) MYNN2, (d) ACM2, (e) BouLac and (f) UW.

5.5 Surface flux, precipitation and PBL height

TC development requires continuous supply of heat and water vapor. Generally, the larger the surface upward heat flux and water vapor flux, the stronger the TC. Fig. 10 shows the forecasted surface heat flux and water vapor flux in the inner core region at 48 h for Rammasun by the 6 PBL schemes. As shown in Fig. 10, among the 6 schemes, the weakest TC predicted by the ACM2 scheme has both the smallest surface heat flux and water vapor flux. The strongest TC by the YSU scheme has the largest heat flux, but its water vapor flux is smaller than that by the MYJ scheme. In addition,
although the TC by using the UW scheme is obviously stronger than that by using the MYJ scheme at 48 h as shown in Fig. 3 and Fig. 5, the water vapor flux by the UW scheme is smaller than that by using the MYJ scheme, and the heat flux that by using the UW scheme is almost as big as by using the MYJ scheme.

![Figure 10](image1.png)

**Figure 10.** The same as in Fig. 5, but for the 48-h forecasted surface heat flux (color shading; W m\(^{-2}\)) and water vapor flux (contours; g m\(^{-2}\) s\(^{-1}\)).

With ascending motion, the surface water vapor rises to a certain height and then condenses to form precipitation. Precipitation amount is related to the amount of surface upward water vapor and the strength of convective activity. Generally, larger precipitation corresponds to larger water vapor flux, stronger convective activity, and stronger TC.

Figure 11 shows the forecasted 1-h (47–48 h) precipitation for Rammasun by using the 6 PBL schemes. As shown in Fig. 11, among the 6 schemes, the

![Figure 11](image2.png)

**Figure 11.** The forecasted 1-h (47–48 h) precipitation (mm) for Rammasun by the 6 PBL schemes: (a) YSU, (b) MYJ, (c) MYNN2, (d) ACM2, (e) BouLac and (f) UW.
no

PBL schemes Colors indicate the PBL schemes (48 h for Rammasun (12).—used sun by the ric

Figure 12 shows the radial distribution of the forecasted axisymmetric 1-h (47–48 h) time-averaged PBL height for Rammasun by using the 6 PBL schemes. As shown in Fig. 12, the difference of the PBL heights predicted by using the 6 schemes is very large. Among the predictions, the TC predicted by using the UW scheme has the lowest PBL height, much lower than that by using other schemes. The weakest TC by using the ACM2 scheme has the highest PBL height outside the eye wall. The PBL height by using the MYJ scheme is the highest within the eyeball, and is only lower than the highest PBL height by using the ACM2 scheme outside the eyeball.

![Figure 12](image)

**Figure 12.** The radial distribution of the forecasted axisymmetric 1-h (47–48 h) time-averaged PBL height (m) for Rammasun by the 6 PBL schemes. Colors indicate the PBL schemes used.

The PBL is the transition zone and the exchange channel between the surface and the atmosphere. With the airflow ascending, the surface heat and water vapor pass through the PBL and enter the atmosphere. Generally, under the same conditions, the higher the PBL height, the more the loss of the heat and water vapor before entering the atmosphere.

Among the predictions of the 6 PBL schemes, the TC predicted by the UW scheme has the lowest PBL height, which makes the loss of its water vapor much less than that by other schemes. On the other hand, as shown in Fig. 7, it has the largest vertical upward wind, and at the lower levels, its inflow wind is as large as that by the YSU scheme, much larger than those by other schemes. All these factors help to transport more water vapor to the upper atmosphere and reinforce the convective activity, and then generate more precipitation. Therefore, although the water vapor flux by the UW scheme is not the largest, its effective water vapor is the largest, which makes its precipitation the largest. For the strongest TC predicted by the YSU scheme, although its water vapor flux is as big as that by the UW scheme, its PBL height is much higher and its vertical upward wind is a little smaller than that by the UW scheme, which makes its precipitation smaller than that by the UW scheme. However, its heat flux is larger than that by the UW scheme. These heat and water vapor transported upward from the surface contribute to TC development and strengthening.

The results of idealized HWRF simulations (Tang et al. [24]) show that corresponding to the greater intensity, the kinematic boundary layer height is noticeably smaller in the run by the MYJ scheme than that in the run by the GFS scheme. In our results, the TC predicted by the UW (YSU) scheme has the lowest (second lowest) PBL height as shown in Fig. 12, and the TC by these two schemes is the strongest as shown in Fig. 2(b). This result is roughly similar to that of Tang et al. [24].

### 6 SUMMARY

The physical processes in the PBL play an important role in TC genesis and development. The uncertainty of model describing the TC PBL processes leads to the uncertainty in TC prediction.

Using the WRF (V3.4) model and choosing 6 PBL parameterization schemes, we study the uncertainty of intensity and structure of the Super-strong Typhoon Rammasun (1409) based on different PBL parameterization schemes. The results confirm that PBL uncertainty leads to the uncertainty in TC prediction. This uncertainty increases with forecast time and is mainly reflected in the uncertainty in TC intensity prediction. There are significant differences in the TC intensity forecast by various PBL schemes. At 48 h, the maximum difference between the intensity forecasts by various schemes reaches 15 m s$^{-1}$ (maximum HWS10) and 32 hPa (minimum SLP).

Before 24 h, the TCs predicted by the 6 PBL schemes all develop slowly, and the TC with the strongest final intensity is not the strongest among the predicted TCs at that stage. After 24 h, these TCs’ developments all accelerate, and the TC by the YSU scheme strengthens more than others and becomes the strongest at 48 h. As the TCs strengthen, their maximum wind radii and eye wall thicknesses both gradually decrease, and their strong wind regions gradually expand outward. The evolutions of the TCs’ warm core structures are consistent with the evolutions of their vortex structures.

The uncertainty in TC prediction is also reflected in
the uncertainty in TC structures. The stronger the predicted TC, the smaller the vortex width and the typhoon eye, and the tighter the vortex structure. The stronger the predicted TC, the stronger the wind in the near-surface layer and in the middle and lower troposphere, the greater the airflow’s inflow (outflow) velocity at the lower (upper) levels, and the stronger the vertical upward wind. The stronger the predicted TC, the smaller the thickness of the eye wall, and the smaller the outward extension of the eye wall. In addition, stronger TC has warmer warm core at upper levels of eye, greater humidity difference between the eye wall and eye, and warmer and dryer eye.

Different PBL parameterization scheme uses different method to describe the PBL processes, which lead to the difference in the predicted variables. In this study, we find that the difference in surface upward heat flux, water vapor flux and PBL height play an important role in causing the difference in TC intensity and structure. The more surface upward heat flux and water vapor flux and the lower PBL height, the more heat and water vapor enter the free atmosphere, which accelerates the TC development and makes the TC stronger. Among the 6 predicted TCs, the stronger TC generally not only has the larger surface upward heat flux and water vapor flux, but also has the lower PBL height, and vice versa. In addition, the magnitude of the vertical upward wind and the inflow wind at the lower levels is also important for TC development.

Obviously, for the deterministic prediction of TC intensity, it is an extremely critical issue that which PBL scheme is the most appropriate. In this study, we find that among the 6 schemes, the TC intensity predicted by the YSU and UW schemes is the closest to the observed intensity. However, we only focus on one TC. More TCs with different characteristics should be studied. Even so, it is unlikely to be able to determine the optimum scheme for the reason that other aspects such as the representation of cloud microphysics have inherent uncertainty as well.

Just like the studies of Braun and Tao [13], Smith and Thomsen [17], Kepert [19] and Tang et al. [24], our study further provides an estimate of the uncertainty in TC intensity prediction that stems from the uncertainty of PBL physics. This forecast uncertainty has implications for the predictability of TC intensification. At present, ensemble forecast is an effective method to reduce the impact of various uncertainties. Our future work will focus on the ensemble forecast of TC intensity to help improve the prediction of TC intensity.

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