Article ID: 1006-8775(2018) 02-0123-08

A STUDY OF THE INFLUENCE OF MICROPHYSICAL PROCESSES ON TYPHOON NIDA (2016) USING A NEW DOUBLE-MOMENT MICROPHYSICS SCHEME IN THE WEATHER RESEARCH AND FORECASTING MODEL

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Abstract: The basic structure and cloud features of Typhoon Nida (2016) are simulated using a new microphysics scheme (Liuma) within the Weather Research and Forecasting (WRF) model. Typhoon characteristics simulated with the Liuma microphysics scheme are compared with observations and those simulated with a commonly-used microphysics scheme (WSM6). Results show that using different microphysics schemes does not significantly alter the track of the typhoon but does significantly affect the intensity and the cloud structure of the typhoon. Results also show that the vertical distribution of cloud hydrometeors and the horizontal distribution of peripheral rainband are affected by the microphysics scheme. The mixing ratios of rain water and graupel correlate highly with the vertical velocity component and equivalent potential temperature at the typhoon eye-wall region. According to the simulation with WSM 6 scheme, it is likely that the very low typhoon central pressure results from the positive feedback between hydrometeors and typhoon intensity. As the ice-phase hydrometeors are mostly graupel in the Liuma microphysics scheme, further improvement in this aspect is required.

Key words: Liuma microphysics scheme; typhoon intensity; cloud microphysics; typhoon structure; Weather Research and Forecasting model
CLC number: P401 **Document code:** A
doi: 10.16555/j.1006-8775.2018.02.001

1 INTRODUCTION

Cloud structure and its development are significantly affected by microphysical processes. The representation of cloud microphysical processes plays an important role in numerical weather prediction models. Nowadays, corresponding to the development of computational resources, numerical weather prediction models operate with a higher resolution and more complicated physical parameterizations corresponding to the development of computational resources. Thus, the explicit representation of microphysical processes is increasingly necessary.

Microphysical processes determine the formation, evolution and distribution of cloud hydrometeors, which can affect typhoon cloud structure, precipitation features, and even typhoon track and intensity. Cheng et al.[1] suggested that cloud microphysical processes have a greater influence on the precipitation features than on typhoon's central pressure and track. Wang[2] pointed out that using different microphysics schemes may change the horizontal distribution of the peripheral rainband. Recent research has shown that different microphysics schemes affect the track of typhoons because of alterations of the western Pacific subtropical high resulting from the heating rate profiles produced by different microphysics schemes (Sun et al.[3]). However, microphysical processes may have little effect on the tracks of strong typhoons (Zhu and Zhang[4]; Pattnaik and Krishnamurti[5]).

The impact of microphysical processes on typhoon intensity is highly uncertain. Lord et al.[6] and Willoughby et al.[7] pointed out that simulations with ice processes give more realistic downdrafts and stronger intensity compared with simulations without ice processes. Other studies also found more intense hurricanes when ice processes are considered (Zhu and Zhang[4]). Wang[2] suggested that ice processes do not significantly affect hurricane intensity, as similar downdrafts are found regardless of the inclusion of ice-phase processes. In contrast, Yang and Ching[8] simulated a weaker typhoon with the inclusion of ice processes. Therefore, the development of more accurate

Received 2017-09-06; **Revised** 2018-03-06; **Accepted** 2018-05-15
Foundation item: Ministry of Science and Technology of China (2017YFC1501406); National Key Research and Development Plan Program of China (2017YFA0604500); CMA Youth Founding Program (Q201706 & NWPC-QNJJ-201702)
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microphysics may be necessary for the investigation of cloud processes.

Currently, the two types of microphysics schemes widely used in cloud resolving models are spectral bins and bulk microphysics schemes. As the former type uses tens of bins to describe the mass and number distribution of hydrometeors and aerosols, it gives more detailed cloud microphysical processes at the cloud-resolving scale. However, the spectral bin microphysics scheme requires large computational resources and cannot be used in regional long-term simulations and global climate models. The bulk microphysics scheme uses a certain type of distribution function, such as the Gamma or Marshall-Palmer function, to prescribe the shape of each hydrometeor size distribution. Hence, as bulk microphysics scheme represents hydrometeors with only one or two variables, it requires less computational resources, making it more suitable for long-term simulations with large-scale models.

The Liuma microphysics scheme (Liuqijun & Mazhanshan) is a two-moment bulk microphysics scheme used in the Global/Regional Assimilation and PrEdiction System (GRAPES) for weather forecasting and scientific research (e.g., Liu et al.[9]; Zhang and Liu[10]; Shi et al.[11]). Previous studies of the Liuma microphysics scheme have, therefore, been based on the GRAPES framework. Chen et al.[12] used the GRAPES model with the Liuma parameterization (GRAPES-Liuma) to study cloud seeding in a cloud system of the Qilian Mountain region, and pointed out that the Liuma microphysics scheme produces a reasonable microstructure of the cloud system in this area. Hua and Liu[13] investigated typhoon landfall using GRAPES-Liuma and showed that the simulated typhoon track matches well with observations before landfall. Further improvement in the Liuma microphysics scheme requires the testing of its simulation performance in other mesoscale models.

Here, the Liuma microphysics scheme is implemented to the Weather Research and Forecasting (WRF) model, with the major objective to test the performance of the Liuma microphysics scheme in the simulation of Typhoon Nida (2016) based on comparisons of the results with observational data. Another commonly-used microphysics scheme, the WRF-Single-Moment-6-class (WSM6; Hong et al.[14, 15]) scheme is also used to simulate the same case. The article focuses on typhoon track, intensity, hydrometeor distribution, and precipitation. A brief overview of typhoon Nida is given in Section 2, with the detailed Liuma microphysics scheme and model configuration described in Section 3. The simulation and verification of Typhoon Nida are demonstrated in Section 4. An analysis and a discussion of the effects of the microphysical processes on typhoon characteristics are presented in Section 5, with the final section providing a summary.

2 A SYNOPTIC OVERVIEW OF TYPHOON NIDA

Typhoon Nida (2016) was a tropical cyclone that struck Luzon, Philippines and Guangdong, China in late July and early August, respectively, according to the digital typhoon project (http://agora.ex.nii.ac.jp/digital-typhoon/). Nida formed on July 28, 2016 as a tropical depression over the Philippine Sea. Tracking generally north-northwestward, it intensified into a severe tropical storm on July 30 and skirted northern Luzon before turning to the west-northwest, entering the South China Sea and intensifying further till July 31 (maximum wind speeds around 60 m s^{-1} and a central pressure of 975 hPa). Nida made landfall at Guangzhou on August 1 (maximum wind speeds around 50 m s^{-1} and a central pressure of 980 hPa), and then moved toward the southwest with heavy precipitation, before dissipating on August 3. Here the study focuses on the characteristics of this typhoon after its landfall.

3 THE LIUMA MICROPHYSICS SCHEME AND EXPERIMENTAL DESIGN

3.1 *The Liuma microphysics scheme*

The Liuma microphysics scheme is a two-moment mixed-phase scheme developed from the convective and stratus cloud model of Hu et al.[16, 17]. This scheme predicts the mass mixing ratios of cloud water, rain water, cloud ice, snow, graupel and the number concentrations of rain drops, cloud ice, snow and graupel. The Liuma microphysics scheme also prognoses the riming rate function of ice and snow (*Fi*, *Fs*), according to

$$\partial F_i/\partial t=[\frac{F_iQ_i+C_{ci}\cdot\delta t}{Q_i+(C_{ci}+S_{vi})\delta t}-F_i]/\delta t \quad (1)$$

and

$$\partial F_s/\partial t=[\frac{F_sQ_s+[C_{cs}+F_i\cdot(C_{ii}+C_{is})]\delta t}{Q_s+(C_{cs}+C_{ii}+C_{is}+S_{vs})\delta t}-F_s]/\delta t\,, \quad (2)$$

respectively, where Q_i, Q_s are mass mixing ratio of ice and snow, respectively, C_{ci}, C_{cs}, C_{ii}, C_{is} are collision rates between cloud-ice, cloud-snow, ice-ice and ice-snow, respectively, S_{vi} and S_{vs} are the sublimation rates of ice and snow, respectively, and F_i, F_s represent the amount of water collected by ice to the total ice and snow to the total snow, respectively. In the Liuma microphysics scheme, F_i, F_s are used to calculate the production rates of graupel from ice and snow, and also serve as the thresholds of riming processes. For the other bulk scheme, i.e., WSM6, only the rain water mixing ratio is used as the threshold of riming processes. The production rates of graupel from ice and snow (A_{ig}, A_{sg}) of the Liuma microphysics scheme are calculated with

$$A_{ig} = \frac{Q_i}{10}\exp[18\cdot(F_i - 1)] \qquad (3)$$

and

$$A_{sg} = \frac{Q_s}{10}\exp[18\cdot(F_s - 1)] \qquad (4)$$

respectively. All the prognostic variables are subject to advection, turbulent diffusion and sedimentation, with the details of the scheme described in Hua and Liu[13].

3.2 *Experimental design*

The Liuma two-moment mixed-phase microphysics scheme (Liu et al.[13]; Chen et al.[12]; Hua and Liu[13]; Shi et al. [11]) has been implemented to the WRF model version 3.7.1, and used to simulate cloud microphysical processes. The commonly-used WSM6 scheme is also chosen for comparison. The Yonsei University (YSU) boundary-layer scheme (Hong et al. [18]) is used to parameterize the boundary-layer processes. The rapid-radiative transfer model (Mlawer et al. [19]) and Dudhia shortwave scheme (Dudhia[20]) are adopted to parameterize the radiative transfer process. The new Global Forecast System simplified Arakawa-Schubert scheme (Han and Pan[21]) is used for the cumulus parameterization. Observational data from the best track, satellites and radars are used to assess the simulation results.

The simulation domain covers the whole footprint area of Typhoon Nida (Fig.1). The initial and boundary conditions are supplied by the 1°×1° NCEP/NCAR 6-h reanalysis data. The horizontal resolution is 5 km, and the vertical resolution increases toward the model top. The simulation period starts on 0000 UTC July 29, 2016 and runs for 5 days to simulate the whole typhoon process. The study focuses on the last 2 days when Nida made landfall and caused heavy precipitation in mainland China. This area is highlighted with a white square in Fig.1.

4 VALIDATION OF THE SIMULATION

4.1 *Track and intensity*

Figure 1 shows the simulated and the observed tracks of Typhoon Nida according to the Japan Meteorological Agency ‘best track dataset’ (http://www.jma.go.jp/), which has a temporal resolution of 6 h. Observations show that Typhoon Nida made landfall in Shenzhen, Guangdong Province at 1800 UTC August 1. After landfall, it weakened over central Guangxi Zhuang Autonomous Region (shortened as “Guangxi Region” hereafter) at 0000 UTC on August 3. The landing time of the typhoon simulated with the Liuma microphysics scheme is almost the same as the observations, with the landing point to the north of the observation and the track deviation becoming smaller after landfall. The landing time simulated with the WSM6 scheme is later, the landing point is also to the north of the observation, and the track deviation does not significantly decrease after landfall. In general, both the simulations reproduce the track of the typhoon well.

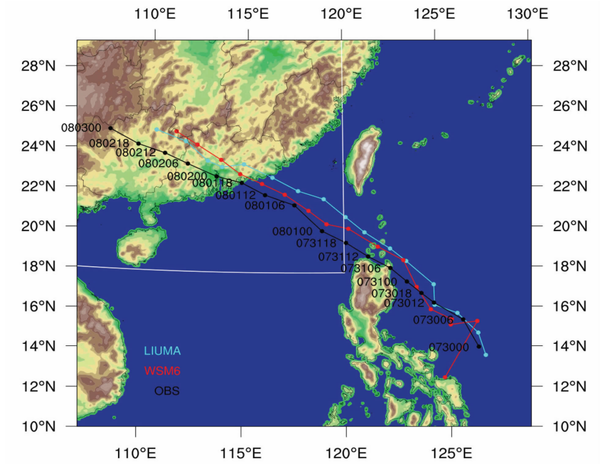

Figure 1. The simulated domain in this study with horizontal resolutions of 5 km. The white square represents the analyzing area of Figs.3-4. Color lines represent Typhoon Nida track. Black line is the observational data from ‘best track dataset’ (http:// www.jma.go.jp/), cyan and red lines are Liuma microphysics scheme and WSM6 scheme respectively.

Figure 2 shows the simulated and observed time evolution of central pressures of the typhoon. Observations show that the central pressure of Typhoon Nida decreased from 1002 hPa at 0000 UTC on July 30, reached its minimum of 975 hPa at 0600–1200 UTC on July 31, and then increased to about 985 hPa at landing time. The typhoon central pressure simulated with the Liuma microphysics scheme is 5 hPa higher than that of the observation. The typhoon central pressure simulated with the WSM6 scheme decreases strongly from 0000 UTC on August 1 till 0000 UTC on August 2. However, the minimum central pressure is 953 hPa, which is 20 hPa lower than that of the observation. In general, the Liuma microphysics scheme shows an acceptable performance in simulating the intensity of Typhoon Nida. In addition, our results show that the type of microphysical scheme significantly affects typhoon intensity, which is consistent with previous studies (Cheng[1]).

4.2 *Radar reflectivity*

Figure 3 shows the simulated (a-f) and observed (g-i) radar reflectivity at 1800 UTC on August 1, 0600 UTC on August 2, and 1800 UTC on August 2. At 1800 UTC on August 1, the observed structure of Typhoon Nida is clear and complete (Fig.3g). The typhoon center is located offshore from Shenzhen and the peripheral rainband is not symmetrically distributed. The maximum radar reflectivity is around 45-50 dBZ in the typhoon eye-wall region, and up to 55-60 dBZ on the edge of the peripheral rainband. The structure and location of the typhoon simulated with the Liuma microphysics scheme at this time are closer to observations compared with that simulated with the WSM6 scheme. From 0600 UTC August 2 to 1800

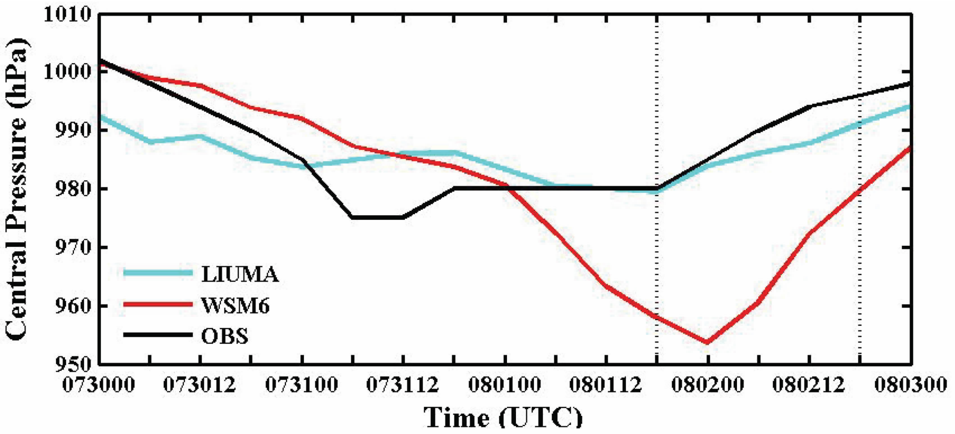

Figure 2. Time evolutions of the observational and simulated typhoon Nida central pressures. Black line is the observational data from 'best track dataset' (http:// www.jma.go.jp/), cyan and red lines are the Liuma microphysics scheme and the WSM6 scheme respectively. Vertical dashed lines imply the start and end time for Figs. 3-4.

UTC August 2, the observed typhoon structure is not complete, the eye-wall region becomes less clear, and the peripheral rainband is moving toward Guangxi Region (Figs.3h-i). The maximum radar reflectivity of the peripheral rainband is up to 50 dBZ in the southern part of Guangxi Region. The typhoon simulated with the Liuma microphysics scheme reproduces the pattern of the observed radar distribution, while the typhoon simulated with the WSM6 scheme does not capture the unsymmetrically distributed peripheral rainband well, as shown in Figs.3b-c and e-f, respectively. However, both simulation results miss the strong radar reflectivity over Guangxi Region as shown in Fig.3i. This is because the simulated typhoons are generally shifted to the north, and the observed movement to Guangxi Region are not captured.

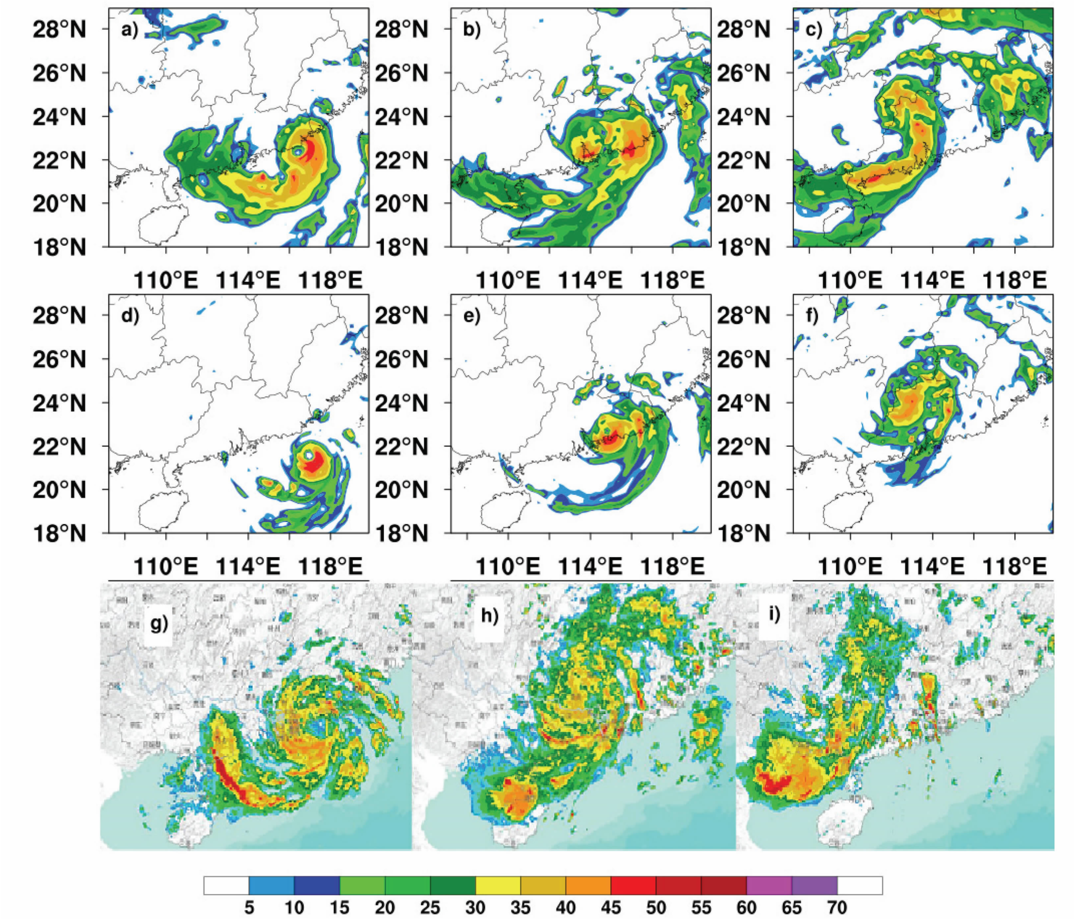

Figure 3. The radar reflectivity at (a) 1800 UTC August 1, (b) 0600 UTC August 2, and (c) 1800 UTC August 2 for the simulation with the Liuma microphysics scheme. (d)(e)(f) are the same as (a)(b)(c) but for the simulation with WSM6 scheme. (g)(h)(i) are the same as (a)(b)(c) but for observation (http://products.weather.com.cn/product/radar).

4.3 *Accumulated precipitation*

Figure 4 shows the simulated and observed accumulated precipitation from 1100 UTC August 1 to 1400 UTC August 1. This period is chosen with the availability of high quality observational data being taken into consideration. As shown in Fig.4, the maximum precipitation of the observed typhoon is up to 70 mm smaller than that of the simulation. Note that heavy precipitation occurs around the peripheral rainband since Typhoon Nida is unsymmetrical. However, both simulated heavy precipitation occurs mostly within the eye-wall region. Compared with the observations, the deviation of the typhoon track and the underestimation of the peripheral rainband for both schemes contribute to the omission of heavy precipitation at the peripheral rainband.

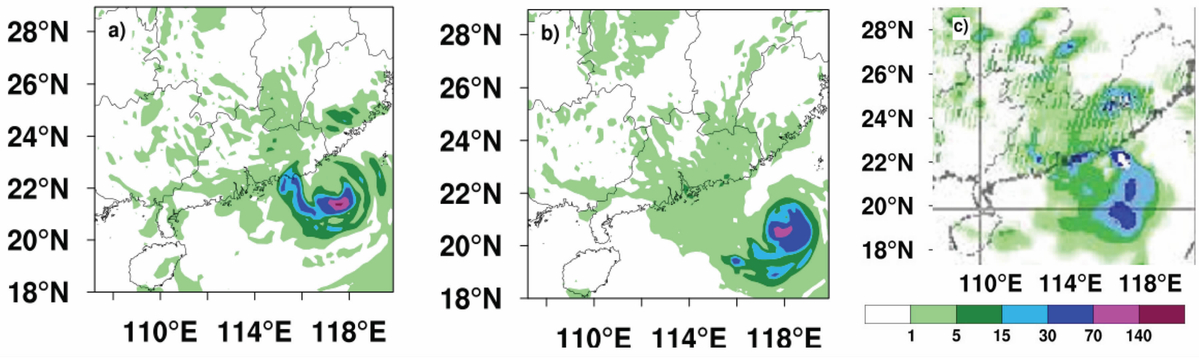

Figure 4. The accumulated precipitation from 1100 UTC August 1 to 1400 UTC August 1. (a) is the simulation with the Liuma microphysics scheme. (b) is the simulation with WSM6 scheme. (c) is the observation (http://satellite.nsmc.org.cn/).In the following analysis, the article focuses on the distribution of hydrometeors simulated with the Liuma and WSM6 microphysics schemes, and the relationship between the hydrometeors and typhoon intensity.

5 INFLUENCE OF MICROPHYSICAL PROCESSES ON TYPHOON NIDA

5.1 *The influence of microphysical processes on hydrometeor distribution*

Figure 5 shows the radius-height cross sections of azimuthally-averaged hydrometeor concentrations (g kg^{-1}) at 1800 UTC on August 1. The distributions of cloud mixing ratios simulated with the two schemes are quite similar. The maximum cloud mixing ratios reach 0.3 g kg^{-1} at around 50 km from the typhoon center, with the high value region of cloud water mixing ratio (>0.1 g kg^{-1}) extending to 120 km for the Liuma microphysics scheme and 100 km for the WSM6 scheme (Figs.5a-b). The maximum rain water mixing ratio simulated with the Liuma microphysics scheme is 1 g kg^{-1} at 60–70 km from the typhoon center, and up to 3 g kg^{-1} at 40 km from the typhoon center for the WSM6 scheme. The high value region of the rain water mixing ratio (>0.1 g kg^{-1}) extends to 170 km for the Liuma microphysics scheme and 110 km for the WSM6 scheme (Figs.5c-d). Note that there is another high value of rain water mixing ratio simulated with the Liuma microphysics scheme at 210–220 km from the center, which corresponds to the simulated high radar reflectivity of the peripheral rainband (Fig.3a).

For the distribution of ice-phase hydrometeors, there is a large difference between the two microphysics schemes. The ice-phase hydrometeors simulated with the Liuma microphysics scheme are almost entirely graupel, which possibly results from the excessively rapid production of graupel by riming. The maximum graupel mixing ratio reaches 3 g kg^{-1} at around 70 km from the typhoon center. The high value area of the graupel mixing ratio (> 1 g kg^{-1}) extends from 50 to 120 km from the typhoon center radially, and from 550 to 100 hPa vertically (Fig.5i). The rapid riming also reduces the amount of ice water and snow water, resulting in small mixing ratios (~0.01 g kg^{-1}). The ice water mixing ratio simulated with the WSM6 scheme is also quite low (0.01–0.1 g kg^{-1}). Both snow and graupel mixing ratios have similar maximum values of 2-3 g kg^{-1} at about 40 km from the typhoon center. High value regions of snow and graupel mixing ratios are within 100 km radially from the eye-wall, snow appears at 200-400 hPa and graupel appears at 300-550 hPa vertically (Figs.5h-j).

5.2 *The influence of microphysical processes on typhoon intensity*

Figure 6 shows the time evolution of the averaged typhoon eye-wall region hydrometeor mixing ratios (g kg^{-1}), the vertical velocity component (m s^{-1}) and the equivalent potential temperature (K) from 0000 UTC August 1 to 0000 UTC August 3. The study focuses on the last 2 days when the typhoon central pressure simulated with the WSM6 scheme decreases significantly. The maximum rain water mixing ratio occurs at around 1200 UTC August 1 for the Liuma microphysics scheme and 0000 UTC August 2 for the WSM6 scheme. These are also the times of maximum eye-wall ice-phase hydrometeor mixing ratios (Figs. 6e-f). The averaged maximum vertical velocity component is about 0.4 m s^{-1} at 1200 UTC August 1 for

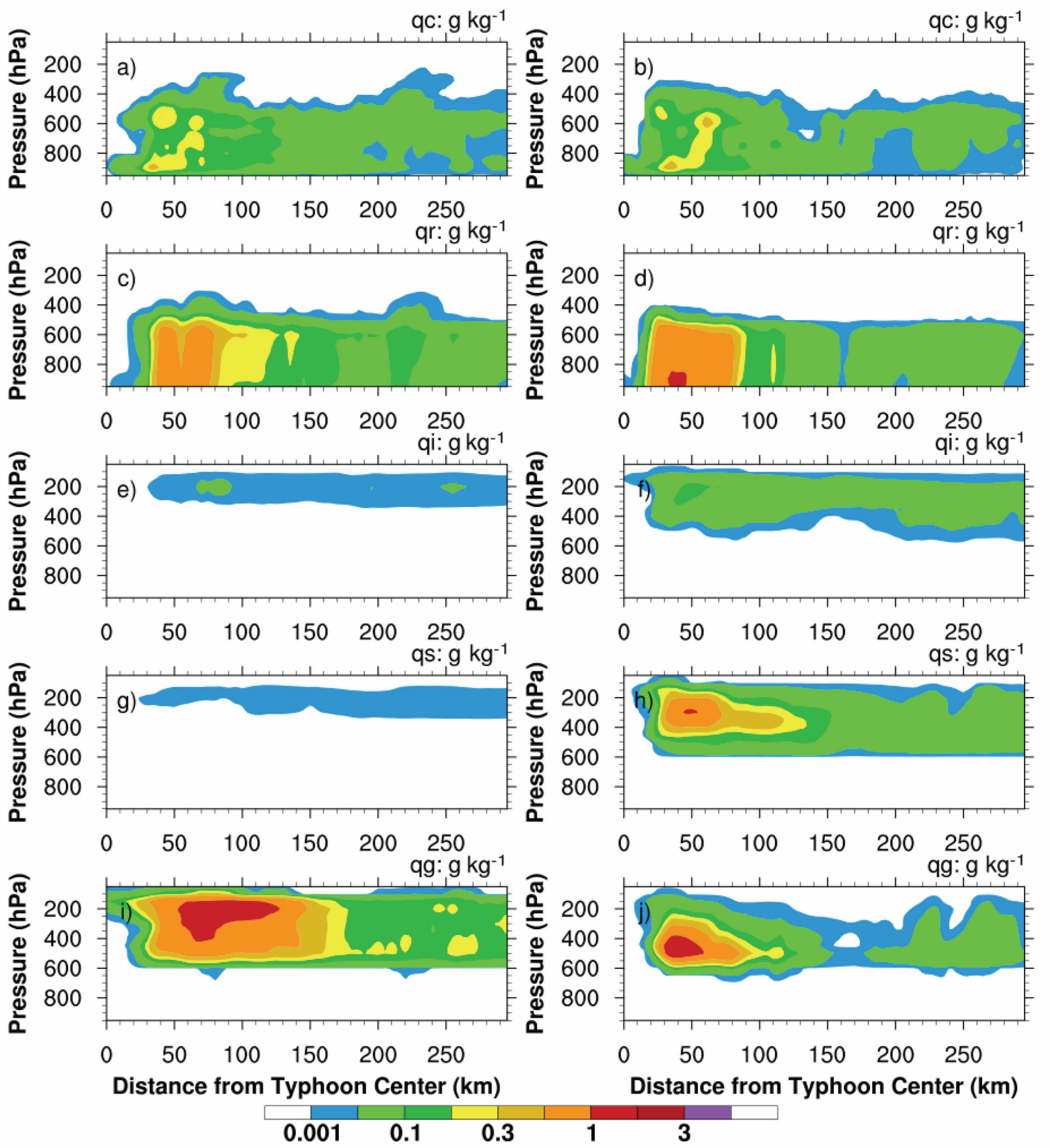

Figure 5. The radius-height cross-sections of azimuthally averaged hydrometeor concentrations (g kg^{-1}) at 1800 UTC August 1. Hydrometeors are cloud water (qc), rain water (qr), cloud ice (qi), snow (qs) and graupel (qg) from up to down. The left column represents result from Liuma microphysics scheme, Right column represent WSM6 results.

the Liuma microphysics scheme (Fig.6g), and above 0.5 m s^{-1} for the WSM6 scheme at 0000 UTC August 2 (Fig.6h). Note that Typhoon Nida is not symmetric, and that the maximum vertical velocity component for both schemes is as high as 10 m s^{-1} for our simulations (not shown). Again, the time when the vertical velocity component reaches maximum corresponds to the moment when the rain water and ice-phase hydrometeor mixing ratios reach their maximum. The results also show that the increase of the vertical velocity component corresponds to the increase of the equivalent potential temperature in the lower and middle troposphere.

These results imply that the more active ice phase processes (which increase the ice-phase hydrometeors) correlate with the typhoon strength, which is consistent with previous studies (Zhu and Zhang[4]). The high value of rain water and graupel also correlates highly with the typhoon intensity, implying a positive feedback between hydrometeors and typhoon intensity. Specifically, the condensation of more hydrometeors induces larger adiabatic heating, resulting in an increase in the instability of the typhoon eye-wall, and an enhanced vertical velocity component, which in turn, produces more hydrometeors. However, how such feedback is triggered needs further investigation.

6 SUMMARY

The basic structure and cloud features of Typhoon Nida (2016) are simulated using a new microphysics

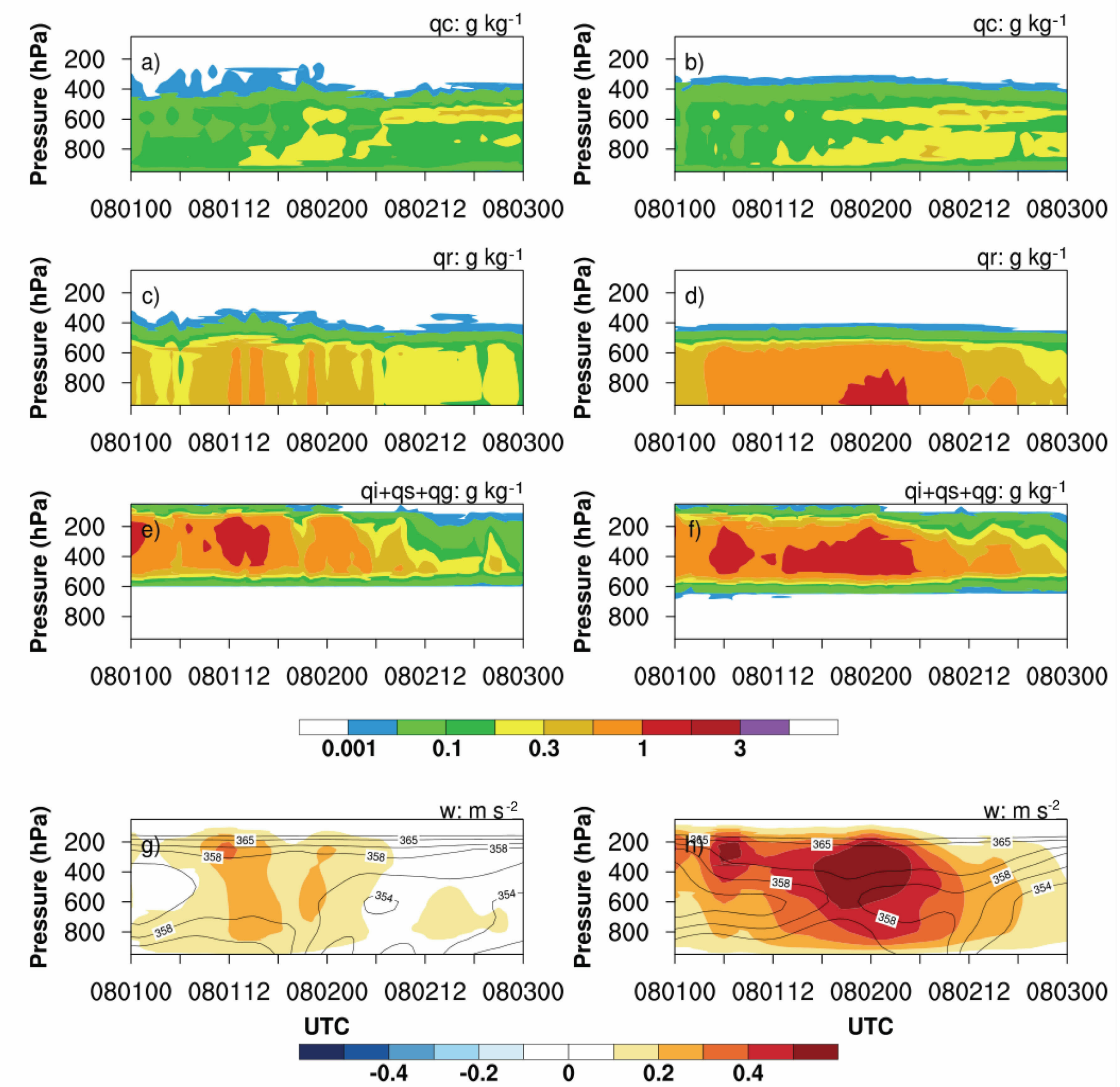

Figure 6. Time evolution of averaged typhoon eye-wall region (20-70 km from typhoon center) hydrometeor concentrations (g kg^{-1}), vertical velocity component (m s^{-1}) and the equivalent potential temperature (K) from 0000 UTC August 1 to 0000 UTC August 3. The hydrometeors are the cloud water, rain water, ice-phased hydrometeors from top to bottom. The left column represents results from the Liuma microphysics scheme, and the right column represents the WSM6 results.

scheme implemented into the WRF model. The typhoon track, intensity, precipitation and hydrometeor distribution simulated with the Liuma microphysics scheme are compared with both observations and a commonly-used microphysics scheme to evaluate its performance. In general, the results show that the Liuma microphysics scheme describes the cloud microphysics reasonably, with a better intensity and radar structure compared with the WSM6 scheme. The influence of microphysical processes on the typhoon is also studied, with major points noted as follows.

In the case of Typhoon Nida, the microphysical scheme does not have a significant impact on the track of the typhoon, but the microphysical schemes can affect typhoon intensity noticeably, which is consistent with previous studies (e.g. Cheng, et al.[1]; Tao, et al.[22]). The pressure of the typhoon center simulated with the Liuma scheme is close to the observations, while that simulated with the WSM6 scheme is much lower than the observations.

The results also show that the vertical distribution of cloud hydrometeors and the horizontal distribution of the peripheral rainband are affected by the microphysical schemes. One characteristic of the Liuma microphysics scheme is that the ice-phase hydrometeors are mostly graupel during Typhoon Nida.

The mixing ratios of rain water and graupel correlate highly with the vertical velocity component at the eye-wall region. Stronger typhoons tend to have greater rain water and ice-phase hydrometeor mixing ratios according to previous investigations (e.g. Cheng et al.[1]). The study suggests the existence of a positive feedback between the degree of hydrometeors and the typhoon intensity. However, the trigger for the positive feedback needs further investigation.

Only one case has been tested for the Liuma microphysics scheme in the WRF model. Additional case studies aimed at microphysical processes, including a more comprehensive microphysical sensitivity testing of individual processes, especially for the overestimation of graupel, will be conducted in future research.

Acknowledgement: We thank Richard Foreman, PhD, from Liwen Bianji, Edanz Editing China (www.liwenbianji.cn/ac), for editing the English text of a draft of this manuscript.

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Citation: LI Zhe, ZHANG Yu-tao, LIU Qi-jun, et al. A study of the influence of microphysical processes on Typhoon Nida (2016) using a new double-moment microphysics scheme in the weather research and forecasting model [J]. J Trop Meteor, 2018, 24(2): 123-130.