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Sensitivity of the Simulation of Tropical Cyclone Size to Microphysics Schemes

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ABSTRACT

The sensitivity of the simulation of tropical cyclone (TC) size to microphysics schemes is studied using the Advanced Hurricane Weather Research and Forecasting Model (WRF). Six TCs during the 2013 western North Pacific typhoon season and three mainstream microphysics schemes–Ferrier (FER), WRF Single-Moment 5-class (WSM5) and WRF Single-Moment 6-class (WSM6)–are investigated. The results consistently show that the simulated TC track is not sensitive to the choice of microphysics scheme in the early simulation, especially in the open ocean. However, the sensitivity is much greater for TC intensity and inner-core size. The TC intensity and size simulated using the WSM5 and WSM6 schemes are respectively higher and larger than those using the FER scheme in general, which likely results from more diabatic heating being generated outside the eyewall in rainbands. More diabatic heating in rainbands gives higher inflow in the lower troposphere and higher outflow in the upper troposphere, with higher upward motion outside the eyewall. The lower-tropospheric inflow would transport absolute angular momentum inward to spin up tangential wind predominantly near the eyewall, leading to the increment in TC intensity and size (the inner-core size, especially). In addition, the inclusion of graupel microphysics processes (as in WSM6) may not have a significant impact on the simulation of TC track, intensity and size.

Key words: tropical cyclone, microphysics, size, intensity, track, numerical modelling

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1. Introduction

The size of a tropical cyclone (TC) is an important quantity to describe how large its area of influence is. Studying TC size can therefore help in our understanding of the destructive potential brought by a TC. By making use of observational data, for example, best-track data, aircraft reconnaissance measurements, satellite-derived and infrared imageries, the climatology of TC size has been well studied in recent decades, especially over the western North Pacific and North Atlantic (e.g. Merrill, 1984; Kimball and Mulekar, 2004; Yuan et al., 2007; Chavas and Emanuel, 2010; Chan and Chan, 2012, 2015a; Knaff et al., 2014). Although the definition of TC size differs among some studies, significant seasonal and spatial variation in TC size has been observed, and found to be related to TC lifetime, ENSO, and subtropical high activity. By making use of numerical experiments and reanalysis data, TC size has been found to be sensitive to the lower-tropospheric absolute angular momentum transport (Chan and Chan, 2013), environmental humidity (Hill and Lackmann, 2009), surface entropy flux (Xu and Wang, 2010a), initial vortex size (Xu and Wang, 2010b; Chan and Chan, 2014), planetary vorticity (Smith et al., 2011; Chan and Chan, 2014), vortex intensification (Knaff et al., 2014; Chan and Chan, 2015b), spiral rainbands (Wang, 2009; Fudeyasu and Wang, 2011; Wang, 2012) and outer winds (Chan and Chan, 2015b).

Owing to increased model resolution (e.g. Miyoshi et al., 2010), improved physical parameterizations, ensemble forecasting techniques (e.g. Krishnamurti et al., 1997; Goerss, 2000; Srinivas et al., 2007), and the availability of high-quality satellite-derived data, especially over the data-scarce ocean (e.g. Leslie et al., 1998), the ability of NWP models to forecast the TC track has increased substantially (e.g. Rogers et al., 2006; Rappaport et al., 2009). TC bogussing (e.g. Kurihara et al., 1990; Heming et al., 1995; Leslie and Holland, 1995) and enhanced initialization techniques, including data assimilation (e.g. Zou and Xiao, 2000; Torn, 2010), have also helped. However, improvement in the ability to forecast TC intensity and size has been rather minimal. In fact, to the best of our best knowledge, there are no published studies that examined forecasting skill with respect to TC size.

Given this knowledge gap, the present study represents a first step toward investigating how well NWP models can predict TC size; specifically, by examining the differences in simulated TC size using different mainstream microphysics schemes currently available: Ferrier (FER; Rogers et al., 2001); WRF Single-Moment five-class (WSM5; Hong et al., 2004); and WRF Single-Moment six-class (WSM6; Hong et al., 2006). Fovell and Su (2007) tested the Kessler (Kessler, 1995), Lin (Lin et al., 1983; Chen and Sun, 2002), WRF

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Single-Moment three-class (WSM3; Hong et al., 2004) and WSM5 microphysics schemes and suggested that they appear to directly or indirectly modulate vortex characteristics, including size and winds, at a large radius, and possibly other factors involved in TC motion. Fovell et al. (2009) further revealed that the influence of microphysics and hydrometeor falling speeds on radial temperature gradients could lead to different outer wind strengths and tracks when using an idealized model. Cloud microphysical processes may also emerge through cloud-radiative feedback (Fovell et al., 2010). On the other hand, many other studies have shown that microphysics schemes do not have any significant impact on track forecasts, but do have more of an effect on the simulated TC intensity (e.g. Yang and Ching, 2005; Zhu and Zhang, 2006; Li and Pu, 2008; Tao et al., 2011). They also found that simulated TCs have their strongest deepening or intensification when using warm-rain physics only (e.g. Wang, 2002; Yang and Ching, 2005, Zhu and Zhang, 2006; Li and Pu, 2008). However, how widely-used microphysics schemes might affect the simulation of TC size remains unknown; and addressing this issue is the objective of this study.

In section 2, the model configuration and experimental design are described. The model results are compared and analyzed in section 3. And finally, conclusions and a discussion are presented in section 4.

2. Model configuration and experimental design

The Advanced Hurricane Weather Research and Forecasting Model (WRF, known also as AHW), version 3.6, is employed to simulate six TCs in the 2013 western North Pacific typhoon season. They are: Soulik, Usagi, Danas, Wipha, Francisco and Haiyan. These six cases are chosen because they had a lifetime of more than three days, reached hurricane force at least once during their lifetime, and their tracks were diverse enough to represent the general spread of tracks over the western North Pacific (Fig. 1). The same typhoon season is chosen so as to minimize the uncertainty from different data assimilation techniques used in different years. All six TC cases have different initial size. Note also that six cases are used in this study, rather than a single case, because this could increase the robustness of the conclusions.

The model domain is triple-nested with two-way interactive nesting and with the inner meshes automatically vortex-following. The horizontal grid resolutions are 36, 12 and 4 km, and the corresponding domain sizes are 9360×6840, 1440×1440 and 840×840 km^2, respectively. The outermost static domain is centered at (23.5°N, 140°E), which is broad enough to cover all the TC cases and the western North Pacific. The model has 36 vertical eta (η) levels, with higher vertical resolution in the planetary boundary layer, and the reference model top pressure is 20 hPa. Complex topography and land–sea contrast are included. The initial and lateral boundary conditions are respectively initialized and six-hourly updated from the NCEP Final Operational Global Analysis data [FNL; 1° (lat) ×1° (lon)].

For the model physics, the unified Noah land surface model (Tewari et al., 2004), MM5 (The PSU/NCAR mesoscale model) similarity surface layer physics (Jiménez et al., 2012) and Yonsei University (YSU) planetary boundary layer scheme (Hong et al., 2006) are employed. The Rapid Radiative Transfer Model for general circulation models (RRTMG) radiation scheme (Iacono et al., 2008) is taken to model the shortwave and longwave radiation physics. The Tiedtke cumulus parameterization scheme (Tiedtke, 1989; Zhang et al., 2011) is used for the outer two domains (36 and 12 km) only. To be more in line with recent research results regarding tropical storms and hurricanes, the modified surface bulk drag (Donelan et al., 2004) and enthalpy coefficients (Brutsaert, 1975) are applied in all domains.

Three mainstream microphysics schemes that are widely used in the community—Ferrier (FER; simple three-class ice; Rogers et al., 2001), WRF Single-Moment five-class (WSM5; two-class ice; Hong et al., 2004), and WRF Single-Moment six-class (WSM6; three-class ice; Hong et al., 2006)—are employed for the sensitivity tests in this study. FER is currently an operational microphysics scheme in NCEP models, and is a simple and efficient scheme with diagnostic mixed-phase (ice, snow and graupel) processes, while the phase processes are all distinct in WSM5 and WSM6. The major difference between the WSM5 and WSM6 schemes is that the WSM6 scheme includes additional microphysics processes related to graupel. All other physical schemes and model settings are the same in all the experiments. More details of WRF physics and dynamics can be found in Skamarock et al. (2008). Results from 18 experiments in total (six TC cases with three microphysics schemes) are compared to examine how the microphysics scheme affects the simulation of TC size.

The model configuration and experimental design of the present study are summarized in Table 1. The details of the six TC simulations are listed in Table 2. To minimize the uncertainty and influence of other factors that can affect or be affected by TC track on the TC size, e.g. the environmental synoptic flow around a TC (Chan and Chan, 2013) and the planetary vorticity (Chan and Chan, 2014), the first 72 hours of model results are mainly discussed in this study. Results within the first three days should be largely representative because the mean track error at 72 h (T72) of the simulations is ~170 km (i.e. ~1.5° latitude), which is largely acceptable. The best-track data used in this study are based on those from the Joint Typhoon Warning Center.

3. Results

Previous studies have suggested that synoptic flows around a TC (e.g. Liu and Chan, 2002; Chan and Chan, 2013) and the TC inner-core–induced intensification (e.g. Chan and Chan, 2014) can affect TC size, which imply that TC track and intensity should also be examined when examining TC size. Hence, the impacts of the microphysics schemes on

Table 1. Summary of the WRF V3.6 model configuration.

Horizontal resolution	36 km	12 km	4 km
Horizontal dimension	260×190 grids (9360×6840 km^2)	120×120 grids (1440×1440 km^2)	210×210 grids (840×840 km^2)
Moving nest	Static	Vortex-following	Vortex-following
Number of eta levels	36	36	36
Model top	20 hPa	20 hPa	20 hPa
Time step	135 s	45 s	15 s
Land surface physics	Unified Noah land surface model (Tewari et al., 2004)	Unified Noah land surface model (Tewari et al., 2004)	Unified Noah land surface model (Tewari et al., 2004)
Surface layer physics	MM5 similarity (Jimenez et al., 2012) with modified surface drag (Donelan, 2004) and enthalpy (Brutsaert, 1975)	MM5 similarity (Jimenez et al., 2012) with modified surface drag (Donelan, 2004) and enthalpy (Brutsaert, 1975)	MM5 similarity (Jimenez et al., 2012) with modified surface drag (Donelan, 2004) and enthalpy (Brutsaert, 1975)
Land use	USGS 24-Category	USGS 24-Category	USGS 24-Category
Microphysics	FER (Rogers et al., 2001) WSM5 (Hong et al., 2004) WSM6 (Hong and Lim, 2006)	FER (Rogers et al., 2001) WSM5 (Hong et al., 2004) WSM6 (Hong and Lim, 2006)	FER (Rogers et al., 2001) WSM5 (Hong et al., 2004) WSM6 (Hong and Lim, 2006)
Planetary boundary layer	YSU (Hong et al., 2006)	YSU (Hong et al., 2006)	YSU (Hong et al., 2006)
Longwave and shortwave radiation	RRTMG (Iacono et al., 2008)	RRTMG (Iacono et al., 2008)	RRTMG (Iacono et al., 2008)
Cumulus parameterization	Tiedtke (Tiedtke, 1989; Zhang et al., 2011)	Tiedtke (Tiedtke, 1989; Zhang et al., 2011)	Nil
Initial condition	NCEP FNL	NCEP FNL	NCEP FNL
Lateral boundary condition	NCEP FNL	Parent domain	Parent domain

Table 2. Summary of the TCs tested.

TC name	Initial time	Initial intensity (knots)	Simulation hours
Soulik	1200 UTC 8 July 2013	60	120
Usagi	0000 UTC 18 September 2013	50	126
Danas	1200 UTC 5 October 2013	60	72
Wipha	1200 UTC 11 October 2013	50	108
Francisco	0000 UTC 17 October 2013	65	144
Haiyan	0000 UTC 5 November 2013	70	144

the simulations of TC track, intensity and size are discussed simultaneously.

3.1. *Track*

Consistent with the findings from many previous studies (e.g. Yang and Ching, 2005; Zhu and Zhang, 2006; Li and Pu, 2008; Tao et al., 2011), the simulated TC tracks are not sensitive to the microphysics schemes (Fig. 1) in general, especially in the first 72 h when the TCs are over the open ocean where the influence of the landmass and topography on TC track is limited. This result suggests that the choice of the microphysics scheme among FER, WSM5 and WSM6 is likely not important in simulating the subtropical high in the early simulation, as the latter is a main factor in steering the TC.

3.2. *Intensity*

The trends of the simulated TC intensity largely agree with the best-track data in the first 72 h, but the minimum sea-level pressure (MSLP) is generally higher than observed [~20 hPa higher at 48 h of simulation (T48) on average; not shown]. As the main objective of this study is to investigate the impacts of microphysics schemes on the simulation of TC size, the difference between the simulated and observational TC intensity is not examined further. Instead, the comparisons among the three schemes on their simulations of TC intensity are discussed below.

The model results suggest that the simulated TC intensity can be influenced by the choice of microphysics scheme. The TCs in the simulations with the WSM5 and WSM6 schemes are found to have lower MSLP than those with the FER scheme during the first 72 h in general (Fig. 2a). A higher maximum wind is attained for the TCs with the WSM6 scheme on average (Fig. 2b). For example, for Soulik, the WSM5 and WSM6 schemes give lower MSLP than that from the FER scheme throughout the entire simulation (Fig. 3a) although the differences in maximum wind are not that obvious in this case (Fig. 3b). The azimuthally averaged lower-tropospheric inflow and upper-tropospheric outflow between 25 and 48 h in the simulations with the WSM5 and WSM6 schemes are generally higher than those with the FER scheme (Fig. 4). Chan and Chan (2013) found that the change in TC intensity is positively related to the change in the upper-level angular momentum export, while the change in TC size is positively proportional to the change in the lower-tropospheric angular momentum import. Chan and Chan (2015b) further showed that the inner-core induced intensification is favorable for size growth. Inner-core induced intensification mainly results from the inner-core dynamics: for example, an increase in upper-tropospheric outflow leads to a decrease in surface pressure, and thus it favors the lower-tropospheric inflow near the inner core so that more

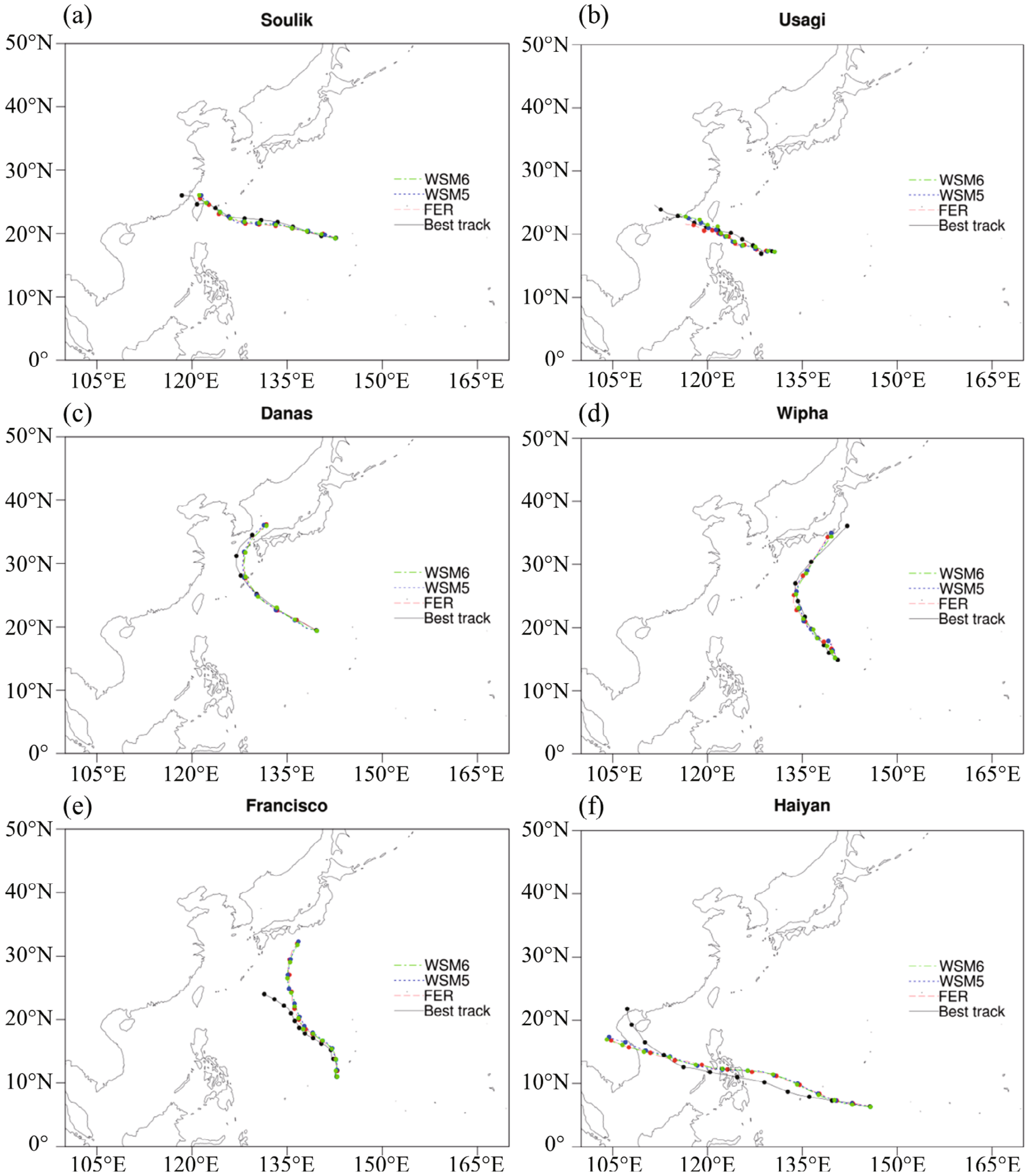

Fig. 1. Summary of TC tracks with different microphysics schemes in different TC cases.

angular momentum is transported towards the vortex center and consequently yields an expansion of horizontal wind fields.

All the six TC cases in this study possess inner-core–induced intensification in the early simulation. The stronger upper-tropospheric outflow found in the simulations with WSM5 and WSM6 may be attributable to the greater diabatic heating generated outside the eyewall in the rainbands (Fig. 5). Wang (2009), Fudeyasu and Wang (2011) and Wang (2012) suggested that greater diabatic heating in rainbands gives higher inflow in the lower troposphere and higher outflow in the upper troposphere (Fig. 4), with higher upward motion (Fig. 6) outside the eyewall. The lower-tropospheric inflow would transport absolute angular momentum inward to spin up tangential wind predominantly near the eyewall (Fig. 7), leading to the increase in TC intensity and size (see TC size definition and details of the sensitivity of TC size to microphysics in sections 3.3 and 3.4). This is consistent with the convection such that more precipitation is found for TCs using the WSM5 and WSM6 schemes (Fig. 8). All these results imply that the WSM5 and WSM6 schemes could drive a stronger secondary circulation than the FER scheme and therefore result in a higher TC intensity. Such circumstances are also generally found in other cases and therefore

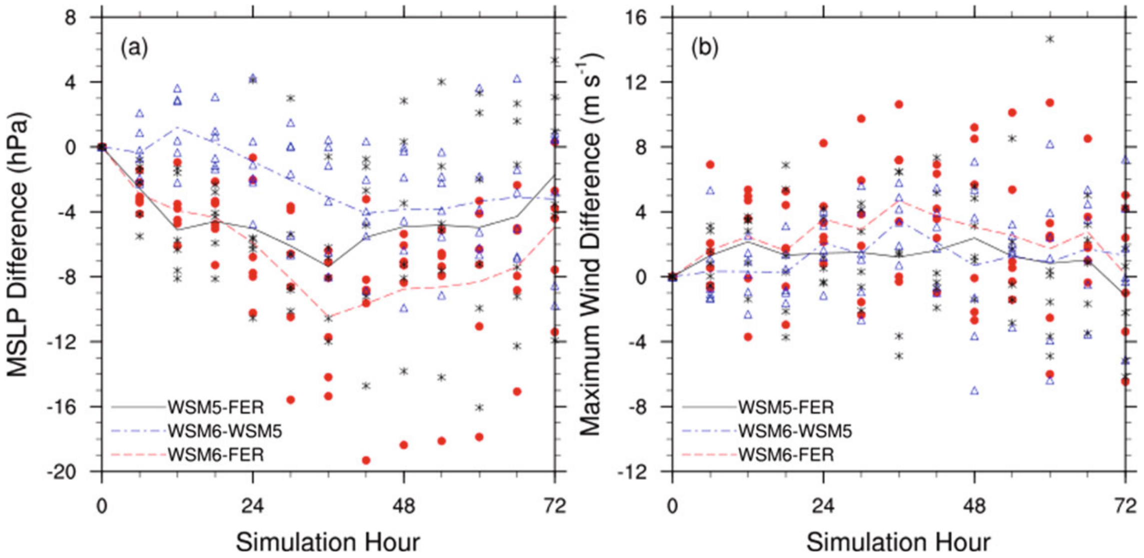

Fig. 2. Differences among the microphysics schemes for (a) MSLP and (b) maximum wind in the first 72 h of six TC simulations. Black asterisks, blue triangles and red dots are the spreads of differences between WSM5 and FER, WSM6 and WSM5, and WSM6 and FER from the 6 TC simulations, respectively. Black solid, blue dash-dotted and red dashed lines indicate their means, respectively.

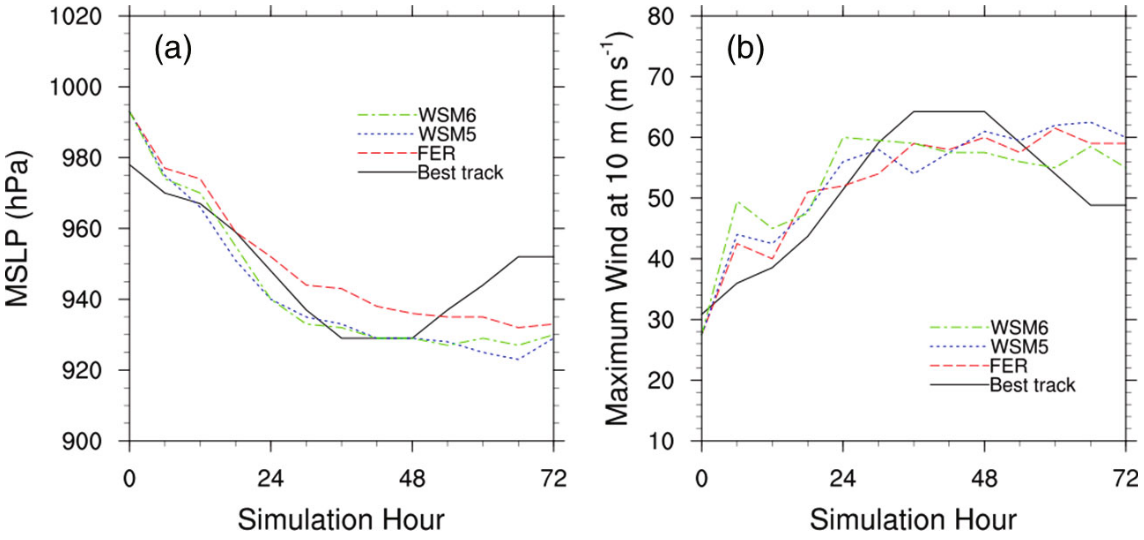

Fig. 3. Time-series of (a) MSLP and (b) maximum wind of Soulik with different microphysics schemes.

not shown.

3.3. *Size*

An important result of this study is that TCs in the simulations with the WSM5 and WSM6 schemes are found to be generally larger than those with the FER scheme during the first 72 h of the simulation (Fig. 9). This suggests the selection of microphysics scheme can lead to differing simulations of TC size. In the early simulation, vortices can be assumed to experience almost the same environmental influence (as evidenced from section 3.1) so that the effects of the peripheral synoptic flows, environmental humidity and planetary vorticity (e.g. Liu and Chan, 2002; Hill and Lackmann, 2009; Chan and Chan, 2013, 2014) on the TC size difference might be negligible. Therefore, the factor or factors leading to such size differences likely relate to the inner-core microphysics processes.

The inner- and outer-core sizes in this study are defined as the azimuthal mean radius of storm-force (25 m s^{-1}; R25) and gale-force (17 m s^{-1}; R17) 10-m winds from the TC center, respectively. Figure 9 shows that the mean values of the differences among different microphysics schemes in R17 and R25 are similar. This means that the percentage difference of R25 is higher than that of R17 because R17 is about two to three times larger than R25 in general, which is given from the climatology. This is expected because, apart from the sur-

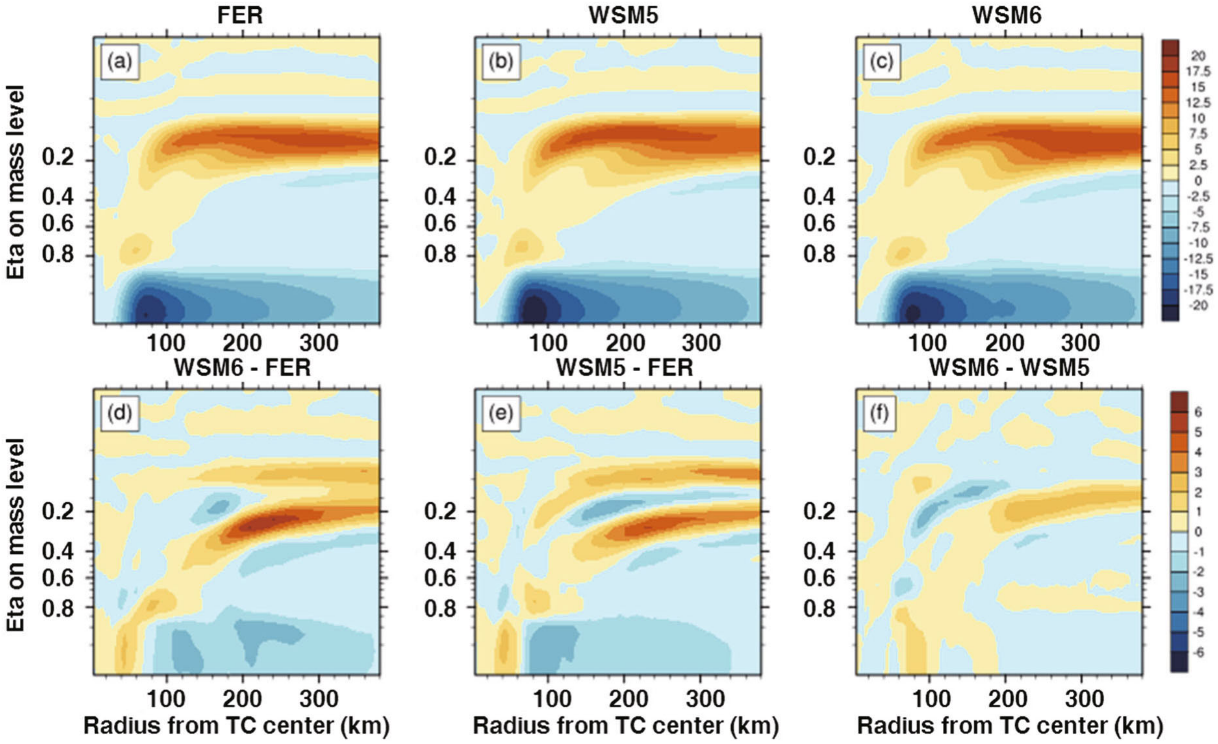

Fig. 4. Radius–height plots of the 24-h averaged azimuthal mean radial wind (units: m s^{-1}) between T25 and T48 in the case of Soulik among the (a) FER, (b) WSM5 and (c) WSM6 microphysics schemes. Negative and positive values indicate inflow and outflow, respectively. Panels (d–f) are the differences of the results shown in (a–c); see the titles of the plots for details of the subtractions. Note that the contour scales between (a–c) and (d–f) are different.

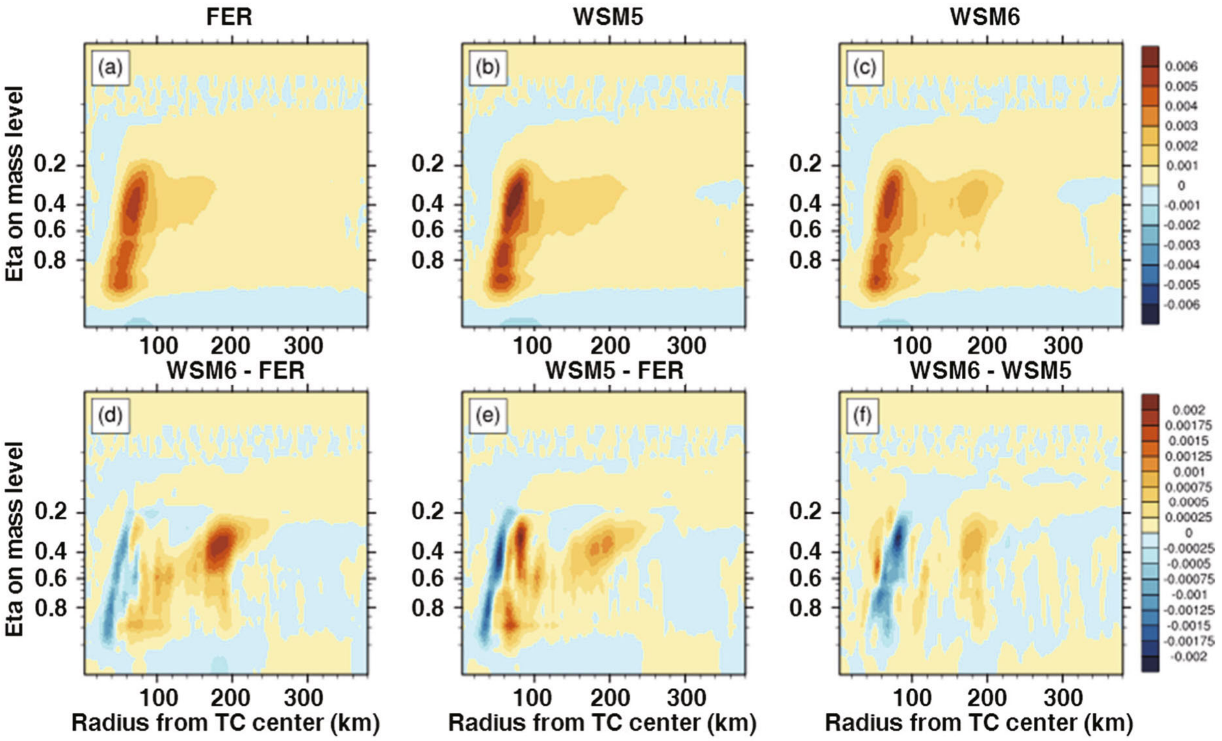

Fig. 5. As in Fig. 4 but for diabatic heating (units: K s^{-1}) due to microphysics. In (a–c), negative and positive values indicate absorption and generation, respectively.

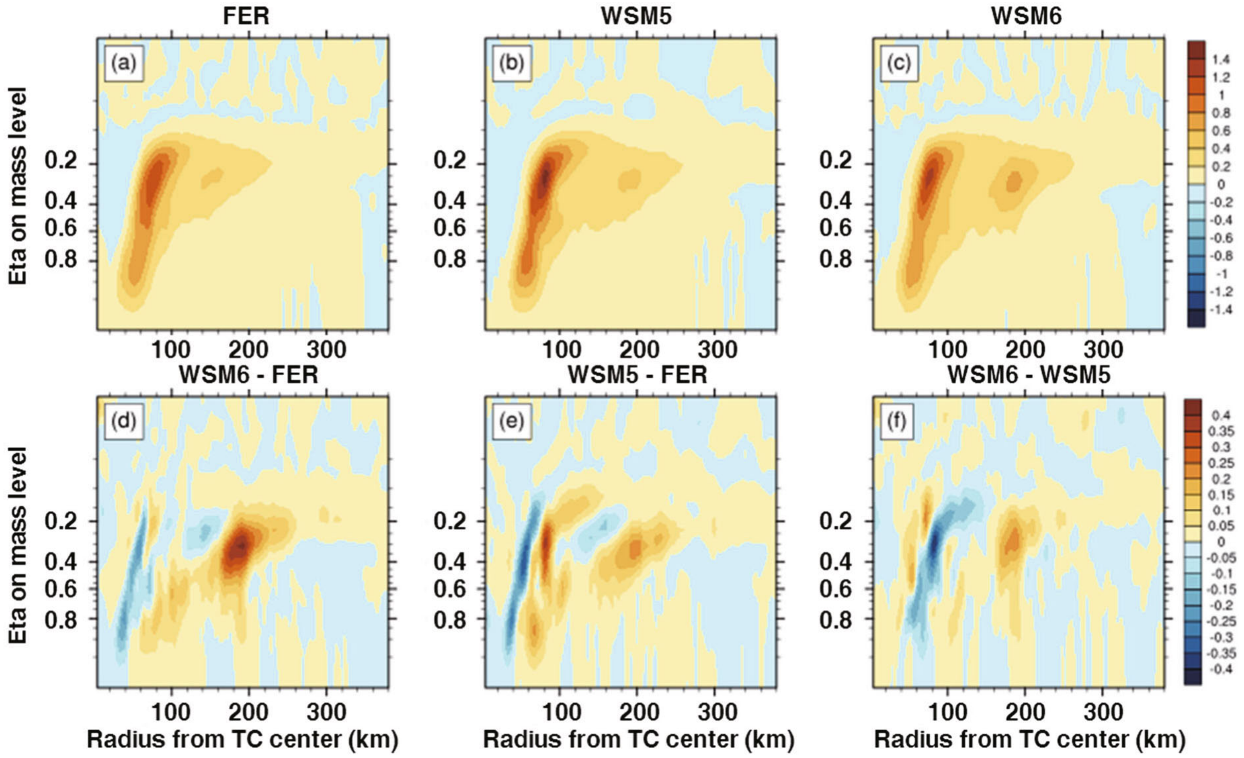

Fig. 6. As in Fig. 4 but for vertical wind (units: m s^{-1}). In (a–c), negative and positive values indicate downward and upward motions, respectively.

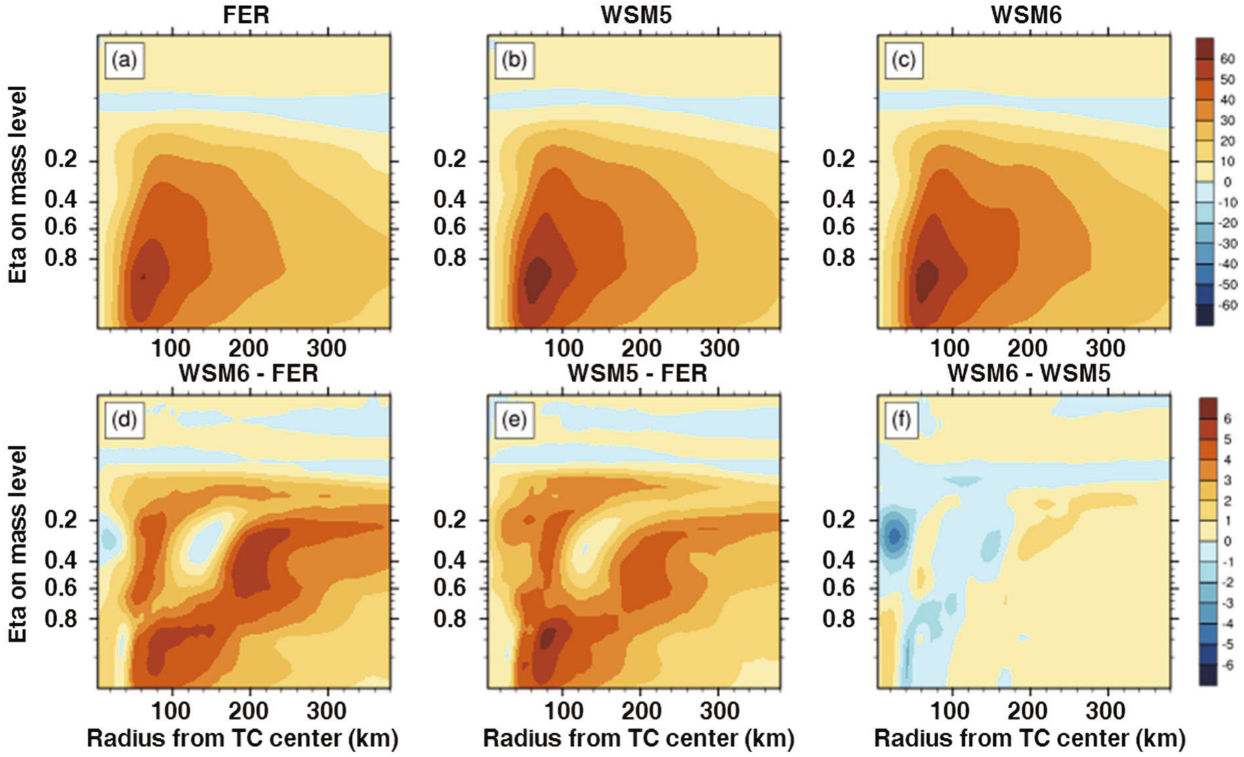

Fig. 7. As in Fig. 4 but for tangential wind (units: m s^{-1}). In (a–c), negative and positive values indicate cyclonic and anticyclone flows, respectively.

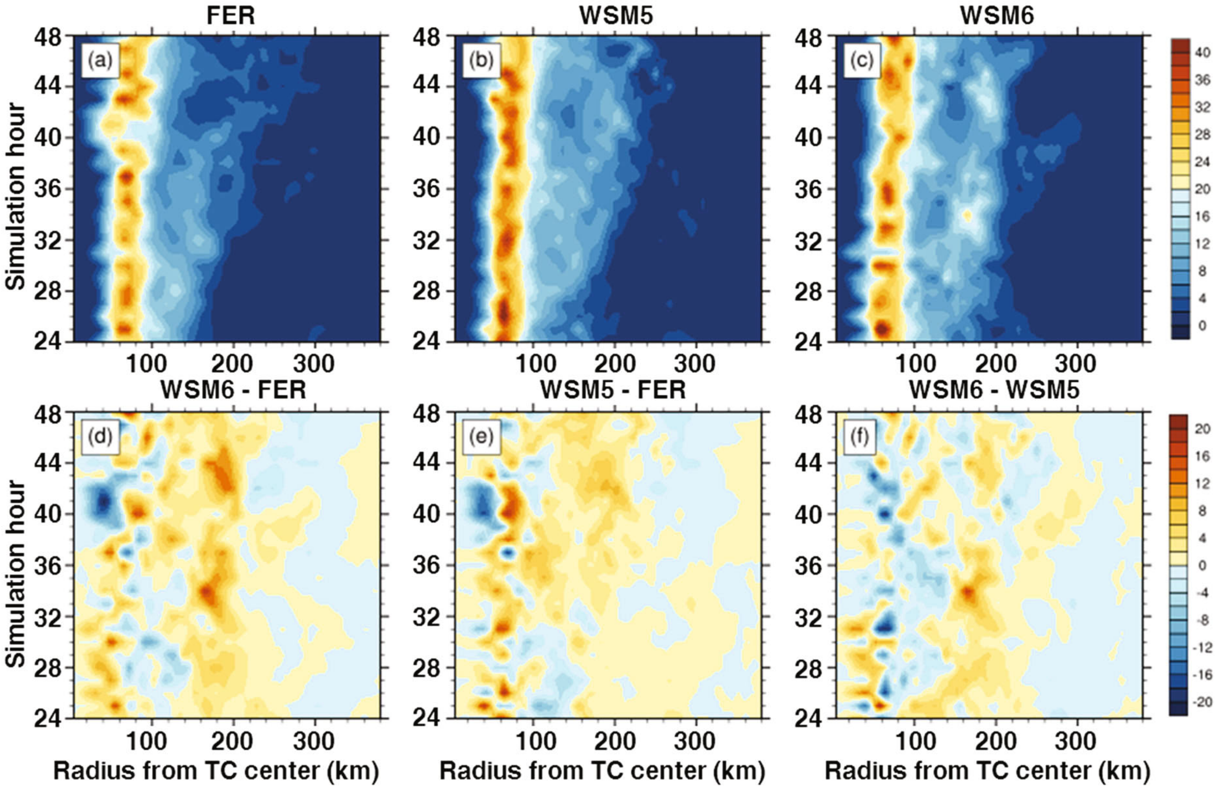

Fig. 8. Radius–time plots of 24-h averaged azimuthal mean precipitation (units: mm h^{-1}) between T25 and T48 in the case of Soulik among the (a) FER, (b) WSM5 and (c) WSM6 microphysics schemes. Panels (d–f) are the differences of the results shown in (a–c); see the titles of the plots for details of the subtractions. Note that the contour scales between (a–c) and (d–f) are different.

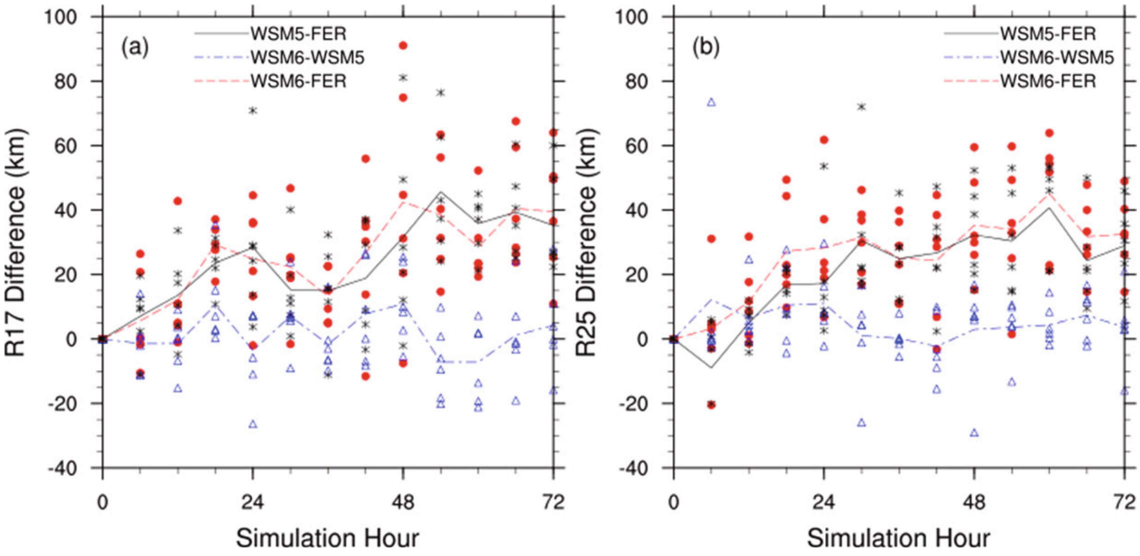

Fig. 9. Differences among the microphysics schemes of (a) R17 and (b) R25 in the first 72 h of six TC simulations. Black asterisks, blue triangles and red dots are the spreads of differences between WSM5 and FER, WSM6 and WSM5, and WSM6 and FER from the six TC simulations, respectively. Black solid, blue dash-dotted and red dashed lines indicate their means, respectively.

face friction and upper-tropospheric divergence, the lower-tropospheric inflow can also be triggered by the diabatic heating through the inner-core–induced intensification (section 3.2). Such an intensification process would consequently lead to the decrease in surface pressure and enhance the lower-tropospheric inflow near the inner core such that absolute angular momentum is transported inward to expand the horizontal wind field, leading to the increase in TC size. The strongest lower-tropospheric inflow (e.g. Figs. 4a–c) and the maximum lower-tropospheric inflow difference (e.g. Figs. 4d and e) are therefore found somewhere within the inner core. The lower-tropospheric inflow then decreases radially such that its enhancements when using the WSM5 and WSM6 schemes are very small in the outer-core region. These results imply that the inner-core size is much more sensitive to the choice of microphysics scheme (among FER, WSM5 and WSM6) when comparing to the outer-core size.

3.4. *Discussion*

Sun et al. (2015) recently examined the sensitivity of the track of Typhoon Megi (2010) to the WSM3, Lin, WSM6 and Thompson microphysics schemes. They found that the microphysics could affect the activity of the subtropical high and potentially affect the track. This somehow contradicts what we have found in this study, as well as the findings of some other studies (Yang and Ching, 2005; Zhu and Zhang, 2006; Li and Pu, 2008; Tao et al., 2011). It therefore remains unclear as to whether TC track is sensitive to the choice of microphysics scheme. More studies are needed.

On the other hand, the choice of microphysics scheme is found to be important in the simulation of TC intensity and size. The WSM5 and WSM6 schemes give a higher TC intensity and a larger size than the FER scheme in general, because they can give higher diabatic heating outside the eyewall in the rainbands, which consequently drives a stronger secondary circulation. To investigate why this is the case, the diabatic heating due to the microphysics processes is diagnosed. The model results coherently show that stronger diabatic heating is found within a 200 km radius from the TC center with the WSM5 and WSM6 schemes (e.g. Fig. 5). The more diabatic heating is generated, the higher the potential for the air parcel to move upward. Part of the moisture condenses and falls as precipitation, but most of the air continues to rise to the upper troposphere and results in stronger upper-tropospheric divergence. Such effects then enhance the lower-tropospheric inflow, and hence favor an increase in TC intensity and a growth in size (especially the inner-core size), because of the concept of the conservation of absolute angular momentum (Wang, 2009; Fudeyasu and Wang, 2011; Wang, 2012; Chan and Chan, 2013). Indeed, this is a kind of Sawyer–Eliassen balance (Bui et al., 2009). In addition, the present result evidences that the diabatic heating in the rapid filamentation zone mainly contributes to the increase in inner-core size, as revealed in Li et al. (2014, 2015), because the diabatic heating in the rapid filamentation zone (approximately 60–160 km from the TC center) is stronger in WSM5 and WSM6 than that in FER. Note that because the lower-tropospheric inflow that resulted from the inner-core–induced intensification decreases radially, more diabatic heating in the inner core does not necessarily lead to larger outer-core size if R17 is much larger than the radius of maximum wind (RMW).

To understand why more diabatic heating is generated in the WSM5 and WSM6 schemes than in the FER scheme, the hydrometeor distributions (especially ice, snow, graupel and rain) and microphysics processes among these three schemes are investigated. Compared with the simulations from the FER scheme, those using the WSM5 and WSM6 schemes have less cloud water (e.g. Fig. 10a), more rain (e.g. Fig. 10b), and more ice condensate (ice/snow/graupel; e.g. Fig. 10c) mixing ratios in the region with stronger diabatic heating (e.g. cf. Figs. 5 and 10). This suggests the microphysics processes of autoconversion, freezing and accretion of cloud water by rain, snow and/or graupel, as well as the deposition of ice and snow, are stronger in the WSM5 and WSM6 schemes. Therefore, the WSM5 and WSM6 schemes result in more diabatic heating generation than the FER scheme. The detailed calculation comparisons of the microphysics processes among the schemes are not explicitly discussed in this study because they involve a lot of different empirical parameterizations, assumptions, simplifications etc. (see Rogers et al., 2001; Hong et al., 2004; Hong et al., 2006 for details). A more comprehensive discussion of these is beyond the scope of this paper.

In addition, the diabatic heating difference between the simulations with the WSM5 and WSM6 schemes are found

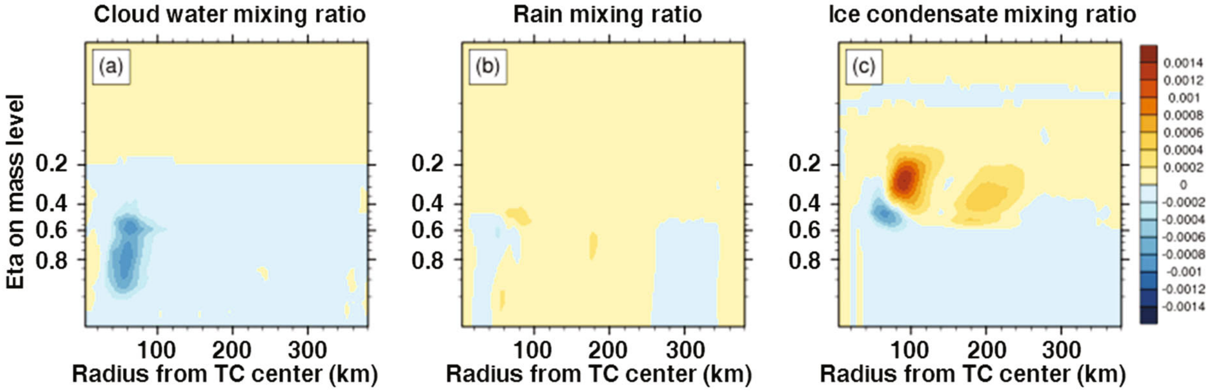

Fig. 10. Radius–height plots of the difference in 24-h averaged azimuthal mean (a) cloud water mixing ratio, (b) rain mixing ratio, and (c) ice condensate mixing ratio between T25 and T48 in the case of Soulik among the WSM5 and FER schemes. Units: dimensionless (g kg^{-1}).

to be small and uneven in general (e.g. Fig. 5f). This is likely due to the small contribution of the graupel processes to the total heating, such that there is no significant intensity and size deviations among the cases (cf. the WSM5 and WSM6 schemes in Figs. 2 and 9). The results of this study could therefore suggest that the TC intensity and size (both R17 and R25) may not be sensitive to the inclusion of graupel microphysics processes. More work is needed to verify this in the future.

Note that similar results are also found in the other five TC cases, and are therefore not discussed in detail in this study. However, caution should be exercised insofar as that although consistent results are found, they may not be universally applicable due to the limited testing (six TC cases in this study). In order to conduct a quantitatively significant investigation, more experiments, and TC cases, are needed. This study should be treated as a first step toward showing the potential impacts of three mainstream microphysics schemes on the simulated TC size.

4. Conclusions and discussion

The impacts of the choice of microphysics scheme on the simulation of TC size are studied using the Advanced Hurricane WRF model. Six TCs in the 2013 western North Pacific typhoon season and three mainstream microphysics schemes–FER, WSM5 and WSM6–are investigated. The inner- and outer-core sizes are defined as the azimuthal mean radius of storm-force (25 m s^{-1}; R25) and gale-force (17 m s^{-1}; R17) 10-m winds from the TC center, respectively. All the results (18 experiments in total) consistently show that the simulated TC track is not sensitive to these three microphysics schemes, which is consistent with results from previous studies. On the other hand, the simulated TC intensity and inner-core size are found to be significantly influenced by the choice of microphysics scheme. The simulated TC intensity and size (both R17 and R25) are similar in the simulations using the WSM5 and WSM6 schemes, and both are higher and larger than those using the FER scheme. The WSM5 and WSM6 schemes are shown to generate more diabatic heating then the FER scheme, which could be the main reason for such results. More diabatic heating could lead to higher upward motion, and hence result in higher upper-tropospheric divergence, lower-tropospheric convergence and precipitation rate. This consequently induces higher inflows at the lower troposphere and gives higher TC intensity and larger size (the inner-core size especially). It is important to note that this is a six-case sensitivity study, so the conclusions drawn should be more reliable than those from single case studies. This paper is helpful for explaining the impacts of various mainstream microphysics schemes on the simulation of TC track, intensity and, particularly, size.

The sensitivity of three mainstream cumulus parameterizations [Kain–Fritsch (Kain, 2004), Tiedtke (Tiedtke, 1989; Zhang et al., 2011), and New Simplified Arakawa–Schubert (Han and Pan, 2011)] on TC size has also been examined (not shown because it is not the focus of this study). The simulated TC track, intensity and size are found to be insensitive to such cumulus parameterizations in the first 72 h of simulation in general. In addition, comparing the relative importance of the microphysics schemes and cumulus parameterizations, the impacts of microphysics schemes on the simulated TC size are higher than those from the cumulus parameterizations.

Note again that the objective of the present study is not to search for the "best" microphysics scheme or matrix for TC prediction in WRF, although it is undoubtedly important. Many more numerical experiments and sensitivity tests have to be carried out in order to achieve this, and this is left for future work. Moreover, although the radiative forcing is likely an important factor in TC track, intensity and size (Fovell et al., 2010; Bu et al., 2014), the objective of this study was not to investigate different radiation schemes or the coupling between the microphysics scheme and the radiation scheme. The idea of this study was that, given the same radiation scheme, different microphysics schemes might give different simulations of intensity and size because of the heating that is generated being different in different schemes. It is possible that different radiation schemes could negate or enhance such heating, but this is not the point of the present paper.

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