A comparative study between bulk and bin microphysical schemes of a simulated squall line in East China

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Abstract
A squall line occurred in East China during 12 July 2014 was simulated with the Weather Research and Forecasting (WRF) model using spectral bin and two-moment bulk microphysical parameterization scheme, respectively. Comparative study showed that significant differences existed in the dynamic, thermodynamic and microphysical structures of squall line between bulk and bin simulation results. The bulk scheme produced a well-organized but shorter radar structure while bin scheme simulated scattered but stronger radar echo which was more consistent with observation. Bulk scheme had a better performance in predicting the strong rainfall areas and amount. The strong rear-to-front (RTF) inflow and convective updrafts were identified in bulk scheme by comparison with weak RTF and updrafts in bin scheme. In addition, bulk simulated a deeper cold pool than bin. Much higher cloud droplet number concentration was simulated by bulk scheme, while higher raindrop mass and number concentration was generated by bin scheme. Detailed analysis and sensitivity tests are needed in future to further investigate the possible mechanisms that responsible for the distinctive results.

Keywords: squall line; microphysical parameterization scheme; SBM; bulk; comparative study

1. Introduction

Squall line is defined as ‘a line of active thunderstorms, either continuous or with breaks, including contiguous precipitation areas resulting from the existence of the thunderstorms’ (Glickman, 2000). Due to the distinctive geometrical and dynamical structure, squall lines are commonly simulated and tested with different explicit microphysics in the same dynamical framework (Lynn et al., 2005b; Seifert et al., 2006; Lynn and Khain, 2007; Khain et al., 2009; Li et al., 2009a; Morrison et al., 2009; Bryan and Morrison, 2012; Van Weverbergh et al., 2012).

Two types of microphysical parameterization schemes were used in recent numerical models: bulk-microphysics scheme and spectral (bin) microphysics (SBM). In the traditional bulk scheme, the size distribution of hydrometeors is assumed as an empirical function and not changes during the simulation. It includes the one-moment (e.g. Kessler, 1969; Lin et al., 1983), two-moment (e.g. Thompson et al., 2008; Morrison et al., 2009) and three-moment (e.g. Milbrandt and Yau, 2005) bulk schemes. In the three-moment scheme, the predictive equation of radar reflectivity is added and the shape parameter \( \mu (N(D) = N_0 D^\mu e^{-\beta D}) \) becomes a fully prognostic variable. The simplification of bulk scheme makes it conceptually simple and computationally efficient and is widely used in numerical models, but on the other hand inevitably causes some limitations. For instance, the mean terminal velocity assumption of each type of hydrometeor which actually depends on the particle size may lead to errors in the spatial distribution of different particles (Lynn et al., 2005a). In addition, it does not solve the equation for diffusion growth of drops which is replaced by transformation of all supersaturated water vapor into cloud water mass and instead of solving the stochastic equation of collisions, semiempirical relationships for auto-conversion rates are used (Khain et al., 2009).

Another approach is the SBM. By comparison with bulk one, it uses dozens, even hundreds of mass bins to describe the size distributions of each type of hydrometeors as well as the cloud condensation nuclei (CCN). For example, the SBM implemented in Hebrew University Cloud Model (HUCM) solves prognostic equations for seven types of hydrometeors and CCN: water drops, three types of ice crystals (columnar, plate-like and dendrites), snowflakes (aggregates), graupel, hail/frozen drops. Each size distribution is represented by 33 mass bins. Lynn et al. (2005a) initially developed a fast version of SBM (SBM Fast) in which the number of size distributions decreased from eight to four (water drops, small ice particles, large ice particles and aerosol) and coupled it with a three-dimensional mesoscale model. One of their numerical experiments revealed the SBM fast had almost similar results to the full
version, which made it a good choice for our simulation experiments.

Several studies have been made to compare the bulk and SBM microphysics with the different dynamical frameworks. For instance, Lynn et al. (2005b) found the SBM Fast had a more realistic reproduction of radar reflectivity, surface rainfall and cloud structure than bulk schemes. By using a cloud-resolving model, Li et al. (2009a, 2009b) found the bulk scheme produced a multicell storm with rapid and strong evolution, while SBM produced a unicell storm with slow and weak evolution, which could be explained by different rain evaporation rate and fall velocities of precipitable ice particles between the two schemes. Note that similar results were also obtained by Khain et al. (2009). In terms of the Chinese cases, Fan et al. (2012) found a two-moment bulk scheme predicted much higher cloud droplet number and the opposite CCN effects on convection and heavy rain compared with SBM.

In summary, the differences between bulk and bin simulation results are case-dependent and no definite conclusions have been obtained. Sometimes SBM even had worse results than bulk scheme (Iguchi, 2014). On the other hand, it seems that most previous studies focused on idealized experiments or squall lines occurred in North America, where the weather background and atmospheric stratification were quite different from that in China (Meng et al., 2013). How the bin microphysical scheme performs in a realistic severe convective cloud such as squall line in East China? Are there any differences from the previous results? In this article we will try to answer the two questions.

This article is organized as follows: Section 2 describes the brief description of the squall line of interest. Section 3 gives the design of numerical experiment. Section 4 compares the simulation results with observation and focuses on the differences between bin and bulk microphysical schemes. Section 5 briefly describes the results of another squall-line case. A summary and discussion is given in Section 6.

2. Case description

A severe squall line occurred in Anhui and Jiangsu province of East China on 12 July 2014 was studied in this work. Based on the radar mosaics composited by several S and C band Doppler radars in East China, the squall line was originated from scattered clouds at 0400 UTC 12 July 2014 and then merged into a thin bow echo near the border of Hubei, Hunan and Jiangxi Province at 0500 UTC (Figure 1(a)). As moving eastward, the northern part of squall line gradually enhanced and it matured at 0900 UTC (Figure 1(b)) with a 400-km long band of convective towers in the leading edge and an intense meso-β-scale convective cell behind it. After 1000 UTC (Figure 1(c)) a broad stratiform cloud started to expand to the rear of the dissipating squall line and when the squall line moved out to sea at around 1300 UTC, it finally decayed. The squall line lasted about 9 h and caused

![Figure 1. Radar mosaics at (a) 0500 UTC, (b) 0900 UTC, (c) 1000 UTC and (d) 1200 UTC on 12 July 2014.](image-url)
heavy rainstorms and strong winds in Anhui, Jiangsu, Hunan and Hubei provinces. For example, the 24-h total rainfall in Lianu city of Anhui Province was up to 168.9 mm.

Based on the Global Forecast System (GFS) reanalysis data from the National Centers for Environmental Prediction (NCEP) and radiosonde observations from China Meteorological Administration (CMA), the weather conditions of squall line are analyzed. From Figure 2(a), the squall line was formed to the southern side of a vortex at 850 hPa and the left front of a low-level jet (Figure 2(a)). Cold and dry air was carried from high latitude by the east-propagating vortex and met with the southwesterly warm and moist air, which triggered convections initially. From the skew-T plot at Anqing station in Anhui Province before squall line passed by (Figure 2(b)), the vertical wind shear within the 0–3 km layer was up to 16 m s\(^{-1}\) and the value of convective available potential energy (CAPE) was 2921.4 J kg\(^{-1}\). The high CAPE and strong wind shear also provided favorable conditions to the longevity of convective activities.

### 3. Design of experiments

The Advanced Research WRF (ARW) v3.6.1 was used in our study to simulate the squall line of interest. The model was designed with three domains and two-way nesting. Each domain has 38 vertical levels with the model top at 50 hPa. Domain 1 has 300×240 grid points with a 13.5 km grid spacing, domain 2 has 361×301 grid points with the grid spacing of 4.5 km and domain 3 has 481×361 points with 1.5 km resolution. Two numerical experiments were conducted using Milbrandt 2-moment (bulk scheme) and HUJI SBM fast (bin scheme) microphysical schemes respectively with the same YSU planetary boundary scheme, Noah Land surface Model, RRTM long radiation scheme, Dudhia shortwave radiation scheme and the improved Kain–Fritsch cumulus parameterization scheme (Tang, 2013). Note that cumulus convection was off in the finest domain. The time step is 60 s for domain 1, 20 s for domain 2 and 6 s for domain 3. It integrated for 15 h starting at 0000 UTC on 12 July 2014. The 3-h GFS data was chosen as the initial and boundary condition with the resolution of 0.5 degree.

The Milbrandt two-moment scheme used in our study is a default version in WRF3.6.1 and it predicts mass and number concentrations of cloud water, rain, ice, snow, graupel and hail. The size distribution of each hydrometeor type is represented by a gamma function with a fixed shape factor (Morrisson and Milbrandt, 2011). The initial cloud droplet number concentration \(N_c\) is set to 500 cm\(^{-3}\) for polluted continental cases and is predicted during the simulation.

The fast version of SBM developed by Lynn et al. (2005a) includes four hydrometeor categories: water drops, ice/snow, graupel/hail and aerosol. The initial aerosol size distribution in SBM fast is determined by the power law function: \(N_{\text{CCN}} = C S^k\), where \(N_{\text{CCN}}\) is the CCN number concentration (cm\(^{-3}\)), \(S\) is the supersaturation with respect to water (%), \(C\) and \(k\) are constants that depend on air mass type. Since the squall line occurred in East China, which was known as a polluted region, a type of continental aerosol concentration was used in our study (\(C = 4000 \text{ cm}^{-3}\) and \(k = 0.308\)). The values of \(C\) and \(k\) were determined with reference to Fan et al. (2012). Based on their study, the total CCN number concentration is about 8600 cm\(^{-3}\), which is close to observations of 10\(^4\) cm\(^{-3}\) in Jinan (a city about 700 km away from Anhui province) during summer by Gao et al. (2007).
4. Comparison of bulk and bin simulation results

4.1. Radar reflectivity and surface rainfall

Figure 3 shows the observed and simulated radar reflectivity and surface rainfall. Since both bulk and bin scheme simulated a squall line occurred 1 h later than observation, we chose the different moment to represent the mature stage of squall line. In view of the radar reflectivity, the observed squall line (Figure 3(a)) matured at 0900 UTC 12 July, with a 400-km long band of convective clouds extended from northwestern Jiangxi to southern Anhui province. Besides, a meso-β-scale convective cell was observed around the border of Anqing and Luan city in Anhui province. Figures 3(c) and (e) show simulated results by bulk and bin scheme. It seems that both of the two schemes captured the general features of the observed squall line, including the orientation, moving direction and organizational mode. However, the bulk scheme (Figure 3(c)) produced weaker and shorter radar echoes and it underestimated the severe convections in southern part of the squall line. By comparison, the bin scheme (Figure 3(e)) simulated stronger and longer radar echoes which is more consistent with observation, although convections were scattered. Note that neither of the two schemes has simulated the strong convective cell in the trailing stratiform (TS) region from observation.

The right part of Figure 3 is the 6-h total rainfall from 0600 to 1200 UTC 12 July. The observed precipitation data is from the National Meteorological Information Center (Sheng et al., 2013). In Figure 3(b), the observed rain band was southwest-northeast oriented and extended from southern Anhui to southern Jiangsu province. Strong precipitation mainly occurred around Wuhu and Yicheng city in Anhui province. Figure 3(d) and (f) show simulated results by bulk and bin scheme. It seems that both of the two schemes captured the general features of the observed squall line, including the orientation, moving direction and organizational mode. However, the bulk scheme (Figure 3(c)) produced weaker and shorter radar echoes and it underestimated the severe convections in southern part of the squall line. By comparison, the bin scheme (Figure 3(e)) simulated stronger and longer radar echoes which is more consistent with observation, although convections were scattered. Note that neither of the two schemes has simulated the strong convective cell in the trailing stratiform (TS) region from observation.
Figure 4. Vertical cross sections of (a, b) radar reflectivity (shading, unit: dbz) and storm-relative wind field (vector), (c, d) horizontal wind speed (shading, unit: m s$^{-1}$), (e, f) vertical velocity (unit: m s$^{-1}$), (g, h) potential temperature perturbation (unit: K). Figures (a, c, e, g) are for bulk scheme while figures (b, d, f, h) are for bin scheme. The black solid line is the water content of 0.2 g kg$^{-1}$ which denotes the outline of the storm.
province with 6-h rainfall amount in excess of 51.2 mm. From simulation results, the bulk scheme (Figure 3(d)) has basically reproduced the strong rainfall areas and amount in observation, whereas the bin scheme (Figure 3(f)) predicted three bogus rainfall centers in the southwestern part of rain band and it also underestimated the rainfall amount in Yicheng city.

In conclusion, significant differences existed in the simulated radar reflectivity and surface rainfall by bulk and bin microphysical schemes during the mature stage of squall line. The bulk scheme produced a shorter and weaker radar echo structure, while the bin scheme simulated a strong but scattered radar echo structure. In addition, the location and amount of rain band simulated by bulk scheme agreed better with observation than that by bin scheme.

4.2. Dynamic and thermodynamic structure

As the squall line we studied is a quasi-two-dimensional system, the vertical cross sections along the moving direction of storm were given in Figure 4. Here we just gave the simulated results because no vertical structure observations were available. In terms of the cross section of radar reflectivity, both of the bulk and bin scheme produced the radar structure of an intense convective core in the leading edge and several dissipating old cells followed by the wide-spread TS region. The structure of radar reflectivity is quite similar to the conceptual model proposed by Houze et al. (1989). The differences between bulk and bin simulation results are the strength of leading convective core and the width of stratiform cloud. The stratiform region in bin scheme was more broken than bulk scheme with some weak reflectivity zones embedded, which could be also

Figure 5. Vertical profiles of (a, b) mixing ratio (unit: g kg\(^{-1}\)) and (c, d) number concentration (unit: 10\(^6\) kg\(^{-1}\)) for cloud droplet (red line), cloud ice (green line), snow (blue line), rain (orange line) and graupel (purple line) for (a, c) bulk scheme and (b, d) bin scheme.
seen from Figure 3. Whereas the bulk scheme simulated a more intense leading cell with higher echo tops than bin scheme. The radar structures of squall line simulated by bulk and bin scheme are also investigated by Lynn et al. (2005b) and Li et al. (2009a). Both of their results revealed bin scheme simulated a more realistic radar echo than bulk scheme.

Figures 4(c) and (d) show cross sections of storm-relative wind field which was obtained by subtracting the mean squall-line moving speed. It was seen that the airflows simulated by bulk scheme (Figure 4(c)) were featured by a storm-relative front-to-rear (FTR) inflow below the height of 2 km (red shading), a descending rear-to-front (RTF) inflow from 2 to 8 km (blue shading) and a FTR outflow on upper troposphere. The FTR in front of squall line ascended abruptly when approaching the surface gust front, then crossed the convective updrafts and eventually flowed out above the altitude of 8 km. The rear inflow descended when approaching the leading convective cell which carried the mid-level environmental air to the near ground. By comparison, the bin scheme (Figure 4(d)) produced much weaker low-level front inflow and mid-level rear inflow. Moreover, the rear inflow was discontinuous despite it still sank near the convective updraft. From the characteristics of vertical velocity, a very strong convective updraft was simulated by bulk scheme with maximum velocity over 15 m s⁻¹ (Figure 4(e)). Around the strong upward motion area, several weak downdrafts were induced probably as a result of mass compensation. However, weaker updrafts and downdrafts were simulated in bin scheme (Figure 4(f)), which is consistent with the features of radar reflectivity. The overestimation of updrafts and production of much too strong convection by bulk scheme has been indicated in many previous studies (Tao et al., 2007; Khain and Lynn, 2009; Li et al., 2009a, 2009b; Fan et al., 2012). The reasons for this feature have been discussed by Khain and Lynn (2009).

Apart from the storm dynamical structures, we also compared the simulated potential temperature perturbation, which was obtained by subtracting the initial temperature. From Figures 4(g) and (h), it was seen that both of bulk and bin scheme have simulated the three-layer structures of potential temperature perturbation, including the cold pool near the ground caused by rain evaporation, thick heating layer in the middle levels associated with non-adiabatic heating and cooling again above 14 km. The difference was that the bulk scheme (Figure 4(g)) had a deeper cold pool than bin (Figure 4(h)). The reason may be that stronger rear inflow was simulated in bulk scheme as shown in Figure 4(c) and more cold-dry air was carried from middle levels, which strengthened the cold pool in the near ground.

4.3. Microphysical structure

Figure 5 shows the vertical profiles of mixing ratio and number concentration for different type of hydrometeors. Both of the mixing ratio and number concentration are averaged over the area of domain 3 and then accumulated from 0000 to 1200 UTC. The most striking differences between bulk and bin results were the simulated cloud droplet (red line), rain water (orange line) and snow (blue line). The bulk scheme predicted much larger mixing ratio of cloud droplet (red line) with the maximum mass content of 2 g kg⁻¹ compared with 0.75 g kg⁻¹ in bin scheme. Similar characteristics were also seen from number concentration. The peak number concentration of cloud droplet in bulk scheme was about 660 × 10⁶ kg⁻¹, while it was just about 360 × 10⁶ kg⁻¹ in bin scheme. Correspondingly, rain number and mass concentration (orange line) in bulk scheme were drastically lower than those in bin scheme. This phenomenon may suggest that the conversion efficiency of cloud droplets to raindrops in Milbrandt scheme was much less than that in SBM. Similar results were also obtained by Fan et al. (2015). Another striking feature was that cloud droplet existed until ~12 km (close to homogeneous freezing level with a temperature of ~−38°C) in bulk scheme, comparing to ~9 km in SBM. This phenomenon was also very obvious for the case on 31 March 2014. The reason for the different existing levels of cloud droplet might be that bulk scheme predicted much stronger updrafts than SBM and cloud droplets had no enough time to grow larger and convert to hydrometeors before reaching the homogeneous freezing level. Thus more cloud droplets were carried to the height of homogenous freezing and were instantly frozen into ice crystals (Xu et al., 2011).

5. Another squall line case

Based on the analysis and discussions above, some preliminary results were obtained about the differences of bulk and bin scheme results. To generalize the conclusions of this study, another squall-line case which occurred over south China on 31 March 2014 was simulated and analyzed in this section. The corresponding plots are given in the Appendix. Here we just described the results briefly.

Figure A1 shows the observed and simulated radar reflectivity and rainfall just like Figure 3. It seems that the simulated squall line moved faster than observation and the radar features were very identical between the two schemes. From the surface rainfall, the observed rain band was in the northeastern and coastal areas of Guangdong province, while neither of two schemes has produced strong precipitation in the coastal area.

In terms of the storm dynamics and thermodynamics, the results of two squall lines had something in common, but still existed differences. For example, the bin scheme had wider but broken stratiform clouds than bulk one, while bulk scheme predicted stronger convective updrafts just as found in Figure 4. The differences...
of rear inflow and cold pool were not apparent between the two schemes.

As to the microphysical properties, a striking difference was that the second squall line had lower convective levels than first one, so the simulated hydrometeors were distributed blow 15 km. Moreover, the bulk scheme also predicted much higher cloud droplet number concentrations and lower raindrop concentrations than SBM. However, this time the differences of cloud droplet number concentrations between two schemes were not as large as that in the previous squall-line case.

6. Summary and discussion

A squall line that developed in East China during 12 July 2014 was simulated using WRF model with traditional bulk and spectral bin scheme respectively. In order to investigate the sensitivity of simulation results to different microphysical schemes, especially test the performance of newly incorporated SBM in WRF model, detailed comparative studies have been carried out.

By comparing the simulated radar reflectivity and surface rainfall with observation, we found that the bulk scheme produced a well-organized but shorter squall line, while the bin scheme produced stronger but scattered radar echoes, which was relatively more consistent with observation. Moreover, the bulk scheme had a better reproduction of the strong rainfall areas by comparison with the bin scheme.

In view of the dynamic and thermodynamic structures, both of bulk and bin scheme have simulated a radar structure with the leading convective tower and TS region. The difference was that bin produced wider convective cores and broken TS clouds than bulk one. The airflow in bulk scheme was characterized by the strong front inflow in low levels and intense rear inflow in middle levels compared with weak and discontinuous rear inflow in bulk scheme. Meanwhile, the bulk scheme simulated much stronger updrafts and deeper cold pool than SBM. In terms of the microphysical properties, much higher cloud droplet number concentrations were simulated by bulk scheme, while lower raindrop mass and number concentrations were generated than those in SBM.

As mentioned in introduction, a lot of comparative studies have been done between bulk and bin microphysical schemes using cloud-resolving models or mesoscale models. Most of the results proved bin scheme had a better performance than bulk scheme no matter in real-time or idealized simulations. Considering that seldom researches has been done in China on the sensitivity of squall lines to bulk and bin microphysics, our conclusions are very preliminary and case-dependent. More cases are needed in future to validate our results. Besides, detailed analysis and sensitivity tests are also required to investigate the mechanisms for the distinctive results between bulk and bin schemes.

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Appendix

Figure A1 Radar reflectivity (unit: dbz) from (a) observation, (c) bulk scheme, (e) bin scheme at 0200 UTC on 31 March 2014 and 12-h total rainfall (unit: mm) from (b) observation, (d) bulk scheme, (f) bin scheme during the period from 1800 UTC on 30 March to 1200 UTC on 31 March 2014.
Figure A2 Same as Figure 4, but for the squall line occurred on 31 March 2014.
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Figure A3 Same as Figure 5, but for the squall line occurred on 31 March 2014.

Supporting information

The following supporting information is available:

Figure S1. Time series of domain-averaged cloud droplet number concentration (unit: $10^6$ kg$^{-1}$).

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