Sensitivity of Cloud-Resolving Simulations of Warm-Season Convection to Cloud Microphysics Parameterizations

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ABSTRACT

This paper investigates the effects of cloud microphysics parameterizations on simulations of warm-season precipitation at convection-permitting grid spacing. The objective is to assess the sensitivity of summertime convection predictions to the bulk microphysics parameterizations (BMPs) at fine-grid spacings applicable to the next generation of operational numerical weather prediction models. Four microphysical parameterization schemes are compared: simple ice (Dudhia), four-class mixed phase (Reisner et al.), Goddard five-class mixed phase (Tao and Simpson), and five-class mixed phase with graupel (Reisner et al.). The experimentation involves a 7-day episode (3–9 July 2003) of U.S. midsummer convection under moderate large-scale forcing. Overall, the precipitation coherency manifested as eastward-moving organized convection in the lee of the Rockies is insensitive to the choice of the microphysics schemes, and the latent heating profiles are also largely comparable among the BMPs. The upper-level condensate and cloudiness, upper-level radiative cooling/heating, and rainfall spectrum are the most sensitive, whereas the domain-mean rainfall rate and areal coverage display moderate sensitivity. Overall, the three mixed-phase schemes outperform the simple ice scheme, but a general conclusion about the degree of sophistication in the microphysics treatment and the performance is not achievable.

1. Introduction

Poor forecast skill is associated with warm-season precipitation forecasting in modern numerical weather prediction (NWP) models (Olson et al. 1995; Fritsch et al. 1998). The inadequate treatment of subgrid convection is widely believed to be a major impediment for improving the vexingly poor performance of NWP models during the warm season (Moncrieff and Liu 2003; Davis et al. 2003). The slow improvement of existing convective parameterizations as well as the progressive advance in computing power suggest the use of high-resolution explicit (convection permitting) numerical models. It is anticipated that the horizontal grid spacing in operational NWP models, perhaps even global models, will be a few kilometers within a decade. It is still not clear, however, whether resolution enhancement alone will meet the challenging difficulties facing the midsummer convection forecasting, even though high-resolution (3–6-km grid spacing) simulations show promise (Fowle and Roebber 2003; Done et al. 2004; Liu et al. 2006; Kain et al. 2006; Moncrieff and Liu 2006; Trier et al. 2006).

Cloud microphysical processes play an important direct role in warm-season precipitating systems through direct influences on the cold pool strength (rainfall evaporation) and latent heating (condensation) as well as indirect influences on gravity waves and cloud-radiation interaction. Therefore, microphysical parameterizations could be a principal source of uncertainty in high-resolution NWP models. During the past few decades, numerous microphysics schemes of various degrees of sophistication have been developed. They can be divided into two broad categories: bin (spectral) microphysics and bulk microphysics parameterizations (BMPs). In the bin approach, tens of mass bins represent the particle spectra, and the evolution of the size distribution is explicitly calculated (e.g., Hall 1980;
Feingold et al. 1994; Khvorostyanov 1995; Reisin et al. 1996; Harrington et al. 1999; Yin et al. 2000; Jiang et al. 2001; Rasmussen et al. 2002). In the bulk schemes, however, the cloud particle size distribution is specified a priori, and either the mixing ratio (one moment) or mixing ratio and number concentration (two moment) for each type of particle are predicted (e.g., Koenig and Murray 1976; Lin et al. 1983; Rutledge and Hobbs 1984; Cotton et al. 1986; Ferrier 1994; Walko et al. 1995; Meyers et al. 1997; Reisner et al. 1998; Straka and Mansell 2005; Morrison et al. 2005). Due to their computational advantage over bin schemes, bulk microphysics have been widely incorporated into cloud-resolving models (CRMs), mesoscale research and operational models, and climate models.

Because of the wide variety of cloud microphysics schemes currently being used, a natural concern is the sensitivity of the prediction and simulation of warm-season precipitation in high-resolution numerical models to the microphysics parameterization. Another important issue is whether realism is consistently gained with increasingly sophisticated cloud microphysics. Addressing these problems is not only of practical significance but also helpful for guiding the future improvement and development of cloud microphysics parameterizations.

The dependency of model results on microphysics parameterizations has traditionally been addressed through short-term idealized simulations of a single precipitation system (e.g., a thunderstorm or a squall line) using CRMs that were initialized with single thermodynamic and wind profiles. The early work was mostly concentrated on the role of ice-phase physics in squall-type mesoscale convective systems (e.g., Nicholls 1987; Fovell and Ogura 1988; Tao and Simpson 1989; Liu et al. 1997). The extensive comparisons between the warm-rain-only and mixed-phase schemes concluded that the inclusion of ice processes is crucial to realistically capture the development of the stratiform region of convective systems. McCumber et al. (1991) compared several ice parameterizations in simulations of two types of tropical convective systems. They found that the use of three ice classes produces better results than two ice classes or ice-free conditions. It was also inferred that application of bulk cloud microphysics might be case specific. Ferrier et al. (1995) performed a series of experiments of two squall lines with four-class and three-class ice schemes, varying fall speed relationships, particle characteristics, and ice collection efficiencies. Their results indicated that the four-class ice scheme improves agreement with observations. Recently, Gilmore et al. (2004a) examined the precipitation, cold pool characteristics (i.e., the effect of the evaporation of rain), and evolution of simulated convective storms as affected by three microphysics schemes. As well as the BMP sensitivity investigations, the impact of the uncertainties in the microphysical parameters was explored. For example, Gilmore et al. (2004b) reported that the precipitation amount from simulated multicell and supercell storms could vary by a factor of 3–4 due to changes in intercept parameters defining the hail/grapel distribution.

The effects of cloud microphysics have also been investigated in real-data simulations using mesoscale numerical models. However, all previous studies have concentrated on cold-season orographic events. For instance, Reisner et al. (1998) evaluated three options of increasing complexity to represent the hydrometeor species (namely, two-class ice, three-class ice with one moment, and three-class ice with two moments) in predicting supercooled liquid water of winter storms. Intercomparisons of the simulations and observations showed that the most sophisticated double-moment scheme provided the best forecast. Colle and Mass (2000) compared five microphysical schemes for a flooding event over the Pacific Northwest. They noted that the warm rain scheme deposited too much precipitation along the windward slopes, but the most sophisticated schemes were not superior. Grubisic et al. (2005) evaluated the dependence of wintertime orographic precipitation predictions in the Sierra Nevada on the choice of BMPs and showed that the quantitative precipitation forecasting (QPF) skill and accuracy do not significantly vary among the four schemes tested.

The present study focuses on the diurnal regeneration and propagation characteristics of warm-season precipitating systems. This important climatological aspect of midsummer convection over the continental United States has been well documented from radar-based observations (Carbone et al. 2002), but was not often verified in previous studies. Herein we evaluate the sensitivity of explicit simulations of coherent rainfall patterns to several BMPs using a set of multiday cloud-system-resolving simulations. We emphasize the statistical characteristics of long-lived precipitation episodes within a weeklong synoptic regime. This is unlike the aforementioned real-data studies, which were almost exclusively focused on the deterministic prediction of specific cool-season weather events. Another special aspect is the use of a large high-resolution computational domain instead of multiple grids, which could complicate the interpretation of fine-grid results by the cumulus parameterizations applied in the outer coarse grids.

The paper is organized as follows. The next section describes the setup of our numerical experiments and
the important features of BMPs to be tested. In section 3, the dependency of the simulated convection on BMPs is evaluated in terms of rainfall coherency, rainfall distribution, rainfall intensity, cloud condensate, cloud amount, and thermodynamics budgets. The paper concludes with a summary of our findings in section 4.

2. Numerical model and experiment design

We use the latest nonhydrostatic version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5; Dudhia et al. 2003). A single computational domain of $2400 \times 1800$ km$^2$ (Fig. 1) is centered at the latitude $41^\circ$N and longitude $95^\circ$W. A 3-km horizontal resolution is employed, representative of the grid spacing affordable to multiday large domain simulations on the currently available computer resources and applicable to the next generation of NWP models. In all simulations, the planetary boundary layer physics is treated by the scheme implemented in the National Centers for Environmental Prediction (NCEP) Medium-Range Forecast model (Hong and Pan 1996), and the land surface processes are represented by a five-layer soil model (Dudhia 1996). The radiative transfer parameterization scheme involves longwave and shortwave interactions with explicit cloud, clear atmosphere, and ground. There are 40 unequally spaced levels in the vertical, and the model top is located at 50 hPa. The numerical experiments differ only in the treatment of cloud microphysics.

Four microphysics parameterization schemes are tested to examine how the warm-season precipitation forecasts depend on the treatment of moisture processes (roughly in the order of increasing complexity): simple ice by Dudhia (1989), two-category ice by Reisner et al. (1998), Goddard three-category ice by Tao and Simpson (1993), and three-category ice by Reisner et al. (1998) and Thompson et al. (2004).

1) Dudhia’s bulk warm rain with simple ice (hereafter DUDH): This scheme optionally allows for ice-phase processes below $0^\circ$C, where cloud water and rainwater are treated as cloud ice and snow, respectively. Supercooled water is not permitted and ice and snow melt instantaneously below the freezing level. Only two prognostic equations for cloud water (ice) and rainwater (snow) mixing ratios are required.

2) Reisner et al.’s four-class mixed phase (hereafter RRB4): This scheme contains four categories of condensate (namely, cloud water, rainwater, cloud ice, and snow). Unlike the simple ice parameterization, it explicitly predicts cloud ice and snow mixing ratios and thus permits the simultaneous presence of cloud ice and cloud water, and snow and rainwater.
Other improvements include a formulation for the melting of snow, evaporation of melting snow, and the heterogeneous freezing of cloud water.

3) Goddard Space Flight Center five-class mixed phase (hereafter GSFC): This scheme is adopted from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center cloud microphysics parameterization implemented in Goddard cumulus ensemble model. It has five prognostic equations for two-class liquid water (cloud water and rain) and three-class ice (cloud ice, snow, and graupel/hail) and is mainly based on Lin et al. (1983) and Rutledge and Hobbs (1984) with several modifications.

4) Reisner et al.’s five-class mixed phase with graupel (hereafter RRB5): This is the most sophisticated microphysics parameterization available in MM5. The primary difference from the aforementioned mixed-phase scheme RRB4 regards the addition of precipitation equations for the graupel mixing ratio and the number concentration of cloud ice.

A 7-day warm-season episode during 3–9 July 2003 is selected for our experimentation. This multiday case was numerically simulated with both explicit and parameterized models (Liu et al. 2006; Moncrieff and Liu 2006; Trier et al. 2006). The main synoptic features (not shown) include an anticyclone over the Southwest and nearly zonal westerly flow over the northern United States at upper levels. At low levels, southerly flow on the backside of a high pressure zone situated over the southeastern United States advects moisture into the Kansas/Nebraska locale and fuels a series of mesoscale convective systems across Nebraska and Iowa involving the effects of a quasi-stationary front. The entire period features a regular daily regeneration of precipitation sequences in the lee of the Rockies and subsequent eastward propagation. Active convection is often associated with upper-tropospheric east-moving short waves superimposed upon a nearly zonal westerly flow (Liu et al. 2006; Trier et al. 2006). As in these previous studies, the 3-hourly, 40-km grid spacing NCEP Eta Model analysis provides the initial and lateral boundary conditions for our numerical experiments.

3. Results

In the following, the effects of various cloud microphysical treatments on the explicitly simulated convection will be evaluated through comparing the statistics of precipitation features, the distributions of hydrometeors and cloudiness, and the vertical profiles of convective heating and moistening among the four microphysics schemes.

a. Rainfall distributions and coherency

Figure 2 compares the 7-day accumulative rainfall distributions in the four simulations with radar analysis. The radar-derived rainfall data in Fig. 2a are as analyzed by Carbone et al. (2002). It is important to note that although the time–space distribution is realistic (i.e., precipitation episodes), the radar data contain considerable uncertainty, stemming from approximations in the Z–R relationship used in converting the radar reflectivity (Z) into the local rainfall rate (R). The unique aspect of this dataset is its high spatial and temporal resolution (~2 km in space and 15 min in time), which is especially desirable to verify the simulated space–time rainfall coherence. As indicated in Fig. 2a, the observed convection concentrates within a narrow zonal corridor, stretching from the lee of the Rockies across the Great Plains. All simulations (Figs. 2b–e) approximate the roughly WNW–ESE-oriented precipitation corridor except for the too-weak intensity and too-wide distribution in the east portion of the domain. GSFC and RRB4 schemes produce a comparatively more realistic intensity than the other two schemes. To quantitatively compare the performance of the four microphysics parameterizations, we calculated the rmse for each simulation. The simplest scheme DUDH is the poorest performer, but the best simulation is associated with RRB4, instead of the most sophisticated RRB5 scheme.

All the microphysics schemes faithfully replicate the temporal and spatial coherence of propagating convection as displayed by concentrated downward-sloping rainfall signatures (hereafter referred to as streaks) in the time–longitude depiction of meridionally averaged rainfall rate over the whole domain in Fig. 3. The observations (Fig. 3a) show precipitation sequences occurring daily and systematically during the 7-day episode. Typically, the genesis of the propagating convection is east of the Continental Divide in the late afternoon or evening. The propagating convection subsequently travels eastward, spanning a sizable fraction of the continent. Visually, all four microphysics parameterizations (Figs. 3b–e) exhibit almost equal performance in predicting the coherent rainfall patterns but share a few common discrepancies too. First, the rainfall frequency over the mountainous area is underestimated. This deficiency is attributed to the 3-km grid resolution (Moncrieff and Liu 2006) as well as the too-smooth lateral boundary conditions on the computational domain (interpolated from 40-km-resolution Eta Model analyses). Previous studies have demonstrated that about 1-km or finer grid spacing is required to adequately deal with convective initiation, and coarse-
resolution explicit models unrealistically delay or even prohibit convection (Liu et al. 2001a,b; Petch 2006), especially in the circumstance of weak large-scale forcing. Another common bias concerns the lifetime and horizontal extent of traveling convection. Compared to observations some simulated streaks do not persist long enough and travel far enough to reach the eastern part of the computational domain. Finally, a persistent period of stationary precipitation during days 4–6 is observed roughly between x = 1800 and 2300 km although there are many tiny propagating streaks embedded in it, but it is not well captured by any of the simulations. These last two discrepancies lead to a too-weak rainfall amount in the eastern part of the domain (Fig. 2).

Figure 4 shows the corresponding diurnal rain-rate Hovmoeller diagrams averaged over the 7-day period. The radar composite (Fig. 4a) shows two parallel streaks that originate in the neighborhood of the Continental Divide about 2100 UTC and subsequently cross the Great Plains. The averaged propagation speed of the composite coherent structures is about 21 m s$^{-1}$, faster than many of the individual rain streaks (Fig. 3a). This may indicate that the mean coherent pattern is largely determined by fast and strong events. The observed double-streak pattern is predicted reasonably by all the simulations (Figs. 4b–e). The DUDH scheme generates unrealistically persistent signatures and is therefore the most problematic. A common discrepancy is the absence of heavy rainfall in the eastmost quarter of the computational domain; the simulated rainfall is too weak and located too far west. This discrepancy could be attributed to either deficiencies in parameterizations (other than microphysics) or, possibly, the effects of the lateral boundary conditions.

The precipitation coherency is objectively quantified by applying a two-dimensional autocorrelation function to the Hovmoeller diagrams in Fig. 3. As in Carbone et al. (2002), the function has a rectangular length of 3° in one dimension and a wavelength of 3 h for the cosine weighting in the other. The rectangular-cosine weighted function is rotated until the maximum correlation coefficient greater than 0.3 is realized, and the continuous fits define the coherent patterns (or rain
streaks). The following discussion is limited to events traveling zonally for at least 500 km. Figure 5 displays the scatterplots of streak span versus duration and span versus propagation speed. For the most part, the horizontal distance is proportional to the corresponding lifetime of streaks in both observations and simulations, but there is seemingly little correlation with the propagation speed. The long-lived and strong events are often associated with migrating upper-level waves (Trier et al. 2006). The observed maximum span reaches roughly 2000 km, whereas in the simulation it varies within the 1500–1850-km range. The simulations produce 7–35 h for duration and 10–24 m s\(^{-1}\) for zonal speed, comparable to the respective observations. Table 1 summarizes the rain streak statistics, including the total numbers, mean and medium values for horizontal span, duration, and zonal propagation component. All simulations somewhat overpredict persistence and underpredict travel speed. The streak frequency and spatial extent are adequately captured by the three mixed-phase schemes. Overall, the simple ice has the largest biases in the total number of streaks, zonal distance, and persistence, although it gives the best prediction of travel speed. These simulated streak features show only moderate differences among the three mixed-phase parameterizations and, moreover, not a single scheme uniformly outperforms the others.

The preceding discussions have exclusively focused on the longitudinal distribution of rainfall and the zonal

Fig. 3. Hovmoeller (space–time) diagrams of rainfall rate averaged in the meridional direction. (a) Radar estimate, and simulations using (b) DUDH, (c) RRB4, (d) GSFC, and (e) RRB5.
component of propagation. The latitude–time plot of the zonally averaged rain rate (not shown) reveals that the observed convection is concentrated within a 600-km-wide area around 42°N with the exception of the first day. As a consequence, the meridional motion and span of precipitation sequences are much less than their zonal counterparts. The model results display similarly concentrated convective activities in the north–south direction. Nevertheless, a careful inspection shows that all simulations, especially the ones with the GSFC and RRB5 schemes, tend to generate more evident meridional propagations than observations, consistent with the too-southward-tilted rainfall distribution discrepancy (Fig. 2).

b. Correspondence of MCSs

Correspondence, which determines whether specific forecast objects have unique observational counterparts, is often employed to evaluate predictions of large-scale and mesoscale weather systems. Herein, it is adopted to verify the simulated mesoscale convective system (MCS) activities against radar observations to quantify the predictability of the important mesoscale convective events during warm seasons. As in Done et

Fig. 4. Same as in Fig. 3, but for diurnal Hovmöller diagrams averaged over the 7 days.

Fig. 5. Scatterplots of (a) rain streak span vs duration and (b) span vs zonal speed.
al. (2004), MCSs are identified on the basis of hourly accumulated surface precipitation. Each is defined as a precipitating system having a contiguous rainfall area extending for at least 100 km in one horizontal direction, exceeding an intensity of 5 mm for at least 6 consecutive hours. An additional requirement is that the extreme hourly rainfall must be larger than 20 mm. The centroid of the rainfall area exceeding 5 mm defines the position of an MCS. We have noticed that these MCS criteria exclude a number of weak and short-lived convective events.

We closely follow the method described by Done et al. (2004) in determining the correspondence of MCSs between the observational and model datasets. Corresponding systems are identified when the differences in their predicted and observed time and location are no more than 3 h and 300 km at either the beginning or ending time, respectively. The beginning (ending) refers to the time and location of the earliest (last) time at which the minimum MCS threshold is met. The statistical results are tabulated in Table 2, including the total number, the number of corresponding MCSs, and the critical success index (CSI) for MCS correspondence. The parameter CSI represents the ratio of the number of hits over the total number of hits, misses, and false alarms of MCS events (see Done et al. 2004 for details). The occurrence of MCSs, albeit underpredicted, is mostly comparable among the four BMPs. All simulations also produce a similar correspondence. In terms of the CSI, the MCS correspondence in our weeklong simulations is somewhat better than the performance of the daily 36-h forecasts at either 4- or 10-km grid spacing by Done et al. (2004), which is likely attributable to the moderately forced conditions in this particular case as well as the daily spinup impact in the short-range real-time forecasts.

c. Rainfall intensity, areal coverage, and spectrum

Figure 6 compares the evolution of the domain-averaged rainfall rate and fractional area in the simulations with radar observations. Overall, the four parameterizations result in similar temporal variations in rainfall amount that are qualitatively in good agreement with the radar estimates, although intensity is underestimated (Fig. 6a). The salient feature is the significant diurnal oscillation characteristic of a peak around 0000 UTC and a minimum around 1500 UTC. The DUDH and GSFC schemes have the smallest and largest rainfall, respectively, during most of the 7-day episode. The temporal means are about 5, 3.1, 3.8, 4.3, and 3.5 mm day$^{-1}$ for observations, DUDH, RRB4, GSFC, and RRB5, respectively. In contrast, although the variability patterns are comparable, the differences in rainfall area (Fig. 6b) are more evident among the simulations, and accordingly more sensitive to the microphysics formulation, than the rainfall intensity. All parameterizations significantly underpredict the observed values almost throughout the integration, probably because the horizontal resolution is insufficient to treat convection under weak forcing conditions. During the 7 days the minimum and maximum mostly occur in RRB5 and DUDH, respectively. On average, the rain areal coverage is 5%, 3.9%, 3.1%, 3.6%, and 2.4% for radar estimates, DUDH, RRB4, GSFC, and RRB5, respectively. The rainfall distribution as a function of the rain rate (Fig. 7) displays a similar pattern: the relative contribution to total rainfall generally decreases as the rain rate increases. (Herein the rain rate is derived from the archived half-hourly accumulated rainfall data, rather than the instantaneous precipitation intensity.) Nevertheless, salient differences exist among the parameterizations. DUDH has the narrowest spectrum, and roughly 90% rainfall results from the rain rate smaller than 25 mm h$^{-1}$. In comparison, RRB4 generates the widest spectrum, and roughly 65% total rain comes from rain rates less than 25 mm h$^{-1}$. In these parameterizations the maximum contribution to rainfall total occurs at the rain rate less than 5 mm h$^{-1}$. Note that the high frequency of weak rainfall in the simple ice scheme is consistent with the small rainfall amount and large areal coverage (Fig. 6).

### Table 1. Statistics of observed and simulated rain streaks greater than 500 km in the zonal span. The numbers outside and inside the brackets correspond to the mean and median values, respectively.

<table>
<thead>
<tr>
<th></th>
<th>Total streaks</th>
<th>Zonal span (km)</th>
<th>Duration (h)</th>
<th>Speed (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADAR</td>
<td>18</td>
<td>927 (779)</td>
<td>14.6 (13.1)</td>
<td>17.9 (18.4)</td>
</tr>
<tr>
<td>DUDH</td>
<td>13</td>
<td>1131 (1116)</td>
<td>19.0 (17.5)</td>
<td>17.3 (17.3)</td>
</tr>
<tr>
<td>RRB4</td>
<td>20</td>
<td>905 (788)</td>
<td>16.9 (15.3)</td>
<td>15.5 (15.1)</td>
</tr>
<tr>
<td>GSFC</td>
<td>18</td>
<td>935 (744)</td>
<td>15.7 (12.5)</td>
<td>16.7 (15.0)</td>
</tr>
<tr>
<td>RRB5</td>
<td>18</td>
<td>924 (870)</td>
<td>15.8 (15.0)</td>
<td>16.7 (16.6)</td>
</tr>
</tbody>
</table>

### Table 2. Number of MCSs (the 2d column), number of corresponding MCSs (the 3d column), and CSI value (the 4th column).

<table>
<thead>
<tr>
<th></th>
<th>No. MCS</th>
<th>No. corresponding</th>
<th>CSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADAR</td>
<td>16</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>DUDH</td>
<td>12</td>
<td>7</td>
<td>0.33</td>
</tr>
<tr>
<td>RRB4</td>
<td>12</td>
<td>7</td>
<td>0.33</td>
</tr>
<tr>
<td>GSFC</td>
<td>15</td>
<td>8</td>
<td>0.35</td>
</tr>
<tr>
<td>RRB5</td>
<td>13</td>
<td>8</td>
<td>0.38</td>
</tr>
</tbody>
</table>
d. Condensate and cloud amount

Figure 8 presents the spatial and temporal averages of different hydrometeor species. One-to-one category comparisons are impossible because of different condensate categories in these parameterizations. Recall that in DUDH cloud water and ice mixing ratio are treated with a single prognostic quantity and differentiated in terms of temperature. Therefore, the cloud liquid water corresponds to the total nonprecipitation particles, and similarly the rainwater contains all precipitation particles in this scheme. However, we can approximate the lower-level nonprecipitating (precipitating) condensate as cloud liquid water (rainwater) and the upper-level nonprecipitating (precipitating) condensate as cloud ice (snow and graupel). The cloud water distribution shows many common features in the lower troposphere, and the rainwater profiles at low-
levels are also remarkably similar in the three mixed-phase schemes. In contrast, the ice content is very different: The maximum ice mixing ratio in RRB5 is about 4.5 times as large as the counterpart in RRB4. The snow mixing ratio has a bell-shaped distribution around 400 mb. The two schemes containing graupel produce a similar distribution in the mixing ratio, but the value in GSFC is almost twice that in RRB5.

The total condensate mixing ratios (Fig. 9a) closely resemble each other in the lower troposphere (i.e., below 650 mb), but striking differences in the upper troposphere are related to the different treatment of ice processes. The maximum and minimum occur in DUDH and RRB4, respectively, while RRB5 corresponds to a double-maximum structure. Arguably, the difference among the three mixed-phase schemes is insignificant. A relatively large variability occurs in the cloud fraction (Fig. 9b). In calculating cloud fraction, 100% cloudiness is assumed over a grid box when the sum of cloud water, ice, and snow mixing ratio exceeds 0.01 g kg$^{-1}$. In DUDH the rainwater mixing ratio at subfreezing temperatures is physically meant to represent snow and is therefore included in the cloud amount computation when the temperature is below 0°C. Cloud fraction is comparable in both the lower and middle troposphere for the mixed-phase parameterizations, although salient differences occur above 400 mb (cirrus). RRB5 has the most extensive and most elevated cirrus shield with a maximum of 30% near 200 mb; GSFC produces an intermediate amount of clouds with a maximum of 22% at 250 mb; RRB4 and DUDH correspond to the lowest cloudiness with a peak value of 11% around 300 mb. Note that a large condensate mixing ratio is not necessarily associated with a large cloud amount.

The large cloudiness variabilities in the simulations are most likely contributed to the different treatment of the sedimentation speed for cloud ice and conversion of ice to snow in the BMPs. In general, a high sedimentation rate could result in cloud ice reduction due to fast fallout into unsaturated subcloud layers and subsequent sublimation. A fast ice-to-snow conversion would also decrease the ice content but increase the snow amount, leading to reduction of total condensate due to the
The key question posed here is: Do the microphysical parameterizations impact the large-scale effects of convection? The apparent heat source $Q_1$ and the apparent moisture sink $Q_2$ (Yanai et al. 1973) compare the collective effects of convection on the large-scale thermodynamics. The expressions for $Q_1$ and $Q_2$ in the vertical $\sigma$ coordinate are

$$Q_1 = \frac{L_v}{c_p} (\bar{r} - \bar{v}) + \frac{L_a}{c_p} (\bar{d} - \bar{z}) + \frac{L_f}{c_p} (\bar{f} - \bar{m})$$

$$- \frac{\bar{\pi}}{\partial \sigma} \left( \bar{\sigma} \frac{\partial \bar{\theta}}{\partial \bar{\theta}} \right) + \frac{\bar{\pi} D_\theta}{\bar{\sigma}} + \bar{D}_R,$$ (1)

$$Q_2 = \frac{L_v}{c_p} (\bar{r} - \bar{v} + \bar{d} - \bar{z}) + \frac{L_v}{c_p} \frac{\partial}{\partial \sigma} \left( \bar{\sigma} \bar{q}_u \right) - \frac{L_v}{c_p} D_{qv},$$ (2)

where the overbar variables represent the horizontal average; the prime variables represent the deviation from the average; $\pi = (p/1000)^{1/5}$ is the Exner function; $D_\theta$ and $D_{qv}$ are the subgrid flux of $\theta$ and $q_v$, respectively; $c$, $e$, $f$, $m$, $d$, and $s$ are the condensation, evaporation, freezing, melting, deposition and sublimation rates, respectively; and $c_p$, $R$, $L_v$, $L_m$, and $L_s$ are the specific heat of dry air at constant pressure, the gas constant, and the latent heats of condensation, fusion, and sublimation, respectively.

Equation (1) indicates that $Q_1$ is the sum of latent heating associated with phase changes (the first three terms on the right-hand side), the vertical eddy transport, the subgrid diffusion that includes the divergence of the surface sensible heat flux, and the radiative heating. Similarly, $Q_2$ consists of the net condensation, the vertical eddy transport of moisture, and the subgrid mixing. Because the archived model output contains the radiation and conventional atmospheric variables but does not include the microphysical processes and subgrid diffusion, $Q_1$ and $Q_2$ are estimated as residuals from thermodynamic conservation equations by horizontally averaging over the budget domain. It follows that

$$Q_1 = \bar{\pi} \left( \frac{\partial \bar{\theta}}{\partial t} + \frac{\partial \bar{\theta}}{\partial x} + \frac{\partial \bar{\theta}}{\partial y} + \frac{\partial \bar{\theta}}{\partial \sigma} \right),$$ (3)

$$Q_2 = - \frac{L_v}{c_p} \left( \frac{\partial \bar{q}_u}{\partial t} + \frac{\partial \bar{q}_u}{\partial x} + \frac{\partial \bar{q}_u}{\partial y} + \frac{\partial \bar{q}_u}{\partial \sigma} \right).$$ (4)

The analysis domain is $800 \times 600 \text{ km}^2$ and covers the major portion of the precipitation corridor as indicated in Fig. 1.

The $Q_1$ profiles averaged over the 7 days (Fig. 10a) show broadly similar features among the four simulations, characteristic of shallow cooling below about 750 mb and deep heating above. In all parameterizations the cooling near the ground is caused by rainfall evaporation and infrared radiative fluxes. The strongest elevated heating varies around 6–7 K day$^{-1}$ in the 350–

**Fig. 9.** Domain- and time-averaged profiles of (a) total condensate and (b) cloud fraction in simulations using DUDH (solid), RRB4 (dashed), GSFC (dotted), and RRB5 (thick dotted).

greater fallout of snow particles. However, both ice sedimentation and ice–snow conversion are formulated quite differently in the tested schemes, and therefore it is difficult to make quantitative comparisons among them without performing budget analysis.

e. Thermodynamic budgets

The key question posed here is: Do the microphysical parameterizations impact the large-scale effects of convection? The apparent heat source $Q_1$ and the apparent moisture sink $Q_2$ (Yanai et al. 1973) compare the collective effects of convection on the large-scale thermodynamics. The expressions for $Q_1$ and $Q_2$ in the vertical $\sigma$ coordinate are

$$Q_1 = \frac{L_v}{c_p} (\bar{r} - \bar{v}) + \frac{L_a}{c_p} (\bar{d} - \bar{z}) + \frac{L_f}{c_p} (\bar{f} - \bar{m})$$

$$- \frac{\bar{\pi}}{\partial \sigma} \left( \bar{\sigma} \frac{\partial \bar{\theta}}{\partial \bar{\theta}} \right) + \frac{\bar{\pi} D_\theta}{\bar{\sigma}} + \bar{D}_R,$$ (1)

$$Q_2 = \frac{L_v}{c_p} (\bar{r} - \bar{v} + \bar{d} - \bar{z}) + \frac{L_v}{c_p} \frac{\partial}{\partial \sigma} \left( \bar{\sigma} \bar{q}_u \right) - \frac{L_v}{c_p} D_{qv},$$ (2)

where the overbar variables represent the horizontal average; the prime variables represent the deviation from the average; $\pi = (p/1000)^{1/5}$ is the Exner function; $D_\theta$ and $D_{qv}$ are the subgrid flux of $\theta$ and $q_v$, respectively; $c$, $e$, $f$, $m$, $d$, and $s$ are the condensation, evaporation, freezing, melting, deposition and sublimation rates, respectively; and $c_p$, $R$, $L_v$, $L_m$, and $L_s$ are the specific heat of dry air at constant pressure, the gas constant, and the latent heats of condensation, fusion, and sublimation, respectively.

Equation (1) indicates that $Q_1$ is the sum of latent heating associated with phase changes (the first three terms on the right-hand side), the vertical eddy transport, the subgrid diffusion that includes the divergence of the surface sensible heat flux, and the radiative heating. Similarly, $Q_2$ consists of the net condensation, the vertical eddy transport of moisture, and the subgrid mixing. Because the archived model output contains the radiation and conventional atmospheric variables but does not include the microphysical processes and subgrid diffusion, $Q_1$ and $Q_2$ are estimated as residuals from thermodynamic conservation equations by horizontally averaging over the budget domain. It follows that

$$Q_1 = \bar{\pi} \left( \frac{\partial \bar{\theta}}{\partial t} + \frac{\partial \bar{\theta}}{\partial x} + \frac{\partial \bar{\theta}}{\partial y} + \frac{\partial \bar{\theta}}{\partial \sigma} \right),$$ (3)

$$Q_2 = - \frac{L_v}{c_p} \left( \frac{\partial \bar{q}_u}{\partial t} + \frac{\partial \bar{q}_u}{\partial x} + \frac{\partial \bar{q}_u}{\partial y} + \frac{\partial \bar{q}_u}{\partial \sigma} \right).$$ (4)

The analysis domain is $800 \times 600 \text{ km}^2$ and covers the major portion of the precipitation corridor as indicated in Fig. 1.

The $Q_1$ profiles averaged over the 7 days (Fig. 10a) show broadly similar features among the four simulations, characteristic of shallow cooling below about 750 mb and deep heating above. In all parameterizations the cooling near the ground is caused by rainfall evaporation and infrared radiative fluxes. The strongest elevated heating varies around 6–7 K day$^{-1}$ in the 350–
400-mb layer. The small $Q_1$ differences at low levels primarily stem from the latent heating/evaporative cooling (Fig. 10b). On the other hand, the relatively large differences in the upper troposphere result from radiative cooling $Q_R$ (Fig. 10c). The low-level cooling in $Q_1$ is mostly attributed to radiative cooling, whereas the precipitation evaporation is largely compensated by the sensible heat transport from the underlying land surface and the eddy-flux convergence, so only a small cooling exists in $Q_1 - Q_R$ in the planetary boundary layer (Fig. 10b).

The differences in the radiative cooling are closely associated with the variability of convectively generated cloudiness. In particular, the extensive cirrus cloud in RRB5 and GSFC (see Fig. 9b) is responsible for the strong radiative warming around 250 mb and overlying cooling through the cloud-top cooling and cloud-bottom warming mechanism. Variability in radiative cooling/heating mostly accounts for the sensitivity of upper-level apparent heat source to the cloud microphysics treatment. The heating profiles caused by phase changes (Fig. 10b) show an extreme difference of approximately 1 K day$^{-1}$ at low levels where RRB4 and RRB5 result in the respective minimum and maximum cooling.

For convenient comparison with the heating, the moisture budget is expressed in the temperature unit of kelvins per day using the identity $L \Delta q = -c_p \Delta T$. (It follows that convective drying corresponds to warming, and moistening to cooling, respectively.) The convective drying prevails throughout the troposphere in all microphysics schemes (Fig. 10d). The largest variations among the simulations are located in the 500–700-mb layer. The $Q_2$ budget is generally more sensitive to the microphysics treatment than $Q_1$ in the low and middle troposphere.

4. Summary

The uncertainty in cloud microphysics parameterization is important in modeling and predicting all kinds of
precipitating convective systems. This study investigated the sensitivity of warm-season convection to four representative bulk microphysics parameterizations by performing multiday cloud-system-resolving simulations at a grid spacing usable in the next generation of NWP models. The selected case is a 7-day episode in midsummer and characterized by daily regeneration of convection east of the Rockies and subsequent up-scale growth and propagation toward the Plains. The principal objective is to quantify the uncertainty associated with the cloud microphysics parameterization—a salient concern in convection-permitting models. The evaluation is based on the temporal and spatial coherence of traveling convection, rainfall amount and area, rain-rate spectrum, hydrometeor and cloudiness fields, and thermodynamic budgets. The major results are summarized as follows:

- The overall morphology of the temporal and spatial rainfall coherency as displayed by the time–longitude depiction is insensitive to the microphysics parameterization. The observed daily convective generation near the Continental Divide and the subsequent propagating organized convection are reproduced qualitatively in all explicit simulations.
- The three mixed-phase schemes approximately capture the rainfall corridor across the Great Plains and share the same discrepancies, such as the underpredicted precipitation over the eastern portion of the domain and the fact that accumulative precipitation distribution is tilted too far southward.
- The mixed-phase schemes are superior to the simple ice scheme at least in terms of the total rainfall distributions and rainfall coherency, even though the increased sophistication in cloud microphysics does not necessarily better resemble observations.
- The rainfall rate, areal coverage, and spectrum show moderate sensitivity among the three mixed-phase parameterizations. The simple ice scheme generates widespread light rainfall because of the narrow and weak rainfall spectrum.
- Strong sensitivity to cloud microphysics occurs in the upper-level condensate and cloudiness. Among the mixed-phase parameterizations, RRB5 produces a dual-peak condensate distribution and significant cirrus cloud shield, whereas RRB4 has much more uniform and the smallest cloudiness.
- The latent heating profiles are comparable in that they feature a maximum difference of ~1 K day\(^{-1}\). The main uncertainty in the apparent heat source results from radiative heating/cooling having a maximum difference of more than 3 K day\(^{-1}\) in the upper troposphere among the microphysics parameterizations.

Most modern NWP models have ~10-km grid spacing, enabling mesoscale organization to be partly resolved, but convective-scale processes are still subgrid and have to be parameterized. As a result, their performance is critically tied and sensitive to the selection of conventional convection schemes. To compare the sensitivity to cloud microphysics treatments in convection-permitting models with the sensitivity to cumulus parameterizations in NWP models, a set of 10-km horizontal grid-spacing simulations are carried out, in which three popular cumulus parameterizations are tested (Liu et al. 2006). It is found that the 10-km grid-spacing model underperforms the explicit model and exhibits greater sensitivity to cumulus parameterizations than the explicit model exhibits to cloud microphysics. The differential sensitivity has potential implications for ensemble forecasting. It suggests that the sensitivity to cloud microphysics in convection-resolving ensembles might not introduce sufficient spread among the ensemble compared with parameterized convection ensembles. It may be more effective to increase the ensemble spread through the effects of other physical processes (such as land surface/PBL) or perturbing the initial and boundary conditions.

The above conclusions regarding sensitivity of warm-season convection to microphysics parameterization derive from a single multiday simulation. To make general statements, multiple cases under different synoptic conditions, a wider selection of cloud microphysics parameterizations, and various combinations with other physics parameterizations (e.g., boundary layer turbulence) are required. An important point is that propagating convective systems over the continental United States are dynamically controlled by wind shear and are therefore less sensitive to microphysical parameterizations than weakly organized convection (Moncrieff and Liu 2006). Finally, cloud microphysics parameterization needs to be vastly improved in order to significantly improve the skill of precipitation forecasts.

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