Impact of Graupel Class in Microphysics Parameterizations on Bow Echo Simulations

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Abstract

In this study, the effect of changes in microphysical cooling rates on bow echo development and longevity are examined, through changes to the graupel parameter in a microphysics parameterization in the Advanced Research Weather Research and Forecasting (WRF-ARW) model. Multiple simulations are performed, testing the sensitivity to numerous graupel size distributions, as well as the complete removal of graupel. It is found that size distributions with larger and heavier, but fewer, graupel particles result in weaker cold pools due to reduced microphysical cooling rates, and therefore weaker mid-level buoyancy and pressure perturbations, weaker rear inflow, and a less intense convective updraft that did not tilt as required for bowing to occur. Graupel size distributions with more numerous, smaller, and lighter particles result in larger microphysical cooling rates, stronger cold pools, and stronger mid-level buoyancy and pressure gradients as well as rear inflow; these systems develop bowing segments earlier and more often. Simulations without graupel initially are weaker, due to limited contributions from cooling by melting from the slowly falling snow. However, the system is able to stay more organized with the slightly weaker cold pool, and over time the increase in melting snow resulted in a strongly developed system with multiple instances of new bowing. Changes in the timing and development of the stratiform rain region and convective line, as well as system propagation speed, are also examined.
1. Introduction

It is well known that a key component to the strength, structure, and longevity of squall lines and bow echoes is the cold pool (Rotunno et al. 1988; Weisman et al. 1992, 1993). Changes in the rates of cooling by microphysical processes naturally have a large effect on the shape and strength of the cold pool, and hence the eventual storm structure and development. While the impact of microphysics scheme variations on cold pool and storm structure have been noted for supercells (Gilmore et al. 2004; van den Heever and Cotton 2004, 2007; Dawson et al. 2007, 2008; Snook and Xue 2008; Lerach et al. 2008), few studies have looked at the effects on mesoscale convective systems, specifically squall lines and bow echoes.

The cold pool is important not only to the longevity of a squall line system, but also to the initiation of any new bowing along the line. A balance among the vorticity generated at the front edge of the cold pool, by the environmental wind, and above and below the rear inflow into the system can act to ensure the longevity of the system (Weisman 1992). However, a temporary, local intensification of the cold pool and its associated vorticity can result in a portion of the storm temporarily tilting upshear. The decrease in cold pool temperature would also increase the mid-level buoyancy gradient, thereby intensifying the mid-level low pressure perturbation; this would also act to tilt the system upshear (Weisman 1993). This tilt allows horizontal momentum to be more easily transported to the surface, resulting in damaging downburst winds. The combination of additional horizontal momentum and a colder cold pool acts to locally increase the speed of the convective line, resulting in development of a new bowing segment.

The microphysical processes in the trailing stratiform region of mesoscale convective system were diagnosed by Gallus and Johnson (1995) using a two-dimensional model, and by Zhang and Gao (1989), Yang and Houze (1995), and Braun and Houze (1997) with three-dimensional models. At initiation, cooling by melting and evaporation takes place just behind the convective line, resulting in a cold pool with a distinct head. As the system
matures enhanced melting and evaporation rates spread farther to the rear of the storm, forming a large “mound-shaped” cold anomaly. Cooling by sublimation is found throughout the base of the stratiform cloud. The microphysics particle distribution observed in a typical trailing stratiform region is noted by Smull and Houze (1985) and Biggerstaff and Houze (1991). Immediately rearward of the convective line is a region of minimal reflectivity, or the “transition zone”. This reflectivity minimum is due to natural sorting by particle fall-speed: the hail and larger graupel particles fall out almost immediately close to the convective line, while smaller snow particles are advected rearward some distance by front-to-rear flow. These smaller particles begin descending in the center of the stratiform region, creating a secondary reflectivity maximum.

Ideally, a simulation of a linear convective system should reproduce these features, as otherwise many other features of the system are not correctly simulated. The importance of the inclusion of ice in convective squall line simulations has been noted multiple times in the literature. The additional intensification of the updraft due to latent heat from freezing is required to best simulate the updraft strength (Nicholls 1987). Cooling by melting also contributes significantly to the mid-level thermal gradient in the stratiform region (Chen and Cotton 1988; Szeto and Cho 1994), and therefore also the mid-level pressure perturbation and magnitude of the rear inflow (Yang and Houze 1995). These same microphysical processes could therefore also be expected to have an impact on the initiation on new bowing development, through changes in the mid-level thermal and pressure gradients in the stratiform region. However, there have been no studies linking the two.

Thus, a cloud-resolving model is used to examine the impacts of microphysics specifically on bow echoes. As ice processes have been shown to have such a large effect on these mid-level thermal and pressure gradients, several characteristics of frozen hydrometeors are varied within this model. The sensitivity of new bowing frequency and intensity to changes in microphysical heating and cooling rates will be investigated, particularly through their relation to cold pool strength and depth, the mid-level thermal and pressure gradients within
the system, and the stratiform precipitation microphysical structure.

Section 2 describes the experiment and model design, as well as the specific microphysics variations. A review of the case study being simulated is presented in Section 3. Sections 4 and 5 contain results from the two different sensitivity studies performed, and Section 6 the conclusions.

2. Model description and setup

a. Model and experiment design

The Advanced Research Weather Research and Forecasting (WRF-ARW) model is widely recognized as a reliable tool for real-data simulations of mesoscale phenomena. Here version 3.2 was used to simulate an isolated bow echo case over Oklahoma on 13 March 2003. For this case study, the initial conditions were provided by the National Center for Environmental Prediction (NCEP) Final Operational Global Analysis data, at 1° by 1° horizontal and six-hour temporal resolution. The model was initialized at 1200 UTC on 12 March 2003, and run for 36 hours to 0000 UTC 14 March 2003. A horizontal resolution of 3 km was used with 35 vertical levels; the domain is shown in Fig. 1. The vertical levels were stretched, with increasing resolution in the lower levels. Parameterization schemes other than microphysics include the Mellor-Yamada-Janjic boundary layer scheme (Janjic 1994), the Noah land surface model, Rapid Radiative Transfer Model longwave radiation scheme, and the Goddard shortwave radiation scheme. No convective parameterization was used. This combination, in addition to the set of microphysics schemes, was chosen after considerable experimentation as they produced the most realistic convective systems as compared to observations.

A set of idealized simulations was run to isolate microphysical effects from synoptic influences, as well as to allow these results to be generalized to more than one specific case study. Higher vertical and horizontal resolution was also used to resolve finer features within the system. The 0000 UTC 13 March 2003 KOUN sounding (Fig. 2) provided the homogenous initial conditions. Other than extrapolation of moisture data at upper levels and minimal smoothing to remove instabilities, the sounding was unmodified. The model
horizontal resolution was 1 km, with 72 stretched vertical levels. In total, the domain extended 600 km in the x direction, 400 km in the y direction, and 18 km vertically. No parameterizations, other than microphysics, were used. The simulations were run for six hours, as this was the approximate lifetime of the observed bow echo. The “cold pool-dam break” initialization scheme, originally created for the CM1 model (Bryan and Fritsch 2002), was modified for these simulations. A “cold dam” of air was created by decreasing the initial potential temperature in the domain, from 0 to 200 km in the x-direction, and 50 to 350 km in the y-direction. The magnitude of the perturbation was 6 K at the surface, and linearly decreased until reaching 0 K 2.5 km aloft. Upon simulation start, the “dam” of cold air would break, surging forward as a gravity current. Air in advance of the gravity current would be forced upward, initiating convective activity. This initialization method was specifically chosen due to the low-level stable layer in the initial sounding (Fig. 2). This stable layer acted as a cap and required a larger amount of forcing to be overcome than would be provided by a warm bubble initialization.

b. Model microphysics

The WRF Single-Moment and Double-Moment 5- and 6-class microphysics schemes (Hong et al. 2004; Hong and Lim 2006; Lim and Hong 2010) were originally based upon the techniques used in Lin et al. (1983) and Rutledge and Hobbs (1983). The 5-class schemes contain explicit classes for water vapor, cloud water, raindrops, cloud ice, and snow; the 6-class schemes add graupel. All of these schemes utilize an inverse exponential Marshall-Palmer size distribution for snow and, for the 6-class, graupel:

\[ n_x(D_x)dD_x = n_{0x} \exp(-\lambda_x D_x)dD_x \]  

where \( x \) is the microphysics class, \( n_x(D_x)dD_x \) is the number of particles per cubic meter with diameters between \( D_x \) and \( D_x + dD_x \), \( n_{0x} \) is the distribution intercept, and \( \lambda_x \) is the slope. The distribution intercept is set to a constant value prior to processing. This is true even for WDM5 and 6, as they only explicitly calculate the second moment of concentration.
for the raindrop and cloud water distributions. The slope is a diagnosed value, defined as:

\[ \lambda_x = \left( \frac{\pi \rho_x n_{0x}}{\rho q_x} \right)^{0.25} \]  

(2)

where \( \rho_x \) is the pre-assigned particle density, \( \rho \) is the local air density, and \( q_x \) is the prognostic particle mixing ratio.

From (1) and (2), it can be seen that the size distribution of a particle is a function of the intercept, \( n_{0x} \), and the slope, \( \lambda_x \), which is a function of the particle density. Due to the inverse nature of the distribution, a large intercept will result in a smaller mean particle size, and vice versa. Within this experiment, graupel particles have a smaller mean particle size (larger intercept) and are less dense, while hail particles have a larger mean particle size (smaller intercept) and are more dense, but in observed data there is quite a bit of overlap between the two. From Gilmore et al. (2004), previous observations of the intercept value for hail and graupel ranged from \( 10^2 \) m\(^{-4} \) for large hail, to \( 10^{10} \) m\(^{-4} \) for extremely small graupel (Cheng et al. 1985, Dennis et al. 1971; Federer and Waldvogel 1975; Spahn 1976; Knight et al. 1982). Observations of graupel density ranged from 50 to 890 kg m\(^{-3} \); hail density varied from 700 to 900 kg m\(^{-3} \) (Pruppacher and Klett 1978). In the first portion of this experiment, model runs are performed using the WSM6 scheme, but covering this range of variables. The most “hail-like” particle has an intercept equal to \( 4 \times 10^2 \) m\(^{-4} \) and a density of 900 kg m\(^{-3} \). The most “graupel-like” particle has an intercept equal to \( 4 \times 10^6 \) m\(^{-4} \) and a density of 300 kg m\(^{-3} \). A plot of the graupel particle size distributions given the chosen intercepts and densities is shown in Fig. 3.

As discussed, it is evident that a decrease in the particle intercept yields an overall increase in the number of large particles while decreasing the number of small particles. This change in mean particle size will increase the mean terminal velocity. This will result in less dwell time in the downdraft, and therefore less time for melting and evaporation. Larger particles also have less surface area-to-volume ratio, which further reduces the melting and evaporation rates (van den Heever and Cotton 2004). A change in density alone has a much smaller effect on these rates, but it will act to slightly decrease the number of very large
particles. This would thereby also decrease the mean terminal velocity, allowing slightly more time for melting and evaporation.

In the second half of the experiment, a comparison of the 5- and 6-class schemes is used to examine the importance of graupel as a class in simulating this type of convective system. These will be termed the “graupel” (6-class) and “no-graupel” (5-class) simulations. A pair of “no-graupel” and “graupel” simulations were run using the WRF Double-Moment 5- and 6-class schemes, and another pair using the WRF Single-Moment 5- and 6-class schemes. Similar results are obtained between these pairs, with one notable exception. The simulated reflectivity in the single-moment simulations is less intense than was observed in the convective line. This deficiency is noted throughout each single-moment simulation, while the WRF double-moment schemes do not have such a problem. However the double-moment schemes instead produce too intense stratiform precipitation. Examination of the differences between the single- and double-moment schemes will be reserved for a later study. For this article, the case-study model runs using the “graupel” and “no-graupel” WDM schemes are compared as these runs better simulated what was observed. However, for the idealized “graupel” and “no-graupel” simulations, the WSM schemes are chosen for the discussion due to their reduced complexity, thus allowing for a more straightforward comparison of microphysics composition and cooling rates.

A full list of the microphysics schemes and associated intercept and density parameters used in each simulation is provided in Table 1.

### 3. Case review

Convection first initiated at 0215 UTC in north-central Oklahoma, and a convective line aligned southwest to northeast approximately 250 km in length formed by 0315 UTC (Fig. 4a). The system moved to the southeast at a speed of approximately 11 m s\(^{-1}\). A trailing stratiform precipitation region appeared at 0500 UTC, and began to develop rearward. At 0600 UTC (Fig. 4b) the center of the convective line bowed out; stratiform precipitation filled in behind the line as it bowed. A secondary reflectivity maximum formed in the strati-
form region at 0700 UTC, separated from the convective line by a transition zone. The bow echo continued to increase in size until 0800 UTC (Fig. 4c). At this point the convective line started to dissipate. The gust front associated with the decaying convective line, and the stratiform precipitation, continued to propagate southeastward over the next four hours. This eventually reformed into another mesoscale convective system in Louisiana.

4. Results from hail-graupel comparison
   a. Case study simulations

   The spectrum of results between the “hail-like” simulation and the “graupel-like” simulation can be summarized by comparing the hail-like and graupel-like runs (Fig. 5). Both the hail-like and graupel-like simulations initiated convection somewhat differently than observed: an isolated convective cell developed in southwestern Oklahoma at 0300 UTC and moved southeast. By 0600 UTC, the convection in the hail-like run was cellular and appeared disorganized (Fig. 5a); a bow-shaped convective line formed in south-central Oklahoma in the graupel-like run (Fig. 5b). The linear convection to the northeast of the initial system will not be considered here as it has no correspondence to observations. As the hail-like simulation progressed, it was simply unable to reproduce any of the typical features of a bow echo, particularly any sort of convective line (0800 UTC, Fig. 5c). The hail-like system has less overall precipitation, both in intensity and area, than the graupel-like system. The system speed was also slower. At 0800 UTC the graupel-like simulation has further developed its bow shape as well as a stratiform precipitation region (Fig. 5d). Both systems began to dissipate at 0900 UTC (not shown), somewhat later than observed. However, the graupel-like system still appeared more organized, retaining its bow shape and some convective intensity while dissipating; this was also true of the observed system (Fig. 4c). The reason for this will become clear after further examination.

   Figures 6, 7, and 8 show cross-sections of each storm system taken across the convective line at 0600 and 0800 UTC (see thick black lines in Fig. 5 for exact placement). In the hail-like simulation at 0600 UTC, cloud ice and water, typically found in the updraft, and hail,
typically found in the downdraft, were located very close together (Fig. 6a). From this one can surmise the hail particles were too large to be sustained aloft in the convective updraft and fell out of the hail-like system almost immediately upon formation. Cloud ice crystal concentrations were also much higher in the upper levels of the storm; these ice crystals were not being scavenged by numerous semi-melted graupel particles as in the graupel-like simulation. The convective updraft in the hail-like simulation, which was almost entirely above 500 hPa (Fig. 8a), was nevertheless very upright and strong. This was due to the large concentration of condensation, freezing, and deposition processes immediately within and next to the updraft. From Fig. 7a, it is evident that the hail particles were so large, and fell so quickly, that significant cooling by melting did not occur until almost reaching the surface. Hence, there was also limited cooling by evaporation of raindrops. As a result, the cold pool was very shallow, and of weaker intensity (Fig. 6a). All cooling at this time was concentrated almost immediately behind the convective line; the cold pool was very narrow as well. Due to the weaker intensity, there was a gentle upward slope of potential temperature contours at the front of the hail-like system (Fig. 6a). Because of this, the forcing of the air upward by the leading edge of the gently-sloped cold pool was not as abrupt, reducing the intensity of the low-level updraft (Fig. 8a).

Additionally, it is known the buoyancy gradient in a system with respect to height can be related to the associated pressure perturbation through

$$\frac{1}{\rho_0} \nabla^2 p' = -\nabla \cdot (\vec{u} \cdot \nabla \vec{u}) + \frac{\partial B}{\partial z}$$

(3)

where $p'$ is the perturbation pressure, $\vec{u}$ is the horizontal wind vector, and $B$ is buoyancy, defined as $g\theta_u / \bar{\theta}$. The mid-level buoyancy gradient is typically positive, due to the warmer updraft overlying the cold pool. In the hail-like case, this gradient was still positive, but smaller, due to the warmer cold pool. Thus, (3) yielded a positive but small $\nabla^2 p'$, and therefore a weak mid-level low pressure perturbation (Fig. 8a). Because this perturbation was so weak, no extra source of vorticity from the rear inflow within the system was required for the updraft to remain upright instead of tilted. Minimal rear-to-front flow was present
In the graupel-like system, precipitation was advected rearward farther from the convective line, as evidenced by the larger, 70-km wide stratiform region (Fig. 6b). There were large concentrations of graupel and snow both closer to the convective line and farther behind the system. Because of the smaller size of the graupel particles, they were more easily held aloft and advected rearward. From Fig. 7b, high rates of deposition, melting, and evaporation of the falling graupel and snow out of the stratiform precipitation region were evident. Due to the smaller size of these particles, and hence the larger surface-area-to-volume ratios, they underwent sublimation, melting, and evaporation quickly; the small particles melted almost immediately after falling below the melting level. These processes were also enhanced by the longer dwell time aloft due to their slower fall speeds. Therefore the cooling rates in graupel-like were much larger, and also were spread over a much larger area than in the hail-like run. The heightened cooling rates resulted in a more intense, deeper, and larger cold pool (Fig. 6b), as discussed earlier. Specifically, the cold pool in the graupel-like simulation was 4 K colder than the hail-like simulation cold pool. Because hydrometeor particles were being advected farther rearward, freezing and deposition rates were higher across the upper levels of the stratiform region. The latent heat released by these processes helped create a stronger and larger stratiform updraft. Additionally, the wider, colder cold pool allowed for a stronger buoyancy gradient with respect to height, increasing the mid-level low pressure gradient, and therefore also increasing the convective updraft intensity and its rearward tilt (Fig. 8b). Rear-to-front flow in the low- and mid-levels of the system to the rear of the convective line also strengthened (not shown). Finally, gravity current theory suggests a more intense cold pool would result in a faster-moving convective system; this was indeed the case.

At 0800 UTC in the hail-like simulation, the hail and rain had begun falling into the updraft (Figs. 6c, 8c). The system appeared similar to a dying pulse-type thunderstorm. The cold pool and mid-level pressure perturbation were both still minimal, almost no rear
inflow was present, and the low-level convective updraft was weak and still upright; no
bowing segments were ever produced. There was almost no rear-to-front flow within the
system. The deepest part of the cold pool had shifted slightly rearward of the convective
line, but peak cooling rates (not shown) still remained much closer to it than in the graupel-
like run. In that simulation, the stratiform region was still significantly larger than in the
hail-like simulation; the cold pool was as well (Fig. 6d). However, peak cooling rates had
shifted farther rearward into the area below the middle of the stratiform region. The deepest
part of the cold pool was approximately 50 km behind the convective line. Meanwhile the
mid-level low pressure perturbation associated with this system had grown stronger and
shifted rearward (Fig. 8d). The rear inflow immediately behind this pressure perturbation,
at the very rear of the system, was still strong. However, the rear-to-front flow forward of
the pressure perturbation had weakened significantly, resulting in no additional sources of
vorticity to help the convective updraft, at the front of the system, remain upright. As a
result the low-level convective updraft was tilted even more rearward over the cold pool.
This proved to be too extreme of a tilt, as the graupel-like system began dissipating shortly
after this by 0900 UTC.

b. Idealized cases

A set of idealized simulations, as described above, were run to determine if the results seen
in the case study were an artifact of that specific case study, or if they could be generalized
to multiple situations. They were also run at a higher horizontal (1 km versus 3 km) and
vertical (72 levels instead of 35) grid spacing to better resolve the storm structure. The
major difference between the idealized and case study simulations was the organization and
intensity of the hail-like simulation. Two hours into the idealized simulations (Fig. 9a,b),
after convection was able to initiate and organize, the hail-like system had an equally intense
but much narrower leading convective line, with a trailing stratiform region similar in size to
the graupel-like system, but also less intense. Both systems began to bow in a similar manner
about three hours into the simulation. At 4.5 hours, the systems were fully mature, and the
hail-like system had actually developed another bowing segment (Figs. 9c,d). Both systems had about equally sized stratiform precipitation regions. The reason for the idealized hail-like system’s increased organization and intensity, as compared to the case study simulations, is likely due to the lack of radiation cooling. As the case study simulation progressed in time, the sun set and the boundary layer naturally cooled (bowing developed in the graupel-like case study simulation at 0000 LST). This did not occur in the idealized simulation, so its system was able to continually ingest warm, unstable air in the lower levels. This helped intensify the updraft and the front-to-rear motion of all precipitation particles, not just the hailstones, creating a somewhat larger stratiform precipitation region. This allowed for additional cooling by melting and evaporation and therefore a slightly stronger cold pool. The associated buoyancy gradient, and stronger, more elevated rear inflow was intense enough to eventually create a bowing convective line. Additionally, the very strong forcing generated by the initial 6 K perturbation density current designed to initialize convection also acted to organize that initial convection. The convection in the case study had little synoptic forcing, and thus had to rely on internal dynamics to organize into a bowing system; we have already noted the internal dynamics in the hail-like case study simulation were weak.

Despite these differences, however, the most important results seen in the case study simulations were also evident in these idealized simulations. In the hail-like system, the hail still fell out of the system very close to the updraft. Its very fast fall speed again resulted in minimal cooling by melting and evaporation, a minimal cold pool, and thus a slower system speed. The vertical buoyancy gradient and related mid-level low pressure perturbation were also less intense, leading initially to less rear inflow and a correspondingly weaker but upright lower-level convective updraft that did not tilt. While bowing did occur, it was over a smaller area than the graupel-like simulation, and occurred approximately half an hour later. Meanwhile, in the graupel-like simulation the system was more organized. Due to the slower fallspeeds of the graupel particles, they not only were advected farther away creating a larger stratiform region, but also melted quickly thereby generating strong
cooling rates. Hence, the cold pool in the graupel-like simulation was intense and deep, and
the speed of the system, as well as the rear-to-front flow within it, was correspondingly fast.
The sharp leading edge of the cold pool helped to intensify the low-level convective updraft,
as did the more intense mid-level pressure perturbation. This led to a temporary tilting of
the low-level convective updraft and a bowing segment forming earlier, and covering a wider
area.

Thus, in both the idealized and the case study simulations, changing the graupel pa-
rameter to take on more hail-like characteristics acted to diminish the microphysical cooling
within the system. This in turn decreased the strength of the cold pool, and weakened
the low-level convective updraft both by decreasing the mid-level pressure perturbation and
flattening the slope of the potential temperature contours at the front edge of the cold pool.
A weaker mid-level pressure perturbation also resulted in the low-level convective updraft
never tilting upshear. Hence bowing segments did not develop as quickly or over as large of
an area - or develop at all without additional forcing, as in the case study.

5. Results from removal of graupel class

The WRF Double-Moment 5-class and 6-class microphysics schemes, and the WRF
Single-Moment 5-class and 6-class microphysics schemes, are identical except for the in-
clusion of graupel as a class in the 6-class schemes (Lim and Hong 2010). Simulations using
both the 5- and 6-class schemes (“no-graupel” and “graupel” simulations) were run to ex-
amine the importance of graupel as a class, as hinted at in the above hail-graupel comparisons.
These comparisons will continue to explore the effect of changes in microphysical cooling
rates on bowing initiation, as naturally removing graupel as a class will affect these rates.
Additionally, many operational models that are intended to forecast convection, such as the
Weather Research and Forecasting Nonhydrostatic Mesoscale Model (WRF-NMM) and the
Regional Global Environmental Multiscale (Regional GEM), all use no more than five classes
within their microphysics schemes due to computing constraints. Thus an exploration of the
differences that can be expected when simulating this type of convection without graupel
would be beneficial for operational purposes.

a. Case study

Figure 10 shows the simulated model reflectivity for the case study 5-class (“no-graupel”) and 6-class (“graupel”) runs. During initiation (0445 UTC), the no-graupel simulation generated unrealistically large stratiform regions both in advance of and behind the still developing convective line (Fig. 10a). This was due to the widespread concentrations of slowly falling snow crystals in the upper levels (Fig. 11a). At this time, the no-graupel system’s stratiform precipitation and minimal melting and evaporative cooling remained entirely aloft, resulting in an almost non-existent cold pool (Fig. 11a). At 0530 UTC, precipitation reached the ground, and the convective line continued to develop and was fully in place by 0600 UTC (Figs. 10b, 11c). The atmospheric layers beneath the stratiform region were saturated as the system reached maturity, and the stratiform precipitation extended completely to the surface. While there were more, smaller snow crystals to melt and evaporate theoretically leading to a stronger cold pool, these saturated layers did not allow as much evaporation to take place. Thus, the cold pool in the no-graupel simulation was significantly shallower and warmer than in the graupel simulation, as will be seen later. By 0730 UTC, however, the no-graupel simulation gained convective intensity and began bowing (Fig. 10c). The system was well organized, with a tightly defined convective line and less intense but extensive stratiform region that by this point was entirely rearward of the convective line. There was additionally a secondary maximum of reflectivity in the stratiform region, separated from the convective line by a transition zone, which matched observations well. The area beneath the stratiform precipitation region was no longer saturated by this time (Fig. 11e) thus allowing for a more developed cold pool. Yet, because the cold pool was initially warmer, the no-graupel system moved relatively slowly. Possibly this speed, and the resulting storm-relative environmental wind shear, was optimal as it allowed the vorticity generated by the cold pool and that by the environmental wind shear to balance each other well. The initially warmer cold pool also meant a less intense mid-level buoyancy gradient and low pressure perturbation, further
helping the convective updraft to remain upright initially, but by 0730 UTC the mid-level pressure perturbation had intensified (Fig. 12a). The low-level convective updraft was able to tilt rearward over the cold pool temporarily, allowing a bowing segment to form; the increase in system rear inflow strengthened the resulting surface winds. The overall system became more intense as time progressed, and a more organized system was created that better matched observations. At 0900 UTC, the system began to dissipate, although the convective line was still fairly intense (greater than 45 dBZ).

The system in the graupel simulation quickly developed intense convection by 0445 UTC (Fig. 10d). At this point the convection was cellular, with minimal stratiform precipitation. The larger graupel hydrometeors were not as mobile, and stayed closer to the convective updraft. (Fig. 11b). The cold pool was still very weak at this point, but was larger than the corresponding time in the no-graupel simulation. Cooling rates due to melting graupel and evaporating rain were approximately equal at this point (not shown); the sub-cloud layer was sub-saturated. By 0600 UTC, the system developed mature mesoscale convective system features, such as a convective line and intense stratiform precipitation region (Fig. 10e). The stratiform region was composed of large concentrations of graupel and snow aloft, but these concentrations were not as large, both in quantity and area, as the snow concentrations in the no-graupel run at the same time (Fig. 11d). The cold pool, created by both melting graupel and evaporating rain falling through a still sub-saturated sub-cloud layer, was much larger, deeper, and cooler than the no-graupel system (6 K cooler at its most intense point). The cold pool at this point also had a distinct head, as the cooling maximum in the graupel system was closer to the convective line due to the graupel not spreading as far from the updraft. At 0730 UTC, the stratiform precipitation area was much less organized (Fig. 10f), with diminished amounts of snow and graupel particles aloft (Fig. 11f). Examination of vertical wind speeds revealed that the low-level convective updraft at the front edge of the cold pool had moved more quickly than the upper-level updraft associated with the stratiform region (Fig. 12b). By this point, the disparate speeds forced the disorganization of the system.
The cold pool developed a mound shape with the deepest point beneath the stratiform precipitation region, as the main source of cooling shifted to beneath the stratiform region (Fig. 11f). The mid-level low pressure perturbation had also remained strong and shifted farther rearward, further helping to tilt the updraft (Fig. 12b), as did the spreading of the rear inflow along the surface up to 50 km behind the convective line (not shown). At this time, the graupel system remained intense, but was disorganized; after 0800 UTC the system lost its convective line and began to slowly dissipate.

b. Idealized cases

Two idealized simulations were also run using the WSM5 (no-graupel) and WSM6 (graupel) microphysics schemes, again to determine if the differences between the 5- and 6-class schemes seen in the case study simulations discussed above were partially due to synoptic heterogeneities, or if they were entirely microphysics-driven. Figure 13 displays the simulated composite reflectivity calculated for the two simulations. The similarities between these idealized systems and those produced in the case study simulations are striking. The large precipitation region ahead of the convective line during the initial hours of its formation in the no-graupel system was still due to the large concentration of slowly falling, easily advected snow produced (Fig. 13a, b). Because the melting and evaporation of the snow initially occurred aloft, the cold pool was minimal, and the system correspondingly slow, until the snow fell below the melting level and began to fall as rain. As in the case-study no-graupel simulation, the cooling by melting and evaporation eventually intensified the cold pool enough to allow the convective line to bow (Fig. 13c), through a local intensification of the buoyancy gradient, mid-level low pressure perturbation, and system rear inflow behind the convective line.

As expected, the stratiform precipitation region was much smaller in the graupel case, due to the relatively larger, faster-falling graupel particles (Fig. 13d). Cooling rates were stronger in the graupel case, due to the melting and subsequent evaporation of the faster-falling graupel spread throughout the lower levels. However, the graupel fallspeeds were not
too fast to preclude large melting and evaporation rates before reaching the surface. The cold pool in the graupel simulation was therefore much stronger. Again, the graupel fell closer to the convective line, making it more intense (Fig. 13e) and thus the peak cooling also remained closer to the convective line. This resulted in the cold pool having a shaper, “head”-shaped leading edge at this time. The steep leading edge of the cold pool helped to intensify the leading updraft, while the increased intensity of the mid-level pressure perturbation due to the stronger buoyancy gradient resulted in a more favorably tilted updraft. Thus, the system rear-to-front flow was stronger, and the system began to bow half an hour earlier. However, the peak cooling rates eventually shifted rearward as in the case study, resulting in a more gentle slope of the potential temperature contours at the front edge of the cold pool, and a very strong mid-level low pressure perturbation that had also shifted rearward. The rear inflow began to spread along the surface far behind the convective line. All of these things acted to tilt the low-level updraft too far rearward over the cold pool, weakening the system.

Thus, the main differences between the no-graupel and graupel systems observed in the case study were also observed in the idealized simulation. Specifically, the no-graupel simulation cold pool transitioned from relatively warmer to cooler as the slower-falling snow finally began to melt; the system itself became more organized as the simulation progressed. Meanwhile the graupel simulation cold pool was very strong from shortly after initialization, due to the large cooling rates produced by melting graupel and evaporating rain spread throughout the lower levels. However, the cooling rates shifted rearward as the simulation progressed; the deepest part of the cold pool shifted rearward as well, as did the mid-level low pressure perturbation. The low-level convective updraft was tilted too far rearward over this intense cold pool, and the system therefore began to weaken earlier than the 5-class simulation.

6. Conclusions

Multiple WRF convective simulations were conducted to examine the effect of changes in microphysical cooling rates on bow echo generation and longevity, specifically through the
connection between the mid-level buoyancy gradient and low-level convective updraft tilt.

Simulations were performed over a spectrum of graupel class parameters in a microphysics parameterization scheme, rendering the class larger, more dense and “hail-like”, or smaller, lighter and “graupel-like”. Additional simulations looked at the effects of removing graupel completely. Both case study and idealized simulations were performed to generalize these results beyond one specific case.

The simulations with a larger, more dense “hail-like” graupel class had these particles fall out of the updraft almost immediately, close to the convective line, allowing little melting or evaporation. This resulted in a minimal stratiform precipitation region, little organization, and reduced convective intensity. Because of this, there were fewer feedbacks to updraft intensity, such as a weaker and more shallow cold pool, very reduced rear inflow, and a weaker mid-level low pressure perturbation. In the case study, there was little convection and no bowing. The idealized case did exhibit bowing behavior, although later in time and over a smaller area than the idealized graupel-like case. It is likely the lack of radiation cooling sustained the system by providing it with a continuous source of warm, moist air at lower levels. This resulted in a slightly more intense updraft, providing the hailstones with enough rearward momentum to avoid falling directly through the updraft. The initiation method also provided additional organization and intensity at the start of convection.

Meanwhile, the idealized and case study simulations with a smaller, less dense “graupel-like” graupel class had a mixture of small snow crystals and larger graupel particles that were slower to fall, creating a wide stratiform precipitation region. This allowed for more melting and evaporation, and yielded a wider, deeper, and stronger cold pool. The mid-level low pressure perturbation associated with the system was stronger, strengthening the low-level convective updraft and aiding it in temporarily tilting rearward. This helped generate bowing segments earlier and over a larger area than the hail-like simulations. The cold pool retained its “head” shape longer. However, the rearward advection of graupel produced an unrealistically intense stratiform precipitation region, with no transition zone reflectivity.
The various cloud and ice particles generated by the no-graupel (5-class) simulations remained entirely aloft for some time after initiation as the large amounts of snow generated fell very slowly. Each stratiform precipitation region only reached the surface as the system became vertically saturated. This saturation allowed for little evaporation; hence the cold pool was less intense and the system was slower. Due to the weaker buoyancy gradient and mid-level low pressure perturbation, the low-level convective updraft was not as strong, the rear inflow weaker, and the convective line initially not as intense as the graupel simulations (6-class). However, this slower speed allowed the no-graupel systems to remain more organized. Over time the cooling by evaporation rates increased, intensifying the mid-level pressure perturbation and temporarily tilting the low-level updraft, developing a bow echo. Due to the increased horizontal resolution, the idealized no-graupel simulation was also able to better segregate its particle sizes in the stratiform precipitation region, creating a transition zone and secondary reflectivity maximum. The graupel simulations initially developed a stronger cold pool, as the sub-cloud layer was not saturated. The stronger cold pool resulted in bowing developing faster. However, as each simulation progressed the cold pool became too strong. The fast speed of the system, coupled with the stronger mid-level lower pressure gradient and the rear inflow spreading to the surface far behind the convective line, helped tilt the updraft too far over the cold pool. The system became disorganized more quickly, approximately an hour earlier than the no-graupel simulations.

Thus, it was found that internal variations in the WRF Single- and Double-Moment microphysics schemes, specifically regarding the graupel class, had a large effect on the structure, strength, and longevity of the simulated convective system. Changes in the microphysical cooling rates affected the tilt of the low-level convective updraft through the mid-level low pressure perturbation, affecting the timing, size, and existence of bowing. These results were noted in both case study and idealized simulations, ensuring they were not due to synoptic heterogeneities.
The similarity of these results to those obtained by Weisman (1993), which used simulations with no ice, is noted. Obviously frozen particles and their associated microphysical processes are not required for bowing development. However, in these simulations it was found that the cooling produced by melting can play a significant role in creating a cold pool strong enough to initiate bowing. A delay in the onset of cooling by melting, as in the no-graupel simulations, helped the system retain its organization for a longer period of time. Extremely low melting rates, such as in the hail case, resulted in much weaker systems that in some cases did not bow. Thus the impacts of melting rates should not be discounted in future bowing simulations.

While this study has examined sensitivities to model microphysical schemes, such variations to the microphysics can occur in reality. For example, introduction of dust, lofted by storm outflow, into a system can drastically modify the concentration of both cloud condensation and ice-forming nuclei, as was seen in Twohy et al. (2010). This naturally results in significantly different size distributions of all microphysical particles, noted by van den Heever et al. (2006) and Storer et al. (2010) for deep convection; this particularly affects the heating and cooling rates as discussed here. There are many further environmental factors that could result in similar microphysical changes, such as variations in nearby temperature, moisture, or shear profiles, so these results are of note. Future work includes using WSR-88D radar data to more fully compare the model simulations to observations. The differences between multi-moment schemes, particularly the single- and double-moment schemes noted at the start of this work, also need to be more fully explored.

7. Acknowledgments

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FIGURE CAPTIONS

Figure 1. WRF-ARW domain. The entire domain was run in 3-km resolution. Later figures will show only a subsection of the domain over eastern Oklahoma for space considerations.

Figure 2. 0000 UTC 13 March 2003 KOUN sounding, modified for use in idealized simulations.

Figure 3. Graupel particle size distributions for the model runs given in Table 1.

Figure 4. 0315 UTC (a), 0600 UTC (b), and 0800 UTC (c) 13 March 2003 WSI NOWrad composite reflectivity data.

Figure 5. Simulated composite reflectivity data from WRF hail-like (a, c) and graupel-like (b, d) case study simulations. 0600 (a, b) and 0800 (c, d) UTC 13 March 2003. Simulated reflectivity calculated as in Stoelinga (2005). Thick black lines delineate location of cross-sections in subsequent figures.

Figure 6. Model output from case study hail-like simulation (a, c) and graupel-like simulation (b, d) at 0600 (a, b) and 0800 (c, d) UTC 13 March 2003. The cross-section is taken along the black lines in Fig. 5; plotted values are averages of 15 km either side of the cross-section. Mixing ratios (g kg\(^{-1}\)) are of graupel (image), cloud water and ice (dashed red, 0.2 g kg\(^{-1}\)), rain water (green, 0.5 g kg\(^{-1}\)), and snow (thin black, 0.1 g kg\(^{-1}\)); the thick solid black lines are cold pool potential temperature contours (2 K) at 294 K and colder. Thick dashed black line is the melting level.

Figure 7. Cooling rates (K (5 min\(^{-1}\)) by evaporation (blue image), melting (red, 0.1K (5 min\(^{-1}\)), and sublimation (purple, 0.1K (5 min\(^{-1}\)) for the hail-like (a) and graupel-like (b) simulations at 0600 UTC 13 March 2003. Thick solid black lines are the simulated reflectivity at 25, 40, and 50 dBZ. Thick dashed black line is the melting level.
Figure 8. As in Fig. 6, but with vertical motion (image, cm s$^{-1}$) and perturbation pressure (black, 0.5 hPa). Perturbation pressure is calculated by subtracting the model pressure field from the MM5 standard atmosphere, as in Stoelinga (2005).

Figure 9. Simulated composite reflectivity data from WRF idealized hail-like (a, c) and graupel-like (b, d) model simulations. 2:00 (a, b) and 4:30 (c, d) simulation time. Simulated reflectivity calculated as in Stoelinga (2005). Horizontal scale is km “east” of left edge of domain, and “north” of bottom edge of domain.

Figure 10. Simulated composite reflectivity data from WRF no-graupel (a,b,c) and graupel (d,e,f) case study simulations. Columns, from left to right, correspond to times 0445 (a, d), 0600 (b, e), and 0730 (c, f) UTC 13 March 2003. Simulated reflectivity calculated as in Stoelinga (2005). Thick black lines delineate location of cross-sections in subsequent figures.

Figure 11. Mixing ratio cross-section from the no-graupel (left column) and graupel (right column) case study simulation, at 0445 (a, b), 0600 (c, d), and 0730 (e, f) UTC 13 March 2003 from cross-section lines shown in Fig. 10. Values are averages of 15 km either side of cross-section. Mixing ratios (g kg$^{-1}$) are of cloud water and ice (dashed red, 0.2 g kg$^{-1}$), rain water (green, 0.5 g kg$^{-1}$), snow (thin black, left column 0.5 g kg$^{-1}$, right column 0.2 g kg$^{-1}$), and graupel (right column, image). The thick solid black lines are cold pool potential temperature contours (2 K) at 294 K and colder. The thick dashed black line is the melting level.

Figure 12. Cross-section of vertical motion (image, cm s$^{-1}$) and perturbation pressure (black, 0.5 hPa) for the no-graupel (a) and graupel (b) case study simulations at 0730 UTC 13 March 2003. Perturbation pressure is calculated by subtracting the model pressure field from the MM5 standard atmosphere, as in Stoelinga (2005).

Figure 13. Simulated composite reflectivity data from idealized WRF model simulations WSM5...
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Figure 13: Simulated composite reflectivity data from idealized WRF model no-graupel (a,b,c) and graupel (d,e,f) simulations. Columns, from left to right, correspond to times 2:30 (a, d), 3:30 (b), 3:00 (e), and 4:00 (c, f) simulation time. Simulated reflectivity calculated as in Stoelinga (2005). Horizontal scale is km “east” of left edge of domain, and “north” of bottom edge of domain.
Table 1: Names of model simulations with the intercept value ($n_{0G}$) and density ($\rho_G$) used. These range from the simulation with the most “hail-like” graupel class to the most “graupel-like”. The default values in WSM6 and WDM6 are an intercept value of $4 \times 10^6$ m$^{-4}$, and density of 500 kg m$^{-3}$.

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