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A triple-moment hail bulk microphysics scheme. Part II: Verification and comparison with two-moment bulk microphysics

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ABSTRACT

Microphysical parameterizations in numerical cloud models continue to grow in complexity as our capability to represent microphysical processes increases owing to greater knowledge of these processes as well as advances in computing power. In Part I of this study, a new triple-moment bulk hail microphysics scheme (3MHAIL) that predicts the spectral shape parameter of the hail size distribution was presented and evaluated against lower order-moment schemes. In this paper, the 3MHAIL scheme is verified in simulations of a well-observed supercell storm that occurred over northwest Kansas on 29 June 2000 during the Severe Thunderstorm and Electrification and Precipitation Study (STEPS). Comparisons of the simulation results with the observations for this case, as well as with results of simulations using two different two-moment (2M) configurations of the RAMS microphysics schemes, suggest a significant improvement of the simulated storm structure and evolution is achieved with the 3MHAIL scheme. The generation of large hail and subsequent fallout in the simulation using 3MHAIL microphysics show particularly good agreement with surface hail reports for this storm as well as with previous studies of hail-producing supercell storms. On the other hand, the simulation with 2M microphysics produces only small hail aloft and virtually no hail at the surface, whereas a 2M version of the 3MHAIL scheme (with a fixed spectral shape parameter) produces unrealistically high amounts of large hail at low levels as a result of artificial shifts in the hail size spectra towards larger diameter hail during the melting process.

1. Introduction

In severe convective storms, such as those that occur in mid-latitudes during the warm season, microphysical processes associated with hail production become increasingly important given the often destructive nature of hail (Changnon, 1977; Changnon and Burroughs, 2003; Gallo et al., 2012; Klimowski et al., 1998; Parker et al., 2005) as well as the impacts of hail on storm dynamics and rainfall (Knight et al., 1974; Heymsfield and Hjelmfelt, 1984; Rasmussen et al., 1984, hereafter RLP84; Srivastava, 1987; Ziegler, 1988; Wakimoto and Bringi, 1988; Hjelmfelt et al., 1989; Orville et al., 1989; Proctor, 1989; Straka and Anderson, 1993, hereafter SA93; Knight and Knight, 2001; Gilmore et al., 2004, hereafter GSR04; van den Heever and Cotton, 2004, hereafter VC04; Morrison and Milbrandt, 2011). In spite of this, many existing one- (1M) and two-moment (2M) bulk microphysics schemes can perform poorly with respect to the production and growth of hail in simulations of deep convection due to constraints imposed by parameter selections and inadequacies in representing processes such as initial formation, sedimentation, and melting (GSR04; Milbrandt and Yau, 2006b, hereafter MY06b; Morrison and Milbrandt, 2011; Van Weverberg et al., 2012; Milbrandt and

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Morrison, 2013). In order to alleviate many of the shortcomings in simulating hail in 1M and 2M bulk schemes, a new triple-moment hail bulk microphysics scheme (3MHAIL) (Loftus et al., in press, hereafter Part I) was recently implemented into the Regional Atmospheric Modeling System (RAMS) cloud-resolving model (Cotton et al., 2003). The 3MHAIL scheme predicts the sixth moment (related to the reflectivity factor Z) of the hail distribution in addition to mass mixing ratio (r) and total number concentration (N_t) to obtain an independently predicted spectral width parameter (ν) for a gamma size distribution function,

$$n(D) = N_t \frac{1}{\Gamma(\nu)} \left(\frac{D}{D_n}\right)^{\nu-1} \frac{1}{D_n} \exp\left(-\frac{D}{D_n}\right), \tag{1}$$

where D is the particle diameter and D_n is the characteristic diameter. This scheme incorporates enhancements to key hail processes such as formation, growth, sedimentation, and melting relative to the existing 2M algorithms, yet retains 2M prediction for non-hail species. Idealized tests in Part I revealed significant improvements to the aforementioned hail processes with the 3MHAIL scheme compared to the original lower-order moment formulations in RAMS.

In order to verify the 3MHAIL model and further gauge its quality, numerical simulations of a tornadic supercell that occurred in northwestern Kansas on 29 June 2000 during the Severe Thunderstorm Electrification and Precipitation Study (STEPS; Lang et al. 2004) field program are performed using the 3MHAIL as well as two other 2M microphysics schemes. This particular storm produced hail in excess of 5 cm, was continuously sampled by three S-band Doppler radars (two of which had polarimetric capabilities) for nearly 4 h within the STEPS domain (Tessendorf et al., 2005, hereafter TMWR05), and involved dedicated surface hail-collection teams (MacGorman et al., 2005; Patrick Kennedy 2008, personal communication) making it an ideal candidate against which to validate the 3MHAIL scheme. Simulations using 1M bulk microphysics are not carried out as numerous studies have already focused on improvements in model solutions when using 2M versus 1M bulk schemes (e.g., Ferrier et al., 1995; Meyers et al., 1997; Reisner et al., 1998; MY06b; Seifert and Beheng, 2006; Mansell, 2008; Morrison et al., 2009; Dawson et al., 2010; Jung et al., 2010; Bryan and Morrison, 2012). Comparisons of the model results with analyses of observations from the actual event assess how well simulations with different microphysical approaches are able to reproduce observed storm features such as reflectivity structures, kinematic fields, and hail distributions. Additional analyses examine differences in microphysical characteristics of the modeled storms produced by the various microphysics schemes, with a particular focus on the processes of hail formation, growth, and melting as well as the role of hail in the morphology of low-level cold-pools. The results tend to show a significant improvement in the prediction of hail and overall storm evolution when the 3MHAIL scheme is applied versus the use of a 2M scheme.

2. Case description

The environment on 29 June 2000 was supportive of strong convection as evident in the 2022 UTC sounding near Goodland, KS from the NCAR Mobile GPS/Loran Sounding Systems (MGLASS) (Fig. 1). This sounding was taken roughly 65 km southeast of where the storm initiated and about 1 h prior to the detection of the storm by radar (Kuhlman et al., 2006). Southerly low-level winds veering to the west-northwest with height, a modest surface-based convective available potential energy (CAPE) value of 1254 J kg^{-1}, and 0–3 km storm relative helicity (SRH) around 330 m^2 s^{-2} indicated the potential for supercell development (Johns and Doswell, 1992; Moller et al., 1994; Rassmussen and Blanchard, 1998). Convection initiated over northeast Colorado during the afternoon along a southwest-northeast oriented dryline and was first detected by radar around 2130 UTC in the vicinity of the Colorado, Kansas, and Nebraska borders. During its early and maturing stages of development, the storm was multicellular and traveled east-southeastward around 10 m s^{-1}, with the updraft and reflectivity cores mostly collocated (Tessendorf et al., 2005, hereafter TMWR05). Analyses of polarimetric radar data by TMWR05 revealed two episodes of hail growth and fallout between 2215 and 2320 UTC in association with radar reflectivity values exceeding 60 dBZ. Surface reports of large hail (defined as having a diameter $D_h \geq 2$ cm) and sizes up to 4.5 cm were confirmed during this period (Storm Data) (Fig. 4). By 2320 UTC, a decline in hail growth and fallout had occurred, along with decreases in reflectivity maxima (<55 dBZ) (Wiens et al. 2005), although the storm remained strong with maximum updraft speeds exceeding 40 m s^{-1} (TMWR05).

Around 2330 UTC, the storm made a right turn (Fig. 2b), assumed a typical supercell structure with a strong mesocyclone at mid and low levels and a pronounced Bounded Weak Echo Region (BWER) in the reflectivity fields (Fig. 3), and traveled slightly slower (~9 m s^{-1}) towards the southeast (TMWR05). A brief tornado also occurred around this time (Fig. 2b). Concurrent with the right turn, the updraft core shifted to the southwest of the reflectivity core, and strong cyclonic flow became established around the updraft's right flank (Fig. 3a and b). A flanking line of weaker radar echoes extending westward from the high reflectivity core was also evident (Fig. 3a) and indicated weaker cells along the storm's outflow (TMWR05). The storm was most intense between approximately 2330 and 0030 UTC, with maximum updraft speeds around 50 m s^{-1} and reflectivity maxima exceeding 65 dBZ aloft. Roughly 20 min after the right turn, hail amounts aloft significantly increased, and a low-level hook echo appeared about 10 min later (TMWR05). Reports of 2.5–4.5 cm diameter hail at the surface were made during this time (Fig. 4) (Storm Data; MacGorman et al., 2005). Shortly after 0030 UTC, the storm's intensity weakened and the hail echo volume declined somewhat (TMWR05; Wiens et al., 2005) as the storm continued moving southeast before merging with a mesoscale convective system in central Kansas (Kuhlman et al., 2006).

3. Model setup

The 3D RAMS cloud-resolving model is utilized for all simulations performed herein. RAMS uses the full set of non-hydrostatic compressible equations, which are integrated in time via a hybrid scheme of second-order accurate leapfrog and forward-in-time (Cotton et al., 2003). The fast acoustic modes