1. Introduction

This study examines the sensitivity of squall line structure to various microphysical schemes. The WRF simulations of an idealized two-dimensional squall line were performed at 1-km horizontal resolution using the Weisman et al. (1988) idealized squall line sounding and a retrospective sounding from a squall line case observed on 12 June 2002 during the IHOP (International H2O Program) field program. Previous studies have shown sensitivity of squall line dynamics to microphysics parameterization (e.g., Yang et al. 1995). A unique aspect of this study is the inclusion of the detailed microphysics schemes of Geresdi et al. (2005) in addition to three more conventional mixed-phase bulk microphysics schemes [Lin, Farley, and Orville (1983); WSM 6-class (Hong et al. 2004); and Thompson et al. (2004)] that are commonly used in the WRF model.

A brief description of the model configuration is given in section 2. Section 3 presents the simulation results. A summary and concluding remarks are given in section 4.

2. Model setups

Two WRF simulations of a two-dimensional squall line were performed. The first simulation was performed using the Weisman et al. (1988) idealized sounding (Fig. 1a). The sounding shows a low-level storm-relative inflow between 0 to 2.3 km and a deep moist layer in the troposphere. The second simulation was initialized with sounding data collected on 12 June 2002 during the IHOP field campaign (Fig. 1b). The IHOP sounding in Fig. 1b was taken from dropsonde data collected just ahead of a dry line in northwestern Oklahoma and rawinsonde data from Norman, OK at ~2100 UTC. The dry line was associated with a squall line that later developed and moved across northern Oklahoma. The presence of a dry layer between 3 and 6 km AGL, capped by a thermal inversion layer, and storm-relative westerly flows in the dry upper levels characterize the atmospheric conditions.

The model domain had a horizontal dimension of 501 km with a 1-km grid spacing and 81 vertical levels. The simulation times with the Weisman et al. and IHOP soundings were six hours and four hours, respectively, with a time step of four seconds. The convection was initialized with a 3.0 and 1.5°C warm
bubble in the Weisman et al. and IHOP sounding simulations, respectively.

The three bulk microphysical schemes examined in this study are: Lin, Farley, and Orville (1983); WSM 6-class (Hong et al. 2004); and Thompson et al. (2004) schemes. In addition, simulations with the detailed microphysics scheme of Geresdi et al. (2005) are compared with those from the three bulk schemes. All of the four schemes involve five hydrometeor categories: cloud water, rain, cloud ice, snow, and graupel.

3. Results

a. Simulation with the Weisman et al. sounding

Figure 2 shows a Hovmuller diagram of rainfall rates simulated with the Weisman et al. sounding. Generally, all of the four microphysics schemes produced a leading squall line with a trailing stratiform region although some differences in the strengths and width of the convective and stratiform regions exist. Vertical cross sections of the system displayed several similarities to the general features of the squall line with trailing stratiform precipitation described in Houze (1993), e.g., the ascending front-to-rear flow, descending rear-to-front flow, precipitation-induced low-level cold pool development, formation of new convective cells in the midlevel on the leading side of the matured intense convective cell, and vertical motions associated with the individual convective cells (Fig. 3).

The simulated system matured rapidly with the Lin et al. and WSM6 schemes developing a maximum rainfall rates in 1.5 hours after the convective initiation (at 0.5 hr) (Fig. 4). The system started its eastward propagation at this model time. The storm development was relatively slower with the detailed and Thompson et al. schemes, requiring ~2.5 hours after the convective initiation for the system to begin its eastward motion due to smaller evaporation rates below the cloud base produced by the two schemes.

b. Simulation with the IHOP retrospective sounding

Rainfall rates simulated with the IHOP sounding are given in Fig. 5. Generally, the system is less organized compared with that of the previous simulation. In this case, the thermal inversion layer capping a relatively dry mid-layer and storm-relative westerly flow in the upper levels in the IHOP sounding (Fig. 1b) affected the storm dynamics. The thermal inversion inhibited the ascending front-to-rear flow to penetrate above ~6 km AGL. Thus, much of the ice and snow that formed in the upper levels of the convective region were advected towards the front of the system (eastward with respect to the storm motion) by the storm-relative westerly flow aloft forming a relatively broader region of overhang instead of a trailing stratiform precipitation (e.g., Fig. 6).

The cooling effects from sublimation, evaporation, and melting of the stratiform precipitation are important to the development of a strong rear inflow jet (Yang et al. 1995) which transports cooler and drier air toward the leading edge of the convective region to form a cold pool (e.g., Houze 1993). In addition, the balance between the strength of the cold pool and low-level wind shear are important factors controlling the strength and longevity of squall lines (e.g., Rutunno et al. 1988; Weisman 1992). For example, in the Weisman et al. sounding simulation, the precipitation-induced rear inflow jet in the stratiform region stayed elevated during the six-hour storm evolution for the four microphysics schemes producing more vigorous convective updrafts at the leading edge of the system as the storm-relative low-level inflow interacted with the cold pool nose.
Figure 3: Average vertical cross sections of (a) total condensate (b) perturbation potential temperature, (c) vertical velocity, and (d) storm-relative horizontal velocity simulated by the WSM6 scheme with the Weisman et al. sounding. The cross sections show the average structure between the simulation times 3.5 and 4 hr with respect to the storm motion. Zero km on the abscissa marks the leading edge of the convective region.

Figure 4: Time history of domain-average rainfall rates (mm h$^{-1}$) from the Weisman et al. sounding simulation.

Compared with the results from the Weisman et al. sounding, the microphysics parameterization had a significant impact on the storm evolution when the simulation was initiated with the IHOP sounding due to the different cold pool dynamics produced by the various schemes. The Lin et al. and WSM6 schemes initially produced a non-propagating convection (Figs. 5a-b). The gust front from this cell formed new cells on the leading side of the initial convection as in the Weisman et al. sounding simulation, but the system became less organized after ~2.5 hours of the simulation as the rear-inflow jet descended and spread cooler and drier air at the surface ahead of the decaying initial convection (at x ~ -75 km in Fig. 6). Eventually, it broke down into multi-cellular weak convection. In comparison, the systems simulated with the Thompson et al. and detailed schemes were relatively more organized with the initial convection near the leading edge of the system and a narrow trailing stratiform region (Figs. 5c-d). The cold pool nose in these two schemes did not extend too far beyond the initial convection during the simulation time compared with those produced by the Lin et al. and WSM6 schemes (e.g., Fig. 7).

Examination of mixing ratios, sinks, and sources of the five individual hydrometeor types suggested that trailing stratiform precipitation did not form in the Lin et al. and WSM6 schemes because snow formed mainly above the ascending front-to-rear flow (> 6 km AGL; Figs. 8a-b). In these two schemes, the dominant sources for snow were aggregation of ice, which formed in the upper levels by vapor diffusion, and ice-snow coagulation. These hydrometeors were transported ahead of the initial convection by the storm-
relative westerly flow aloft and formed an overhang. On the other hand, some snow formed in the ascending front-to-rear flow in the Thompson et al. and detailed schemes by vapor diffusion and were transported rearward; thereby yielding a narrow trailing stratiform precipitation (Figs. 8c-d). Consequently, the sublimation rate of the snow in the stratiform region was significantly larger compared with that of the Lin et al. and WSM6 schemes, which would impact the formation of a rear inflow-jet and the organization of the system through generation of horizontal vorticity. As in the Lin et al. and WSM6 schemes, snow in the upper levels was carried...
toward the front of the system by the upper level flow in
the detailed and Thompson et al. schemes. Vapor
diffusion was the most effective process for producing
snow in the upper levels in these two schemes. [Very
little ice was produced by the Thompson et al. scheme
(Fig. 8c).]

The latent cooling of the precipitation behind
the new cell also affected the cold pool evolution. In the
WSM6 and Lin et al. schemes, graupel formed above
the cold pool nose (between x = -50 and 0km in Figs.
8a-b). Evaporation of the melting graupel (explicitly
computed by the two schemes) further enhanced
evaporative cooling below the cloud deck, and possibly
correlated to the rapid break down of the system in
these two bulk schemes.

4. Summary and concluding remarks

Two WRF simulations of a two-dimensional
squall line system were performed to examine the
sensitivity of the system to microphysical
parameterization. All four microphysics schemes
examined in this study formed a realistic squall line
when the simulation was initialized with the Weisman et
al. sounding. The microphysical parameterization had a
significant impact on the storm evolution with the 12
June 2002 IHOP retrospective squall line case. The Lin
et al. and WSM6 schemes produced a non-propagating
squall line without trailing stratiform precipitation, and
the system rapidly broke down after 2.5 hours. The
system formed with the Thompson et al. and detailed
microphysics schemes was relatively more organized
during the four-hour simulation. The current analysis
indicated that (1) whether snowice formed in the
ascending front-to-rear flow, and (2) latent cooling
effects from precipitation forming over the cold pool
nose were important in the cold pool dynamics. Further
details will be presented at the conference.

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Figure 8: Average vertical cross sections of total condensate, ice, snow, and graupel mixing ratios, and storm-relative horizontal velocity (from top to bottom row) simulated with the (a) Lin et al., (b) WSM6, (c) Thompson et al., and (d) detailed microphysics schemes using the IHOP sounding. The simulation time between 2.5 and 3 h (the onset of the system breakdown period) were averaged in the Lin et al. and WSM6 schemes. For the Thompson et al. and detailed schemes, the simulation times between 3.5 and 4 h were averaged. Color scales for the individual fields are shown on the right.