P7.6 A COMPARISON OF THE STRUCTURAL EVOLUTION AND MICROPHYSICAL STATE OF A FORECASTED MCS USING A ONE- AND TWO-MOMENT MICROPHYSICS SCHEME

Bryan J. Putnam*[1,2], Ming Xue[1,2], Guifu Zhang[1], Youngsun Jung[2], Nate Snook[1,2], Alex D. Schenkman[1,2]

Center for Analysis and Prediction of Storms[1] and School of Meteorology[2]
University of Oklahoma, Norman, OK 73019

1. INTRODUCTION

Recent increases in computer power have allowed for the use of more advanced data assimilation (DA) methods such as the ensemble Kalman filter (EnKF) as well as multi-moment microphysics schemes in convective to mesoscale forecast models (Houtekamer and Mitchell 1998; Anderson 2001; Bishop et al. 2001; Whitaker and Hamill 2002, Morrison et al. 2005, Seifert and Beheng 2006a, Morrison et al. 2009). The EnKF method has several advantages over other methods such as three-dimensional variational data assimilation (3DVAR) including the ability to use the dynamic model equations and handle highly non-linear processes in the assimilation model. However, the 3DVAR method is still widely used in real-time forecasts because of its rather good performance and low computational cost. Additionally, previous research indicates that two-moment (DM) microphysics schemes result in more realistic storm structure and evolution compared to observations over a single-moment (SM) scheme (Jung et al. 2010). Both of these DA methods, as well as a DM microphysics scheme, are available in the Advanced Regional Prediction System (ARPS, Xue et al. 2000; Xue et al. 2001a; Xue et al. 2003). Previously conducted experiments applied both the 3DVAR and EnKF methods to assimilate radar data for the same case. The final analyses of these methods are used in this paper to initialize several ARPS model forecasts using both a SM and DM microphysics scheme for a comparative microphysical state study with polarimetric radar observations.

The case of interest is a mesoscale convective system (MCS) and associated line end vortex (LEV) that occurred in western Oklahoma on 8-9 May 2007. A large complex of storms formed early in the morning on 8 May from upslope flow along the high plains of eastern New Mexico. The storms quickly grew upscale into a large MCS along a cold front as they moved into west Texas. An LEV developed on the northern side of the MCS and traveled northeast through western Oklahoma during the early morning hours of 9 May. Five tornadoes were produced along with widespread flooding rain. The LEV was observed by both the NSF Engineering Research Center for Collaborative and Adaptive Sensing of the Atmosphere's (CASA) Integrated Project One polarimetric radar network as well as the National Severe Storms Laboratory's polarimetric research radar, KOUN.

Radar observations currently provide some of the best temporal and spatial information available for assimilation purposes, especially on the convective scale. Several studies have looked at how both the EnKF and 3DVAR techniques can use this information to provide improved microphysical state estimations. The EnKF uses ensemble covariances between variables to spread information from reflectivity observations to other state variables (Xue et al. 2010, Tong and Xue 2005). 3DVAR, on the other hand, uses a complex cloud analysis procedure within ARPS to retrieve the hydrometeor distribution (Hu et al. 2006a). A polarimetric radar data (PRD) simulator (Jung et al. 2010) has been used to simulate observations using the model data, including the reflectivity at horizontal polarization (Z), specific differential phase (K_{dp}), differential reflectivity (Z_{dr}), and correlation coefficient (ρ_{hv}). The simulated polarimetric variables are compared to the polarimetric observations from the CASA network to evaluate the microphysical state of the final analyses.

The particle size distributions (PSDs) of hydrometeors are often modeled by the three parameter gamma distribution given by the equation

$$N(D) = N_o D^{\alpha} e^{-\Lambda D} \qquad (1)$$

where Λ, N_o, and α are slope, intercept and shape parameters, respectively. For a SM scheme, the PSD is assumed to have an exponential distribution and the ARPS model predicts the mixing ratio (third moment) for up to six hydrometeor species depending on the microphysics option. The SM schemes only the slope parameter to vary. For a DM scheme, ARPS predicts an additional state variable, the total number concentration (zeroth moment), which allows both the intercept and slope parameter to vary independently while the shape parameters to be kept constant. Numerous studies, including that by Dawson et al. (2007), have indicated the importance of varying the intercept parameter in addition to the slope in the PSD to improve the simulation of convective storms. In fact, the PSDs show large variability in real precipitation systems. For example, strong convective rain usually has a broad PSD while stratiform rain is dominated by relatively larger drops (Zhang et al. 2006). Both the previous 3DVAR and EnKF experiments used to study this case employed a SM microphysics scheme and produced relatively accurate SM forecasts. This study will expand on this research to include forecasts using a DM microphysics scheme. The evolution of the LEV using the SM and DM microphysics schemes will be compared. In addition, the impact of the DM scheme on

* Corresponding author address: Bryan J. Putnam, CAPS/SOM, National Weather Center, Suite 5240, David L. Boren Blvd, Norman OK 73072, USA; bryan.j.putnam-1@ou.edu

the microphysical state variables will be assessed compared to KOUN observations using the PRD simulator. As mentioned, these additional polarimetric variables provide more ways to compare the accuracy of the model to observations because they reveal more information on PSDs than reflectivity alone. For example, Xue et al. (2010) noted that the analyzed reflectivity from a DM scheme could be from infinitely different combinations of mixing ratios and number concentrations and thus an incorrect comparison to observations could be made without additional information. Preliminary results from an EnKF experiment using a two-moment microphysics scheme will also be discussed.

The PRD simulator used in this study has so far been used as a tool for Observing System Simulation Experiment (OSSEs). This investigation is the first to be used in comparison to real polarimetric observations. In addition, those studies that have previously investigated the impact of multi-moment microphysics schemes have mainly dealt with a supercell case. There are various differences in both the dynamics and microphysics between a supercell and a larger MCS and it was apparent during this study that the forecast model had a more difficult time correctly resolving the system compared to observations. Also, the MCS does not have the same documented polarimetric signatures that have been used for comparisons in previous studies like that by Jung et al. (2010) with the supercell case. Therefore, the authors focused more on comparing qualitative trends among the variables rather than specific values or those specific documented signatures.

2. METHODOLOGY

As discussed, the experiments in this work are based on previously completed EnKF and 3DVAR final analyses of the May 8-9 MCS. Briefly, both had a one hour assimilation window between 0100 and 0200 UTC 9 May while the storm system resided in southwestern Oklahoma. Given the size of the system, the grids used in these cases were relatively large with a 1000km x 1000km grid for the 3DVAR case and a 512km x 512km grid for the EnKF case. The horizontal grid spacing was 2km in both cases. Observations were assimilated every 5 minutes. These observations include reflectivity and radial velocity from both the CASA radars and 5 (EnKF) and 6 (3DVAR) regional WSR-88Ds. Additional surface and upper air data were assimilated in the 3DVAR case. A SM microphysics scheme was used in both cases. The 3DVAR experiment used the scheme detailed in Lin et al. (1983) (LIN) while the EnKF experiment contained a varied combination of Lin, WRF Single Moment 6 (WSM), and Schultz NEM ice microphysics schemes between its ensemble members. In both cases, the intercept parameter for rain was changed from 8.0 x 10^6 m^{-4} (default) to 8.0 x 10^5 m^{-4} following results from Snook and Xue (2008). The authors found that the default intercept parameter led to larger and stronger surface cold pools than reality and resulted in a poorer forecast. Additional investigations for this paper found that the lower intercept parameter provided the best results when compared to the observed reflectivity. The reader is directed to Schenkman et al. (2010a) and Snook et al. (2009) for more information regarding the details of their experiments.

The aforementioned 3DVAR and EnKF final analyses at 0200 UTC, as well as their grid size and spacing, were used as the initial state for SM and DM model forecasts. For the DM forecast, the number concentrations for each species have been diagnosed using their default intercept parameters and mixing ratios in the same way that Xue et al. (2010) produced the initial ensemble using the perturbed mixing ratios. Therefore, the initial condition for the DM forecast is consistent with the initial condition for the SM forecast. In total, four forecasts were made varying both the DA technique used for initializing the forecast and the type of microphysics scheme. The names of the experiments are self-explanatory with both the technique and microphysics scheme given: EnKF1, EnKF2, 3DVAR1, 3DVAR2. The same Lin scheme employed for the DA experiments was used for the SM forecasts. In addition, the intercept parameter for rain was set at 8.0 x 10^5 m^{-4} as was also done in the previous experiments. For the DM forecasts, Milbrandt and Yau's (2005a,b) (MY) scheme was used. In both cases, the shape parameter was set to 0 for all species resulting in a reverse exponential PSD.

To enable the direct comparison, the simulated observations are created using the PRD simulator based on the rigorous T-matrix method (Jung et al. 2010) on the same 3D grid where the observations are; horizontally on the model grid and vertically on radar elevation angles. In other words, the results from the model are presented as if they were observed by the radar.

3. RESULTS

3.1 Initial State Analyses

The model reflectivity of the final analyses for the EnKF and 3DVAR experiments is shown in Fig. 1. The final analysis from the EnKF fits the observed reflectivity rather well while the 3DVAR result is too intense. The high reflectivity in 3DVAR analysis can be partly attributed to the inability of the cloud analysis to handle the melting species. For example, the DA system increases rain water/hail mixing ratios to account for the enhance reflectivity due to meting hail. Fig. 2 contains subplots of the final analyses from the 3DVAR and EnKF experiments as well as observations from KCYR of the CASA network valid at the same time (0200 UTC). The figure includes Z as well as Z_{dr} and ρ_{hv}. Again, the EnKF final analysis corresponds better to the observations than the 3DVAR analysis with results are too high compared to observations. Additionally, the 3DVAR analysis has an area of lower Z_{dr} values matching the intense reflectivity due to the presence of hail. This same reduction in Z_{dr} does not occur in the observations. These results indicate the 3DVAR analysis has a larger hail and rain mixing ratio

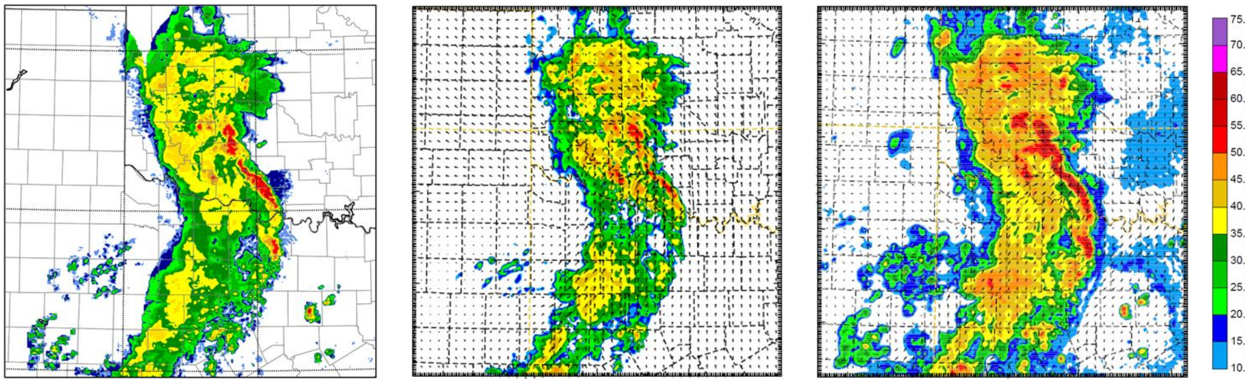

Figure 1: Reflectivity and horizontal wind vectors at 2km at 0200UTC for, from left to right, WSR-88d observation mosaic (no vectors), EnKF final analysis, and 3DVAR final analysis.

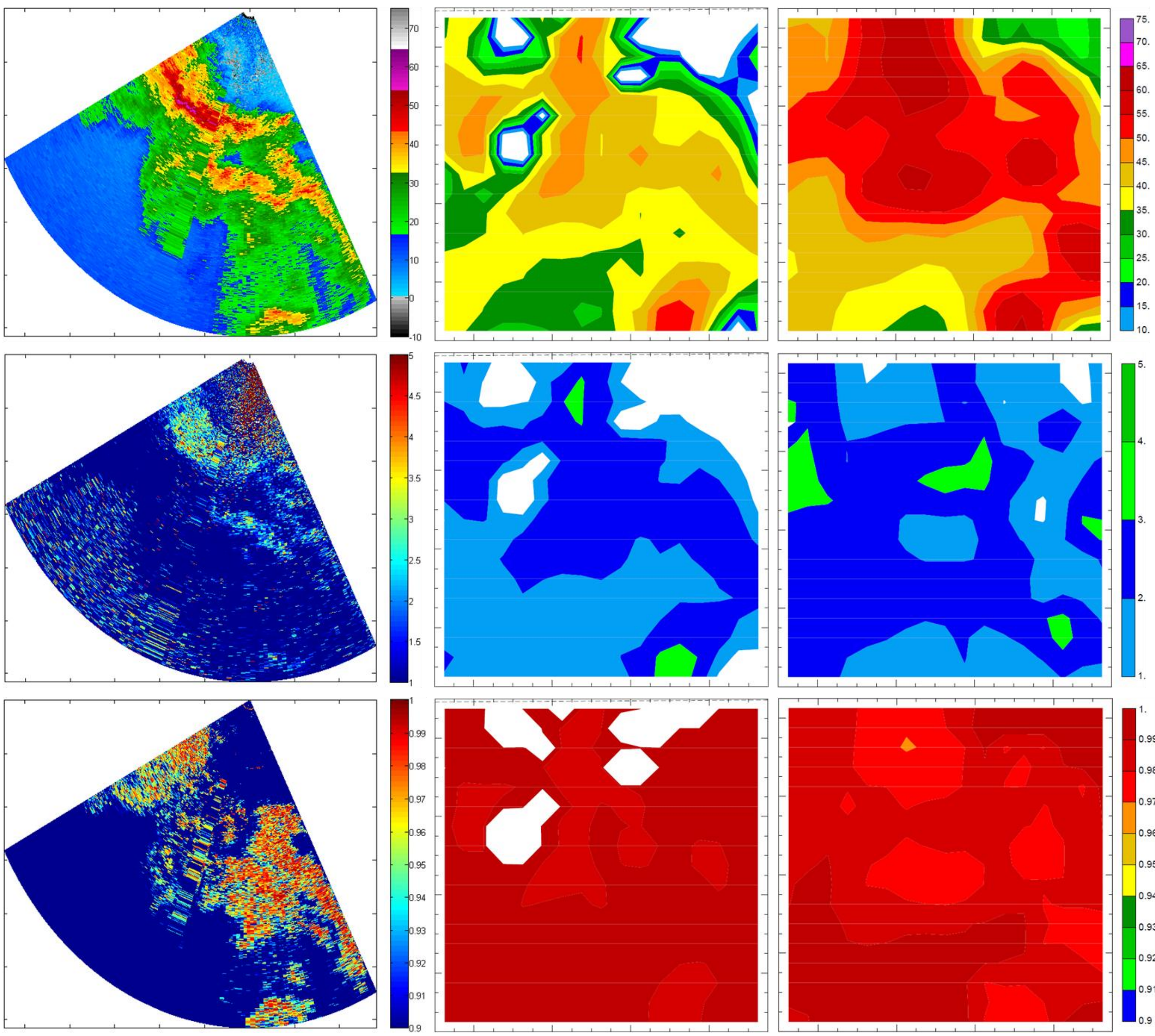

Figure 2: Reflectivity, Z_{dr}, and ρ_{hv} at 0200 UTC for, from left to right column, KCYR observations at 0.5 degree tilt and EnKF final analysis and 3DVAR final analysis at 700m.

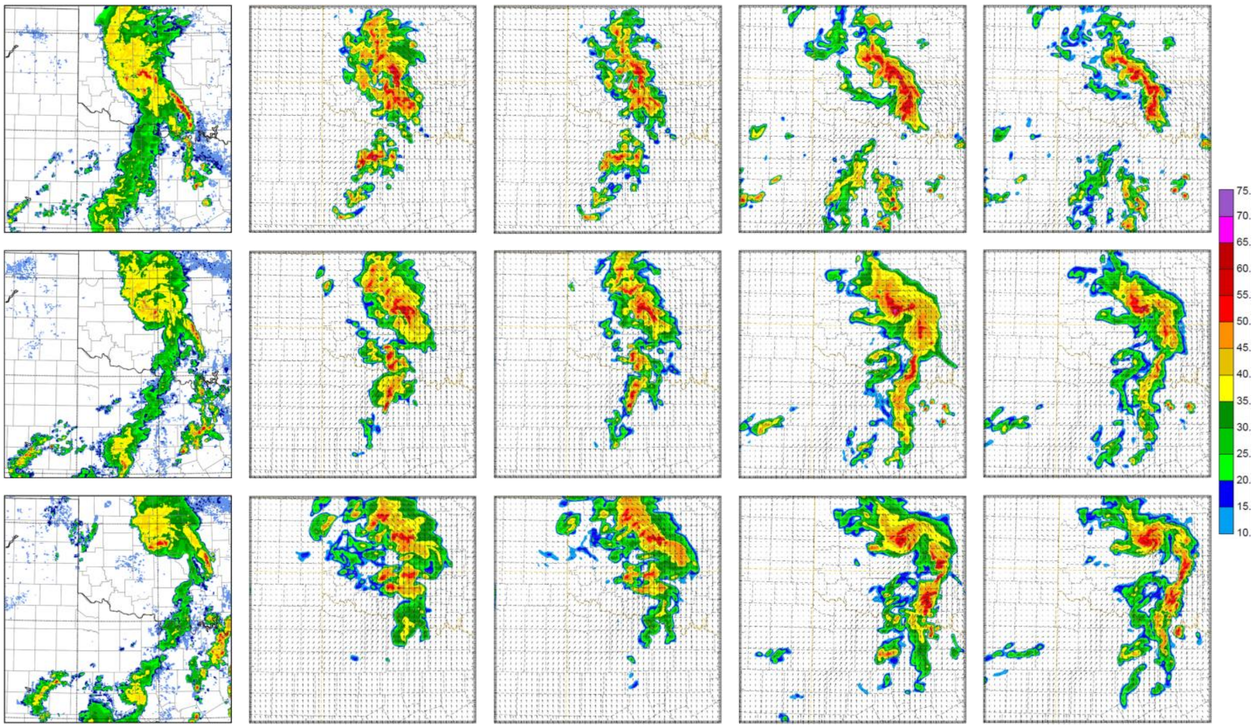

Figure 3: Reflectivity from WSR-88d mosaics at 0300, 0400, and 0500 UTC in first column from top to bottom as well as one, two, and three hour forecasts for EnKF1 (second column), EnKF2 (third column), 3DVAR1 (fourth column), and 3DVAR2 (fifth column) at 2km. Horizontal wind vectors included for forecast.

compared to both the EnKF analysis and observations. However, the EnKF analysis has some differences with the observations as well. The ρ_{hv} simulated from the EnKF final analysis is higher than observed. This bias is due to the simplified modeling of hydrometeors and non-meteorological effects being ignored and has been discussed in Jung et al. (2010). In general, it appears the EnKF analysis compares more favorably with observations than that of the 3DVAR.

3.2 Storm Forecast

Fig. 3 shows the results of one, two and three hour SM and DM forecasts initialized from the EnKF and 3DVAR 0200 UTC analyses as well as a mosaic of regional WSR-88D radar observations from the time of the forecast. The 3DVAR results are presented on the same domain as the EnKF results for comparison. In both cases, the system initially breaks down into smaller convective cells (not pictured). The end results of this are still noticeable in the one hour forecast. This same process was explained in Hu et al. (2006a) as the model microphysics adjusting to the dynamics of the system. By 0400 and 0500 UTC, the convection has become consistent again.

Few differences exist in the structural evolution of the system between the two initializations and microphysics schemes. Both poorly forecast the leading convective line seen on the southeastern side of the LEV in observations. They also over-forecast the intensity of the convection in the secondary line that trails southward into northern Texas. The reflectivity of the system is too intense in all cases, likely the result of a higher amount of rain in the SM case and the overproduction of hail in the DM case. These results imply there is little benefit in using a DM microphysics scheme over a SM scheme under these conditions. Specifically, it should be noted that the forecast cannot fully benefit from using the DM scheme in these experiments because the initial condition is produced using the SM analysis.

3.3 Forecast State

Fig. 4 contains two hour forecast results for both microphysics schemes and initializations but presented as they would be observed by KOUN at a 0.5 degree tilt. For the results using the SM scheme, the simulated polarimetric variable values match the changes in reflectivity intensity. For example, higher Z_{dr} corresponds to higher reflectivity. This is expected given the one to one relationship reliance on rain mixing ratio that dominates in the SM experiments. This doesn't apply to the DM results. Z_{dr} has lower values in regions corresponding to more intense reflectivity. These lower Z_{dr} values indicate the presence of hail, as previously mentioned. This applies to the lower ρ_{hv} values as well. However, the observations for this time still do not contain lower Z_{dr} or ρ_{hv} values. A side investigation using a fuzzy logic scheme with the polarimetric observations confirmed little hail presence.

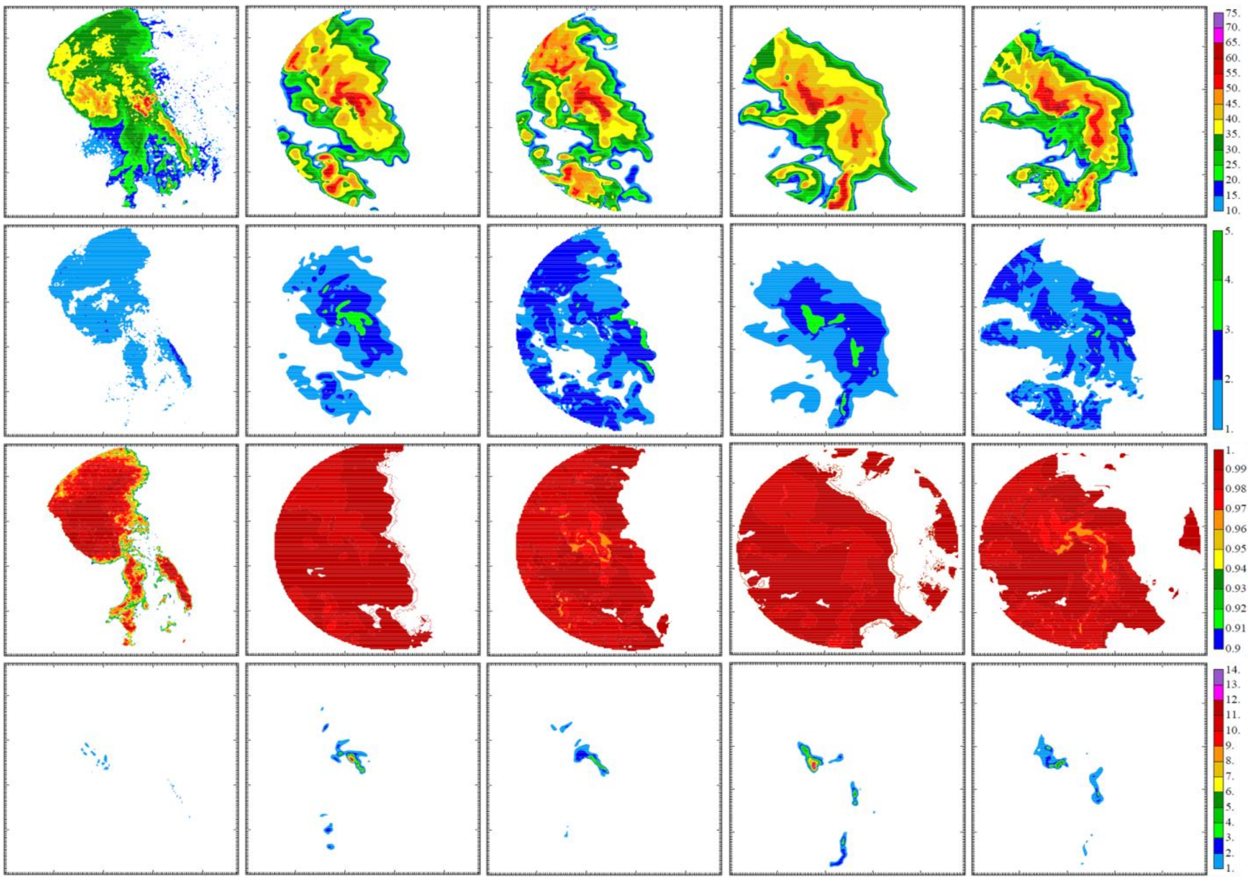

Figure 4: Z, Z_{dr}, K_{dp}, and ρ_{hv} observations at .5 degree tilt from KOUN at 0400 UTC from top to bottom in left column as well as two hour forecast results from EnKF1 (second column), EnKF2 (third column), 3DVAR1 (fourth column), and 3DVAR2 (fifth column).

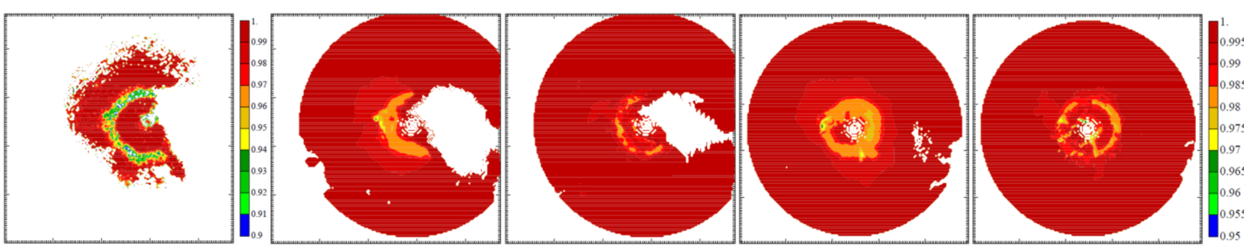

Figure 5: ρ_{hv} at 0400 UTC for, from left to right, KOUN observations and two hour forecasts for EnKF1, EnKF2, 3DVAR1, and 3DVAR2 at 4.0 degree tilt. Note the change in scale to emphasize the melting layer in the mode.

Despite the large amount of hail in the model, there were some noticeable improvements to the state estimates using the DM microphysics scheme. Some of the values where unrealistically large with the SM results compared to the DM, especially K_{dp}. K_{dp} is typically used as a measure of the rain water content in a convective storm. This indicates the DM scheme results in less extreme liquid water amounts in the model. Additionally, the size sorting of hydrometeors was apparent in the higher Z_{dr} values on the eastern side of the convection in both the model results and observations. These results suggest there is some benefit to using the DM scheme for state estimation. Overall, however, there is still a lot of room for improvement in storm forecast state.

One result captured by the PRD simulator and both microphysics schemes was the melting layer. Fig. 5 shows the simulated and observed ρ_{hv} at 0400 UTC at a 4.0 tilt, higher than the previous images. The lower ρ_{hv} values indicate the melting layer. Because the radar beam height increases with radial distance from the radar, the lower ρ_{hv} values form a ring around the radar where the beam reaches the melting layer height. This ring of lower values is also present in the KOUN

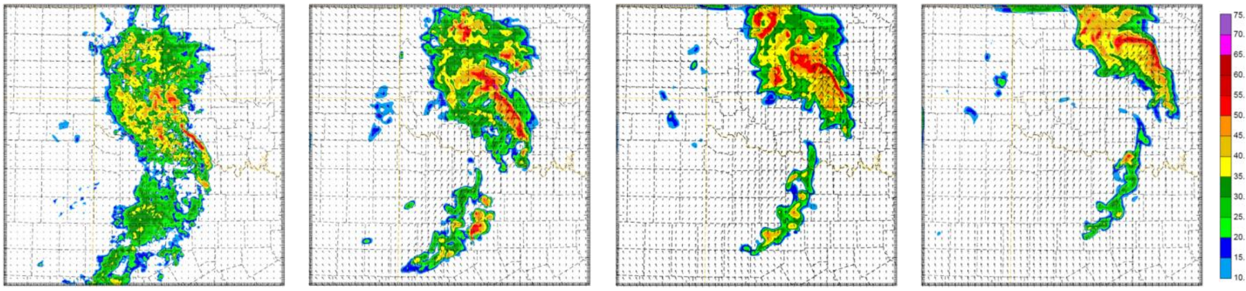

Figure 6: Reflectivity and horizontal wind vectors at 2km for, from left to right, EnKF MY DM final analysis and one, two, and three hour DM forecasts.

observations indicating the model has correctly forecast the location of the melting layer.

4. SUMMARY AND FUTURE WORK

The goal of this work was to investigate different model initializations and microphysics schemes to find what model conditions provide the best microphysical state estimates and forecast. The quality of state estimation is evaluated against polarimetric observations. The structure and intensity of simulated Z and Z_{dr} of the EnKF analysis fits the observations better than those of the 3DVAR analysis. However, the forecast differences found in the evolution of the system between the results using the two final analyses to initialize the model and the use of a multi-moment microphysics scheme were rather small. The DM scheme in both cases resulted in a slightly improved state forecast compared to the SM forecasts based on the polarimetric observations. More realistic polarimetric signatures were produced with improvements in size sorting and rainwater content. However, the overproduction of hail is still a concern. For this MCS case, the hail source and sink terms in the ARPS model may need to be turned off to prevent this.

The rather small improvement obtained using the DM microphysics scheme over the experiment using the SM scheme can largely be attributed the fact that the initial condition is not consistent with the DM microphysics. To fully benefit from the DM scheme, the state estimation is performed using the DM scheme during the analysis. An experiment using the EnKF with a DM MY scheme has yielded promising results (Fig. 6). The leading line fits the observed reflectivity better in the initial analysis and is also present in the forecast compared to these experiments. Additionally, the excess convection in the secondary line is much less prevalent. Since both the EnKF and 3DVAR experiments for this case used a SM microphysics scheme, the intercept parameter was first diagnosed after the system had already been given time to evolve. The fixed intercept parameter would have already affected the development of the system. Another investigation of microphysical state estimates involving the May 10, 2010 Norman, OK tornadic supercell is also underway. With more documented structural information and polarimetric signatures for the supercell case as well as more available observations, more rigorous evaluation of the microphysical state in the model against observations can be made.

ACKNOWLEDGMENTS This work was supported by NSF Grant AGS-0802888. The authors would like to thank the OU Supercomputing Center for Education and Research (OSCER) and the National Institute for Computational Sciences for the use of their supercomputers.

5. REFERENCES

Anderson, J. L., 2001: An ensemble adjustment Kalman filter for data assimilation. Mon. Wea. Rev., 129, 2884–2903.

Bishop, C. H., B. J. Etherton, and S. J. Majumdar, 2001: Adaptive sampling with the ensemble transform Kalman filter. Part I:Theoretical aspects. Mon. Wea. Rev., 129, 420–436.

Dawson, D. T., II, M. Xue, J. A. Milbrandt, M. K. Yau, and G. Zhang, 2007: Impact of multi-moment microphysics and model resolution on predicted cold pool and reflectivity intensity and structures in the Oklahoma tornadic supercell storms of 3 May 1999. 22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Pred., Salt Lake City, Utah, Amer. Meteor. Soc., CDROM 10B.2.

Gao, J.-D., M. Xue, K. Brewster, and K. K. Droegemeier, 2004: A three-dimensional variational data analysis method with recursive filter for Doppler radars. J. Atmos. Ocean. Tech., 21, 457-469

Houtekamer, P. L., and H. L. Mitchell, 1998: Data assimilation using an ensemble Kalman filter technique. Mon. Wea. Rev., 126, 796–811.

Hu, M., M. Xue, and Keith Brewster, 2006: 3DVAR and cloud analysis with WSR-88D Level-II data for the prediction of the Fort Worth tornadic thunderstorms. Part I: Cloud analysis and its impact. Mon. Wea. Rev., 134, 675-698.

Jung, Y., G. Zhang, and M. Xue, 2008: Assimilation of simulated polarimetric radar data for a convective storm using ensemble Kalman filter. Part I: Observation operators for reflectivity and polarimetric variables. Mon. Wea. Rev., 136, 2228–2245.

_____, Ming Xue, Guifu Zhang, 2010: Simulations of Polarimetric Radar Signatures of a Supercell Storm Using a Two-Moment Bulk Microphysics Scheme. J. Appl. Meteor. Climatol., 49, 146–163. doi: 10.1175/2009JAMC2178.1

Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. J. Climate Appl. Meteor., 22, 1065-1092.

Milbrandt, J. A., M. K. Yau, 2005: A Multimoment Bulk Microphysics Parameterization. Part I: Analysis of the Role of the Spectral Shape Parameter. J. Atmos. Sci., 62, 3051–3064.

_____, _____, 2005: A Multimoment Bulk Microphysics Parameterization. Part II: A Proposed Three-Moment Closure and Scheme Description. J. Atmos. Sci., 62, 3065–3081.

Morrison, H., J. A. Curry, V. I. Khvorostyanov, 2005: A New Double-Moment Microphysics Parameterization for Application in Cloud and Climate Models. Part I: Description. J. Atmos. Sci., 62, 1665–1677.

_____, G. Thompson, and V. Tatarskii, 2009: Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: Comparison of one- and two-moment schemes. Mon. Wea. Rev., 137:991–1007.

Schenkman, A., M. Xue, A. Shapiro, K. Brewster, and J. Gao, 2010: Impact of radar data assimilation on the analysis and prediction of the 8-9 May 2007 Oklahoma tornadic mesoscale convective system, Part I: Mesoscale features on a 2 km grid. Mon. Wea. Rev., Submitted.

Seifert, A. and K. D. Beheng, 2006a: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part 1: Model description. Meteor. Atmos. Phys., 92:45–66. doi:10.1007/s00703-005-0112-4.

Snook, N., and M. Xue, 2008: Effects of microphysical drop size distribution on tornadogenesis in supercell thunderstorms. Geophy. Res. Letters, 35, L24803, doi:10.1029/2008GL035866.

_____, _____, and Y. Jung, 2009: Ensemble Kalman Filter Data Assimilation and Probabilistic Forecasting for a Tornadic System using Operational S-band and CASA X-band Radar Data. Kyoto University – University of Oklahoma International Symposium on Radar and Modeling Studies of the Atmosphere, Kyoto, Japan, Po-21.

Tong, M. and M. Xue, 2005: Ensemble Kalman filter assimilation of Doppler radar data with a compressible nonhydrostatic model: OSSE Experiments. Mon. Wea. Rev., 133, 1789-1807.

Whitaker, J. S., and T. M. Hamill, 2002: Ensemble data assimilation without perturbed observations. Mon. Wea. Rev., 130, 1913–1924.

Xue, M., K. K. Droegemeier, and V. Wong, 2000: The Advanced Regional Prediction System (ARPS) - A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part I: Model dynamics and verification. Meteor. Atmos. Physics. 75, 161-193.

_____, _____, V. Wong, A. Shapiro, K. Brewster, F. Carr, D. Weber, Y. Liu, and D.-H. Wang, 2001: The Advanced Regional Prediction System (ARPS) - A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part II: Model physics and applications. Meteor. Atmos. Physics. 76, 143-165.

_____, Y. Jung, and G. Zhang, 2010: State estimation of convective storms with a two-moment microphysics scheme and an ensemble Kalman filter: Experiments with simulated radar data Q. J. Roy. Meteor. Soc, 136, 685-700.

_____, D.-H. Wang, J.-D. Gao, K. Brewster, and K. K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. Meteor. Atmos. Physics, 82, 139-170.

Zhang, G., J. Sun, and E. A. Brandes, 2006: Improving parameterization of rain microphysics with disdrometer and radar observations. J. Atmos. Sci., 63:1273–1290.