Final Report

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Project Title
Retrieving 4-dimensional atmospheric boundary layer structure from surface observations and profiles over a single station

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1. Introduction

Most routine measurements from climate study facilities, such as the Department of Energy's ARM SGP site, come from individual sites over a long period of time. While single-station data are very useful for many studies, it is challenging to obtain 3-dimensional spatial structures of atmospheric boundary layers that include prominent signatures of deep convection from these data. The principal objective of this project is to create realistic estimates of high-resolution (~ 1km × 1km horizontal grids) atmospheric boundary layer structure and the characteristics of precipitating convection. These characteristics include updraft and downdraft cumulus mass fluxes and cold pool properties over a region the size of a GCM grid column from analyses that assimilate surface mesonet observations of wind, temperature, and water vapor mixing ratio and available profiling data from single or multiple surface stations. The ultimate goal of the project is to enhance our understanding of the properties of mesoscale convective systems and also to improve their representation in analysis and numerical simulations.

During the proposed period (09/15/2011–09/14/2014) and the no-cost extension period (09/15/2014–09/14/2015), significant accomplishments have been achieved relating to the stated goals. Efforts have been extended to various research and applications. Results have been published in professional journals and presented in related science team meetings and conferences. These are summarized in the following sections. Specifically, Section 2 outlines major research accomplishments. Section 3 highlights some specific results and outcomes. Section 4 list students' thesis/dissertation, publications and presentations.

2. Summary of major accomplishments

To achieve the proposed tasks, research accomplishments have been made in the following areas using an advanced research version of the mesoscale community Weather Research and Forecasting (WRF) model and innovative data assimilation methods (e.g., the 4-dimensional variational data assimilation method, 3-dimensional data assimilation method, and ensemble Kalman filtering technique):

- *The value of multi-time, single-station observations in improving numerical analyses and simulations of mesoscale convective systems and their properties was evaluated.* Specifically, the impact of assimilating multi-time wind profiles from a single station on numerical simulations of a mesoscale convective system was examined with the 4-dimensional variational data assimilation method. It is found that the data assimilation improves the numerical simulation of the initiation and evolution of a mesoscale convective system, since the data assimilation enhances the representation of related mesoscale convective and environmental conditions. The quantitative precipitation forecasting (QPF) is also improved (Zhang and Pu 2011).

- *An effective surface data assimilation method was evaluated with the ensemble Kalman filter technique* (Pu et al. 2013). The impact of assimilating Oklahoma mesonet surface observations was examined. Results indicate that assimilating these observations improves the numerical simulation of mesoscale convective systems. Specifically, cold pool representation is enhanced by surface data assimilation.

- *Comprehensive numerical simulation and data assimilation studies for mesoscale convective systems observed during the Midlatitude Continental Convective Clouds Experiment (MC3E)*. Sensitivity experiments were performed with various WRF model physical parameterizations (such as PBL and microphysics schemes) at a cloud-permitting scale to investigate the WRF model's ability to represent cold pools during mesoscale convective processes. Results indicate that the WRF-simulated location, intensity, and structure of mesoscale convective systems are sensitive to the model's physical parameterization schemes. However, cold pools were very poorly represented in almost all numerical simulations. Only with the assimilation of surface observations can the uncertainties of cold pool properties be significantly reduced in analyses and forecasts. In addition, the impact of convection-induced cold pools on secondary convective initiation was studied (Pu and Wei 2015; Pu et al. 2015).

- *The significant role of land surface models in numerical simulations of mesoscale convective systems is identified* by examining the sensitivity of numerical simulations of MC3E mesoscale convective systems to the choice of land surface model (Pu 2015).

- *Significant progress has been made in evaluating the double-moment representation of warm rain and ice hydrometeors in bulk microphysical schemes.* The performance of double-moment microphysical schemes (e.g., the Morrison scheme) was compared with a partial double-moment (e.g., WDM6) and a single-moment (e.g., WSM6) scheme in a numerical simulation of a mesoscale convective system. The simulation results were validated by NEXRAD observations, surface mesonet data, and precipitation data products as well as a NEXRAD-derived cloud classification. In addition, the WRF model–produced hydrometeors were compared with the data collected by the University of North Dakota Citation flight during MC3E. Results indicate that although the Morrison scheme leads to better simulation of convective systems, it fails to reproduce hydrometeors that agree with the observations. *The overall results indicate that* cloud microphysics could still be a productive area of future research due to 1) the imperfection of microphysical schemes, and 2) uncertainties in the observations. (Pu and Lin 2015; Pu et al. 2015)

- *An effective cloud initialization scheme with NEXRAD radar observations was tested and examined.* This initialization scheme leads to reasonable cloud analysis and significant reduction of the spin-up problem during numerical simulations of mesoscale convective systems (Pu and Zhang 2015).

3. Highlights of research results and major findings

1) The impact of assimilating multi-time wind profiles on numerical simulations of a mesoscale convective system and quantitative precipitation forecasting

Research has been conducted to examine the ability of data assimilation techniques to retrieve 4-dimensional (both spatial and temporal) atmospheric boundary layer structures from multi-time profiling data at a single station with single-level surface mesonet observations. Specifically, multi-time wind profiles from a single station (near the SGP site) are assimilated into the mesoscale community Weather Research and Forecasting (WRF) model using its 4-dimensional variational data assimilation (4DVAR) system. The impact of data on the numerical simulations of a warm-season mesoscale convection system during IHOP_2002 is evaluated. Results indicate that the assimilation of high temporal and vertical resolution wind profiles has a significant influence on the numerical simulation of convective initiation and evolution. Not only the wind fields but also the structure of moisture fields associated with the convective system are improved. Data assimilation has also resulted in the more accurate prediction of the location and timing of convection initiations; as a consequence, the skill of quantitative precipitation forecasting is greatly enhanced (Figure 1).

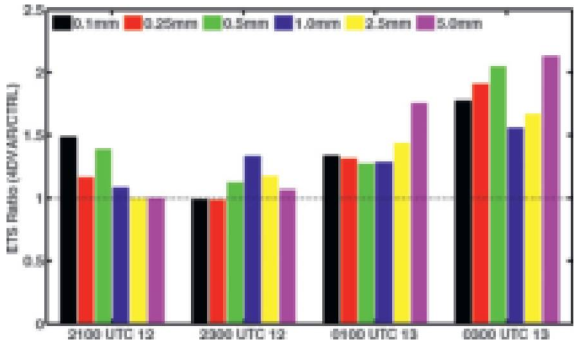

Figure 1. The ratio of equitable threat scores (ETS), defined as $R=ETS_{4DVAR}/ETS_{CTRL}$ for 1-h accumulated precipitation between CTRL (without assimilation of wind profiles) and 4DVAR (with assimilation of wind profiles) experiments with thresholds of 0.1, 0.25, 1.0, 2.5 and 5.0mm at 2100 UTC 12 June 2002, 2300 UTC 12 June 2002, 0100 UTC 13 June 2002, and 0300 UTC 13 June 2002. When the ETS ratio is greater than 1, the QPF skill is improved by 4DVAR.

2) Improving numerical simulations of mesoscale convective systems through assimilation of Oklahoma mesonet surface observations

Considering the comprehensive observations obtained during the field program for verification, numerical simulations were performed for five convective cases during the Midlatitude Continental Convective Clouds Experiment (MC3E) field campaign. Specifically, five time periods with convective systems evolved are identified over the Oklahoma-Kansas area: 1) 18 UCT 23 April to 00 UTC 26 April 2011; 2) 06 UTC 01 May to 00 UTC 03 May 2011; 3) 06 UTC 10 May to 06 UTC 12 May 2011; 4) 12 UTC 19 May to 12 UTC 21 May 2011; 5) 06 UTC 23 May to 12 UTC 25 May 2011.

High-resolution numerical simulations are conducted with the WRF model for these five periods. A multiple-level nested domain technique is used to achieve the cloud-permitting scale simulation. Specifically, the model domains are set up for 3 nested domains with horizontal resolutions at 12 km, 4 km and 1.33 km, respectively. The model initial and boundary conditions are derived from the NCEP North American Mesoscale model (NAM) analysis.

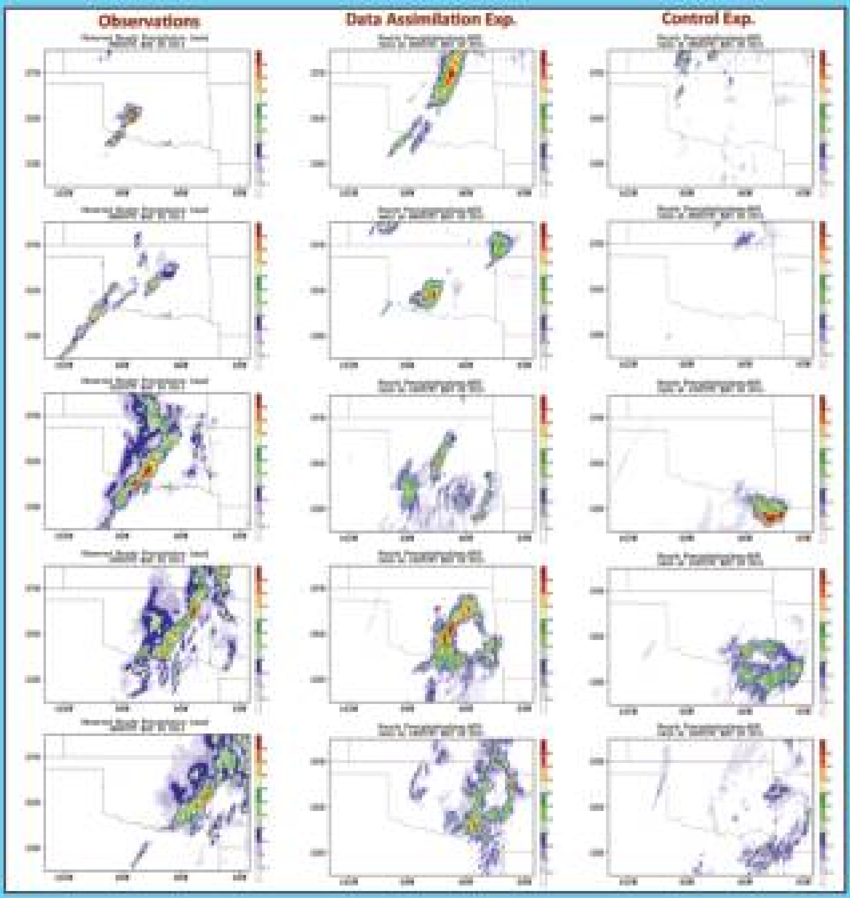

Figure 2. Hourly precipitation (unit: mm) at model domain 3 (1.33 km horizontal resolution), valid at 00 UTC (1st row), 06 UTC (2nd row), 12 UTC (3rd row), 15 UTC (4th Row), and 18 UTC (5th Row) 20 May 2011. The observations (left column) compared with numerical simulation results with (middle column) and without (right column) assimilation of surface mesonet observations

The impact of assimilating Oklahoma surface mesonet observations on the numerical simulation of mesoscale convective systems is examined. For a sample case, hourly surface mesonet observations (wind, temperature, pressure) are assimilated into the WRF model during 12 UTC to 15 UTC 19 May 2011. The forecast is then extended until 12 UTC 21 May 2011. Fig. 2 shows the significant impact of surface mesonet observations on the predictability of a convective system during 0000 UTC to 1800 UTC 20 May over the Oklahoma area. Specifically, without assimilation of surface mesonet observations (control exp.), the WRF forecast misses the development of the convective system. With the assimilation of surface mesonet data, the model gives a better prediction of the initiation and evolution of the convective system, with reasonable rainbands.

It is also found that assimilating Oklahoma mesonet data results in significant improvement in the numerical simulation of convective properties. Not only the time and location of the convective initiation but also the quantitative precipitation forecasting (QPF) are improved in the numerical simulation (e.g., Figure 3).

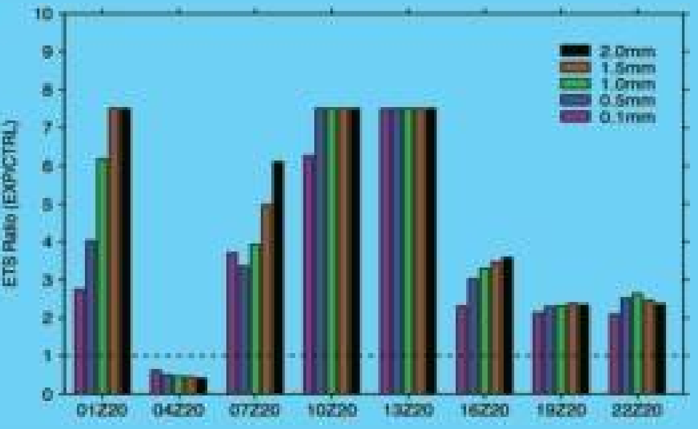

Figure 3. Ratio of equitable threat scores (ETS) for 1-h accumulated precipitation between CTRL and data assimilation (EXP) experiments from 0100 UTC 20 May to 2200 UTC 20 May 2001. When the ratio is greater than 1, the quantitative precipitation forecasting (QPF) skill in the simulation is improved by data assimilation

3) *Sensitivity of cold pool representation to WRF microphysics, PBL schemes, and data assimilation*

Cold pools generated by convective systems could be an important factor in triggering a secondary convective initiation. Thus, accurate numerical simulations of cold pools are not only essential in representing the evolution of convective properties but could also influence the prediction of secondary convective initiation. With this in mind, we first evaluated the WRF model's ability to represent cold pools in numerical simulations of MC3E convective systems.

We used the convective systems of 20 May 2011 as an example. Since numerical simulations of convective systems are sensitive to the choice of microphysics and planetary boundary layer (PBL) schemes in the WRF model, we checked the cold pool in several simulations with various configurations of WRF physical parameterizations (see Table 1 for details). Near-surface atmospheric conditions (e.g., 2-m temperature, surface pressure) from each numerical simulation were compared with mesonet observations.

Table 1. Configurations of WRF sensitivity experiments

Exp	Microphysics	Surface Layer Physics	PBL	Data Assimilation
CTRL	LIN	Monin-Obukhov (Eta)	MYJ	N
WSM6-MYJ	WSM6	Monin-Obukhov (Eta)	MYJ	N
LIN-YSU	LIN	Monin-Obukhov (MM5)	YSU	N
EXP	LIN	Monin-Obukhov (Eta)	MYJ	Y

In order to effectively validate a cold pool in numerical simulations, the surface cold pool should first be identified in the observations. We used Oklahoma mesonet observations over 16 years (1997–2012) to obtain the climate state on 20 May and the weekly average around 20 May 2011 for each station to eliminate the impact of diurnal variation on identifying the cold pool in the observations. Then the model-simulated temperature was compared with the observations to verify whether or not the model simulated the cold pool.

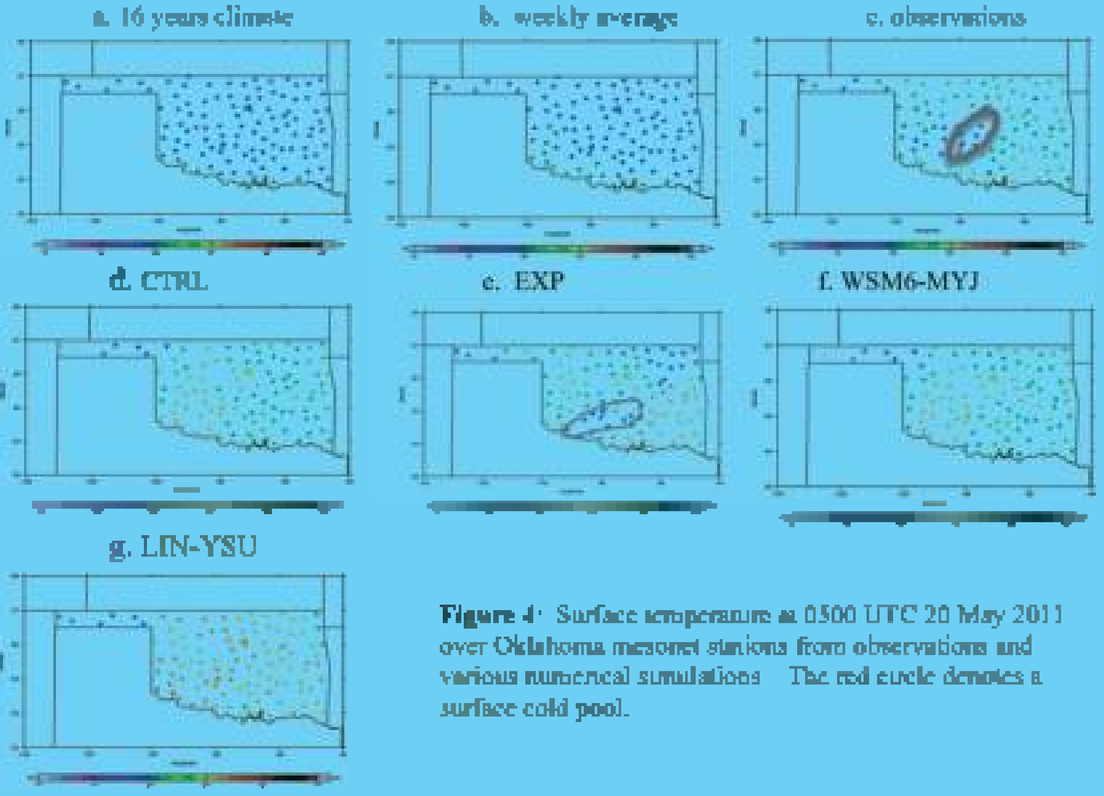
a. 16 years climate
b. weekly average
c. observations
d. CTRL
e. EXP
f. WSM6-MYJ
g. LIN-YSU

Figure 4: Surface temperature at 0500 UTC 20 May 2011 over Oklahoma mesonet stations from observations and various numerical simulations. The red circle denotes a surface cold pool.

It is found that a cold pool occurred around 0400–0600 UTC 20 May 2011. Numerical results reveal that the WRF simulation of surface temperature was sensitive to physical parameterization options (microphysics and PBL). However, **none of these numerical simulations predicted the cold pool. Only when surface mesonet data were assimilated in the first few hours of the simulations could the WRF model produce a reasonable surface cold pool** (Figures 4 and 5).

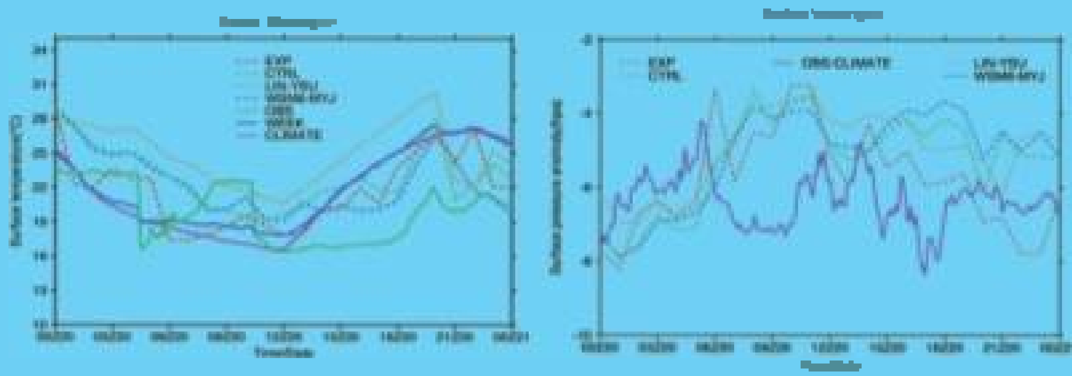

Figure 5: The diurnal variation of surface temperature (left) and pressure (right) between 0000 UTC 20 May and 0000 UTC 21 May 2011 at Washington Station, OK. Observations show a cold pool occurring at 04-06 UTC 20 May. Surface temperature and pressure forecasts are sensitive to the choice of model physical parameterization scheme. However, only the experiment with data assimilation captured the cold pool event.

According to Weiss and Bluestein (2002), interactions among cold fronts, drylines, and cold pools characterize a convective initiation (see conceptual model in Figure 6). We found that the convective initiation that occurred at 1800 UTC 20 May 2011 could be explained by this conceptual model (Figure 7). We also found that only with data assimilation could the WRF simulation capture the surface cold pool and accurately predict the secondary convective initiation near the observed time. Detailed cold pool properties and their associated downdrafts/updrafts are under diagnosis.

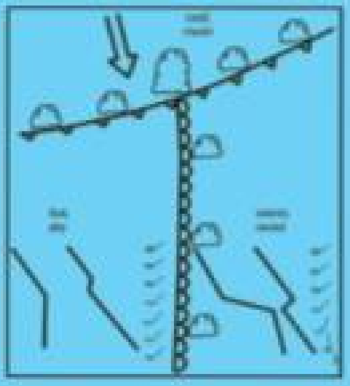

Figure 6. Conceptual model of cold front, dryline, and cold pool interactions. [Weiss and Bluestein (2002)]

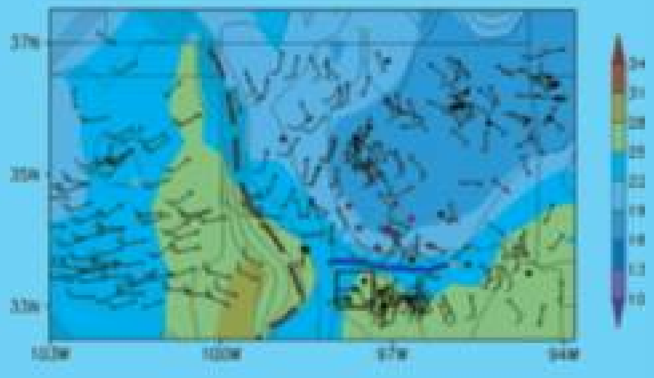

Figure 7. Surface weather map at 1800 UTC 20 May 2011. Wind barbs, temperature (shaded), relative humidity (contours). Red dots denote the cold pool. The thick blue line marks the cold front. The purple dashed line represents the dryline. The small black box indicates the area of convective initiation.

4) The role of land surface processes in the interaction between surface cold pools and mesoscale convective systems

The interaction between surface cold pools and mesoscale convective systems is investigated. Specifically, we examine the properties of surface cold pools that influence the evolution and sustainability of MCSs. High-resolution mesoscale numerical simulations (at ~ 1 km) are performed using the Weather Research and Forecasting (WRF) model with a major MC3E case

(23-24 May 2011). The sensitivity of numerical simulations of MCSs to land surface schemes is evaluated. It is found that accurate numerical simulations of MCSs and surface cold pools are sensitive to land-surface processes. For instance, Figure 8 compares composite radar reflectivity from NEXRAD radar and WRF simulations with NOAH and RUC land surface models during 21 UTC 23 May to 03 UTC 24 May. The figure shows that numerical simulations of the mesoscale convective system are sensitive to the choice of land surface scheme, indicating that land surface processes play a significant role in convective system development and evolution. In addition, the use of two different land surface models results in different structure and intensity of surface cold pools.

Further diagnoses of the model results indicate that the sustainability of a surface cold pool-associated outflow boundary is a major mechanism that determines the maintenance and development of multi-cell mesoscale convective systems. Surface heat and moisture fluxes are strongly associated with the sustainability of the convection and outflow boundary.

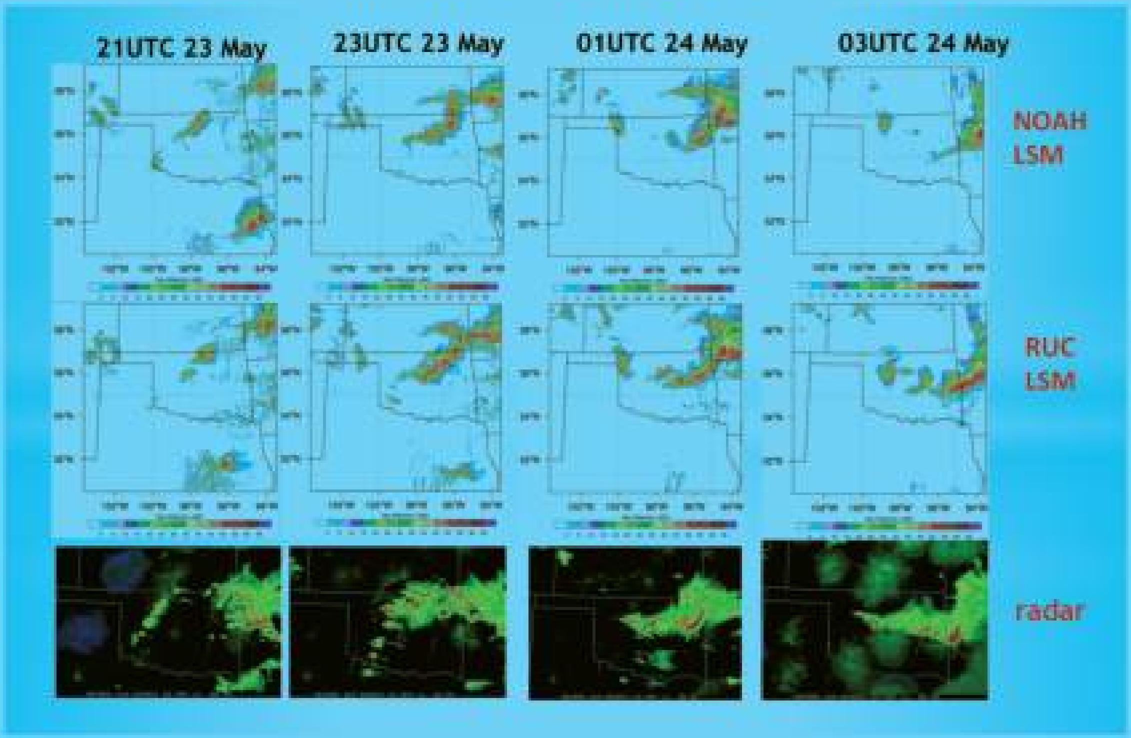

Figure 8: Composite radar reflectivity from NEXRAD radar (bottom row), WRF simulation with NOAH land surface model (top row) and with RUC land surface model (middle row) during 21 UTC 23 May to 03 UTC 24 May. The figure shows that numerical simulations of the mesoscale convective system are sensitive to the choice of land surface scheme, indicating that land surface processes play a role in convective system development and evolution.

3) Evaluation of the double-moment representation of warm rain and ice hydrometeors in bulk microphysical schemes

a. Sensitivity of numerical simulations of a mesoscale convective system to different moment representations of warm-rain and ice hydrometeors in bulk microphysical parameterization

The influence of different moment representations of warm-rain and ice hydrometeors in bulk microphysical schemes on the numerical simulations of a mesoscale convective system (MCS, 23-24 May 2011) over the southern Great Plains has been investigated using the WRF model. It is found that the simulated structure, life cycle, cloud coverage, and precipitation of the convective system as well as its associated cold pools are sensitive to three selected microphysical schemes, namely, the WRF single-moment 6-class (WSM6), WRF double-moment 6-class (WDM6, with the double-moment treatment of warm-rain only), and Morrison double-moment (MORR, with the double-moment representation of both warm-rain and ice) schemes. Compared with observations, the WRF simulation with WDM6 can produce the structure and length of the MCS very well, while WSM6 produces a less organized convection structure with a short lifetime. Both simulations heavily underestimate the precipitation amount, the height of the radar echo top, and stratiform cloud fractions. With MORR, the model performs well in predicting the lifetime, cloud coverage, echo top, and precipitation amount of the convection.

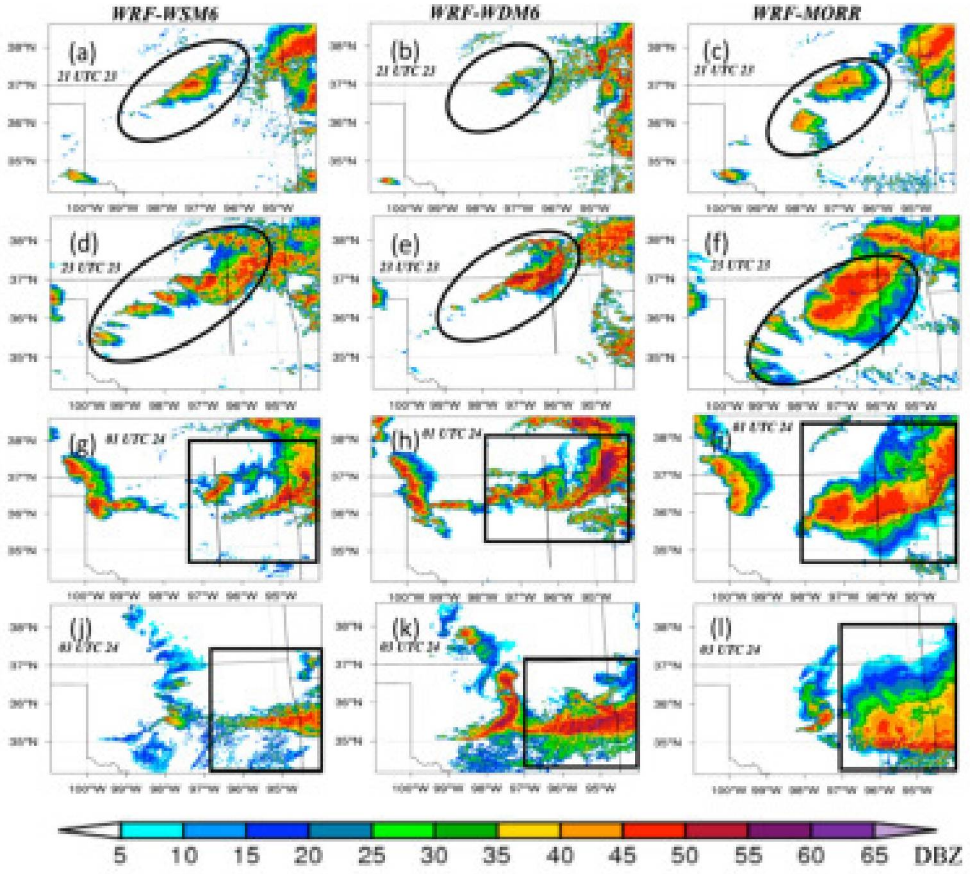

Figure 9. Simulated composite radar reflectivity (unit: dBZ) at (a, b, c) 2100 UTC 23 May 2011; (d, e, f) 2300 UTC 24 May 2011; (g, h, i) 0100 UTC 24 May 2011; and (j, k, l) 0400 UTC 24 May 2011, from (a, d, g, j) WRF-WSM6; (b, e, h, k) WRF-WDM6; and (c, f, i, l) WRF-MORR.

Figures 9 shows the simulation results, as revealed by composite radar reflectivity. In order to validate the model-simulated cloud properties, a radar reflectivity–based cloud classification algorithm is developed following the previous work of Steiner et al. (1995) and Feng et al. (2011). This algorithm classifies the convective system into a convective core (CC), stratiform rain (SR), non-precipitating transitional anvil cloud (ACtrans), and anvil cloud (AC) from NEXRAD radar reflectivity observations (Figure 10). Figures 9 and 10 suggest that the double-moment representation of warm rain (WDM6) helps the model produce a better forecast of the MCS in terms of cloud coverage and components, compared with the forecast from the experiment with a single scheme (WSM6). Moreover, further evaluations (see details in Lin 2014) indicate that with a full double-moment scheme (MORR), the model produces the best simulations with the proper convection life cycle and quantitative precipitation forecasting (QPF). Since the major difference between the MORR and WDM6 schemes is the representation of ice species, the importance of including double-moment representation of ice hydrometeors is evident.

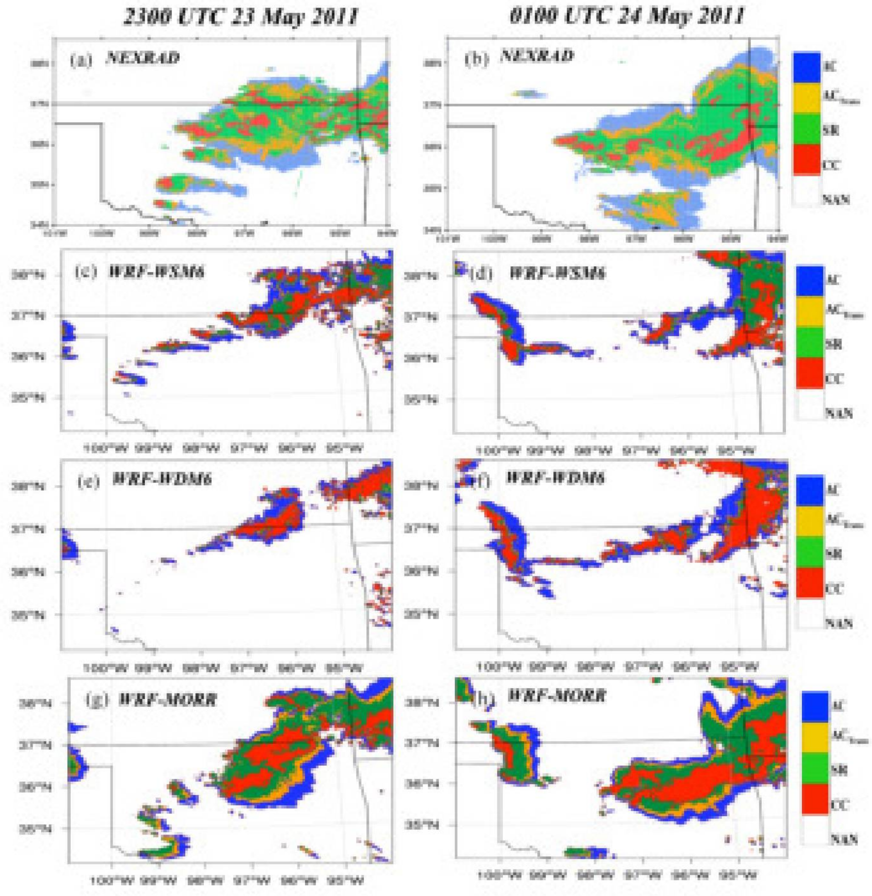

Figure 10. Classified components of the convective system: convective core (CC), stratiform (SR) region, transitional anvil clouds (AC$_{\mathrm{trans}}$) and anvil clouds (AC), following the method of Feng et al. (2011), from (a, b) NEXRAD radar observations and WRF simulations (c, d: WSM6; e, f: WDM6; and g, h: MORR) at (a, c, e, g) 2300 UTC 23 May 2011 and (b, d, f, h) 0100 UTC 24 May 2011.

Overall results demonstrate the importance of including double-moment representation of both warm-rain and ice hydrometeors, as it has a strong influence on convective cloud properties through diabatic heating/cooling rates, which determine hydrometeor drag and cold pool characteristics.

Additional experiments are performed to examine the role of ice hydrometeors in numerical simulations of the mesoscale convective system. Results indicate that replacing graupel with hail in the Morrison microphysical scheme improves the prediction of the convective structure, especially in the convective core region (See Figure 11, also compared with Figure 9).

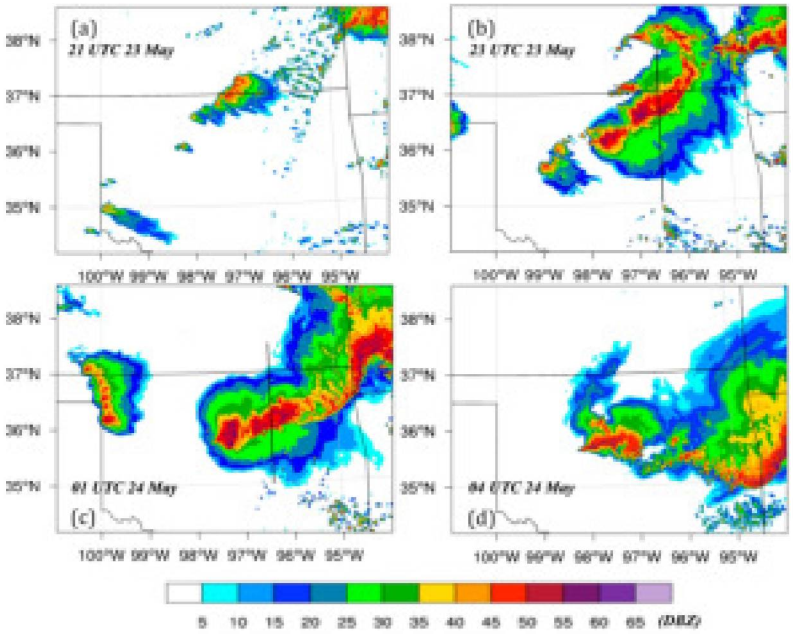

Figure 11. Composite radar reflectivity (unit: dBZ) from the simulation with hail in the Morrison scheme at (a) 2100 UTC 23 May 2011, (b) 2300 UTC 23 May 2011, (c) 0100 UTC 24 May 2011, and (d) 0400 UTC 24 May 2011.

b. Comparison between WRF numerical simulations and UND-Citation data during MC3E

Based on the simulation results above, the WRF-simulated microphysical properties of ice water content and total ice particle number concentration are validated using the UND-Citation aircraft observations that are available from 2100 UTC 23 to 0030 UTC 24 May 2011. The results suggest that double-moment representation of ice hydrometeors in the Morrison microphysical scheme helps the WRF model produce a better forecast of the mesoscale convective system but does not seem to produce realistic ice properties. While the simulation with the Morrison scheme may produce reasonable ice water content (IWC) when compared with the 2DC and HVPS data (Figure 12), there are clear uncertainties in the IWC datasets since large discrepancies are found in IWC measurements from the Nevzorov probe and 2DC and HVPS probes (Figure 13). The total ice number concentrations produced by the model are different from the observations.

Overall, the WRF-simulated ice hydrometeors with all three schemes do not agree well with the observations. The reasons for the disagreements may be, but are not limited to, the following: 1) the model did not reproduce convection structures exactly; 2) Errors in aircraft measurements play an important role; 3) The aircraft data are too sparse to compare with the model, as the aircraft sampled only one point at each specific time. More accurate and denser observations are needed in order to make a more effective comparison. Nevertheless, results from this study suggest that the uncertainty in microphysical schemes could be a productive area of future research from the perspective of both model improvements and observations.

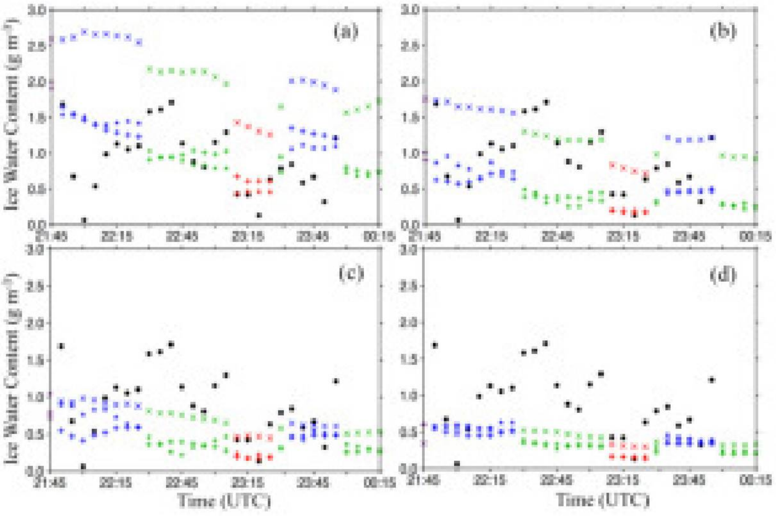

Figure 12. Time series of the averaged ice water content from observations by 2DC and HVPS probes (black dots) and simulations over various convective components (a: over CC region; b: over SR region; c: over ACtrans region; and d: over AC region) from different experiments: WRF-WSM6 ("+"), WRF-WDM6 ("*"), WRF-MORR ("x") at the nearest model levels: purple: 29th level; blue: 30th level; green: 31st level; and red: 32nd level.

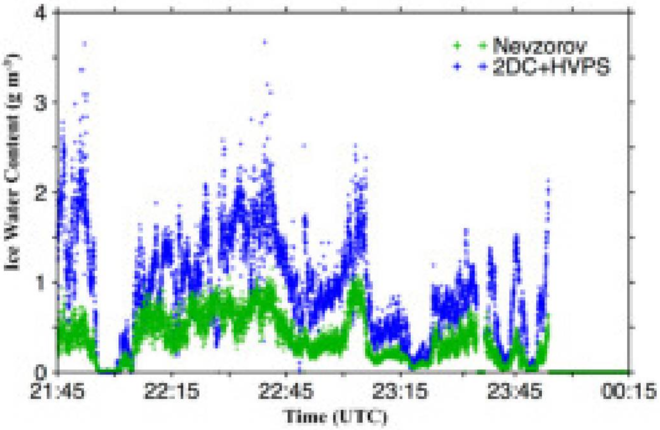

Figure 13. Time series of ice water content observed by 2DC and HVPS probes (blue dots) and by Nevzorov probe (green dots). The time interval is one second for both datasets.

6) An effective cloud initialization scheme with NEXRAD observations

Accurate numerical prediction of mesoscale convective systems (MCSs) is of great importance, yet it remains a challenging problem. Many poor MCS forecasts can be attributed to errors in initial conditions. Specifically, cloud initialization is not included in many data assimilation systems. Thus, the representation of clouds in numerical models relies on the spin-up of the cumulus and microphysical processes.

In order to investigate the impacts of cloud initialization on numerical simulations of MCSs at a cloud-permitting scale, the NCEP Gridpoint Statistical Interpolation (GSI) data assimilation system and its cloud analysis package were tested and improved. The NEXRAD observations were assimilated into the WRF model. First, radar reflectivity observations were assimilated with the GSI cloud analysis package to derive the initial cloud analysis of hydrometeors. The subsequent forecasts indicated that the cloud initialization reduced the model spin-up effects and thus improved the simulations of convective systems. Cloud analysis results were sensitive to the choice of method for hydrometer retrieval and cloud temperature analysis. In addition, radar radial velocities were also assimilated, in conjunction with cloud initialization, to obtain a realistic local dynamical field. The impacts of assimilation of NEXRAD observations, especially cloud initialization, are evaluated in detail. Two cases during May 2011 were used for the study. Results were recently presented at the AMS 16th Conference in Mesoscale Processes and 37th Conference on Radar Meteorology.

4. List of publications/presentations

1) Graduate students' thesis and dissertation (2)

1. Lin, C., 2014: *Evaluation of double-moment representation of warm-rain and Ice hydrometeors in bulk microphysical parameterization*. M.S. Thesis, Department of Atmospheric Sciences, University of Utah, 111pp.
   (Fully supported by this project)

2. Wei, L., 2013: Numerical simulations and data assimilation for mesoscale high-impact weather systems. Ph.D. dissertation, College of Atmospheric Sciences, Lanzhou University, China. 160pp.
   (Partially supported by this project through a visiting scientist program)

2) Journal papers (7)

1. Zhang L., and Z. Pu, 2011: Four-dimensional assimilation of multi-time wind profiles over a single station and numerical simulation of a mesoscale convective system observed during IHOP_2002 *Mon. Wea. Rev.*, **139,** 3369-3388

2. Pu, Z., H. Zhang, and J. A. Anderson, 2013: Ensemble Kalman filter assimilation of near-surface observations over complex terrain: Comparison with 3DVAR for short-range forecasts. *Tellus A,* **65**,19620

3. Pu, Z. and C. Lin, 2015: Evaluation of double-moment representation of ice hydrometeors in bulk microphysical parameterization: Comparison between WRF numerical simulations and UND-Citation data during MC3E. *Geoscience Letter*, (conditionally accepted)

4. Pu, Z. and C. Lin, X. Dong and S. Krueger, 2015: Sensitivity of numerical simulations of a mesoscale convective system to different moment representations of warm-rain and ice hydrometeors in bulk microphysical parameterization. *Journal of Advances in Modeling Earth Systems.* (Under review)

5. Pu, Z. and L. Wei, 2015: The impact of assimilation of surface mesonet observations on numerical simulations of a mesosclae convective system during MC3E. *Mon. Wea. Rev.* (To be submit)

6. Pu, Z., 2015: The role of land surface model in the interaction between cold pool and mesoscale convective systems. (Under preparation)

7. Pu, Z., L. Zhang, 2015: Assimilation of NEXRAD data to improve numerical simulations of mesoscale convective systems with cloud initialization. (Under preparation)

3) Conference, Science Team Meeting and Working Group Meeting Presentations (15)

1. Pu, Z. and L. Zhang, 2015, Assimilation of NEXRAD data to improve numerical simulations of mesoscale convective systems with cloud initialization. *AMS 37th Conference on Radar Meteorology.* September 14 -18, 2015, Norman, OK.

2. Pu, Z., C. Lin, X. Dong and S. Krueger, 2015, Sensitivity of numerical simulations of a mesoscale convective system to double-moment representation of hydrometeors in bulk microphysical parameterization. *AMS 16th Conference on Mesoscale Processes.* August 2-6, 2015, Boston, MA

3. Pu, Z. and L. Zhang, 2015, Assimilation of NEXRAD data to improve numerical simulations of mesoscale convective systems with cloud initialization. *AMS 16th Conference on Mesoscale Processes.* August 2-6, 2015, Boston, MA

4. Pu, Z. and C. Lin, 2015: Evaluation of Double-moment Representation of Warm-rain and Ice Hydrometeors in Bulk Microphysical Parameterization with Numerical Simulations and UND-Citation Aircraft Observations During MC3E. *DOE Atmospheric System Research Science Team Meeting.* March 16-20, 2015, Vienna, VA.

5. Pu, Z. and C. Lin, 2014: Interactions Between Surface Cold Pools and Mesoscale Convective Systems: Sensitivity to Land Surface Processes and Initial Conditions. *DOE Atmospheric System Research Science Team Meeting.* March 10-13, 2014, Potomac, MD.

6. Lin, C. and Z. Pu, 2014: Evaluation of Microphysical Schemes with Radar Data and High-resolution Numerical Simulations of MC3E Mesoscale Deep Convective Systems. *DOE Atmospheric System Research Science Team Meeting.* March 10-13, 2014, Potomac, MD.

7. Pu, Z. and C. Lin, 2013: Interaction Between Surface Cold Pool and Mesoscale Convection Systems: Numerical Simulations with MC3E Cases. *DOE ASR Fall working group meeting,* November 4-8, Washington, D.C.

8. Pu, Z., C. Lin and S. Krueger, 2013: Characteristics of the atmospheric boundary-layer structure and cloud properties for precipitating convection with data assimilation. *DOE Atmospheric System Research Science Team Meeting.* March 18-21, 2013, Potomac, MD.

9. Pu, Z., C, Lin, S. Xie and X. Dong, 2013: High-resolution analysis and simulation of convective systems during MC3E with data assimilation and comparison with radar and large-scale forcing data. MC3E session, *DOE Atmospheric System Research Science Team Meeting*. March 18-21, 2013, Potomac, MD.

10. Neumann, A., M. Poellot, Z. Pu, D. Delene, M. Askelson, 2013: Analysis of a parallel stratiform mesoscale convective system during the Midlatitude Continental Convective Clouds Experiment. *DOE Atmospheric System Research Science Team Meeting*. March 18, 2013, Potomac, MD.

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