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Optimal Utilization and Impact of Water Vapor and Other High Resolution Observations in Storm-Scale QPF

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1 Introduction

According to the original proposal, this project is to perform moisture sensitivity and data assimilation studies with focus on the storm scale and quantitative precipitation. The project involves the following areas: 1) Develop and apply variational techniques for the analysis and assimilation of water and related diabatic fields; 2) Study the impact of high-resolution observations of water vapor and hydrometeor content on the forecasting of convective storm morphology and precipitation; 3) Develop and evaluate techniques for estimating error characteristics of numerical forecasts at the convective scale. 4) Apply single Doppler velocity and thermodynamic retrieval algorithms to mobile radar data collected during IHOP; 5) Provide real-time, high-resolution (2-3 km) analysis and forecasts to assist IHOP field operations. Significant progress has been made in the first 2 years of the project, despite the initial delay in recruiting new graduate students and post-doctoral scientists, primarily due to timing of the grant start date. Accomplishments during 2003 are summarized below.

2 Publications and Other Research Accomplishments

During 2003, 13 referreed papers were published or submitted and 10 conference preprints were submitted by the project PIs, scientists and students, under complete or partial support of this project. Key results from some of these papers are briefly summarized in the following.

2.1 Phase-correction data assimilation technique and ARPS model and data assimilation system development

In 2003, K. Brewster published two papers (Brewster 2003a,b) on a variational phase-correcting technique for storm-scale NWP. It was found that knowledge of phase errors determined from one variable in the dynamic system could be effectively used to update the system, correct error in all the fields and improve the forward forecast of the system state. The technique was successfully applied to a three dimensional thunderstorm simulation.

Xue et al (2003) documents the latest developments within the Advanced Regional Prediction System and presents results of applying high-frequency intermittent data assimilation that includes radar data to the prediction of a tornadic thunderstorm case. A new 3DVAR system developed for storm-scale data assimilation is also described together with an example analysis.

2.2 Development of velocity analysis techniques from Doppler radar data

In Gao et al (2003), the so-called Gradient Velocity Azimuth Display (GVAD) and Gradient Volume Velocity Processing (GVVP) methods are developed for estimating the aerial mean vertical wind profile over a Doppler radar. The methods are much less susceptible to contamination by velocity ambiguities and noise in the data. The methods are tested first on idealized data to examine their sensitivity to different types of errors in radial velocity. It is found that the mean wind profiles retrieved using both methods are not sensitive to random errors in the radial velocities, even with large amplitude. Tests of GVAD on a set of WSR-88D data collected during the 3 May, 1999 tornado outbreak show that it is capable of obtaining accurate wind profiles (Fig. 1 and Fig. 2) even when the raw data contain large errors caused by velocity ambiguities and random noise.

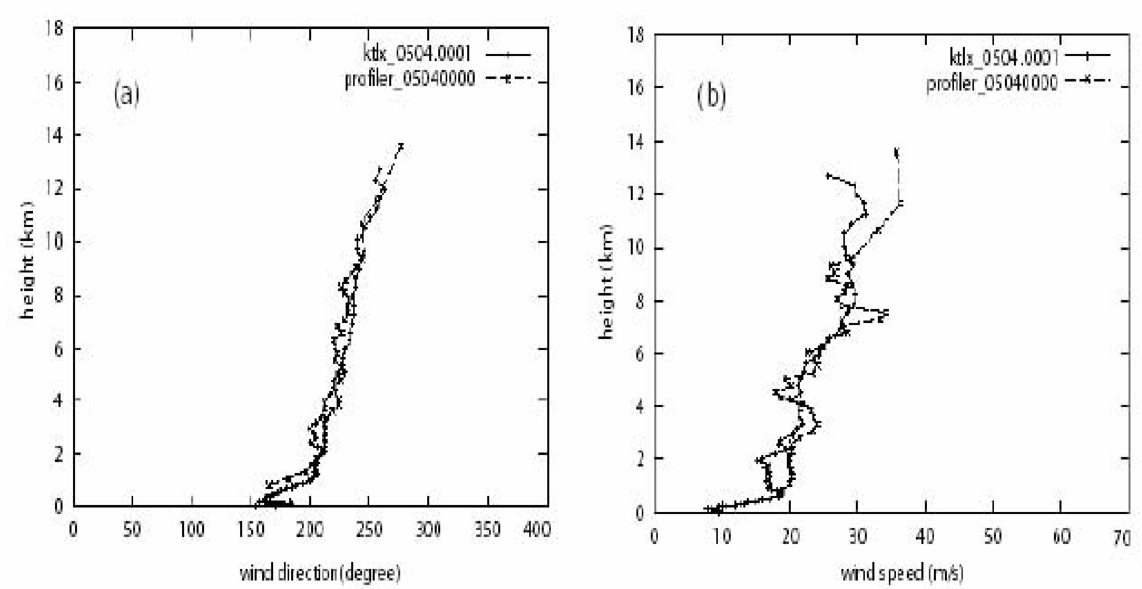

Fig. 1. Comparison of wind profile for 00 Z of 4 May 1999 from wind profiler in Purcell, Oklahoma and that retrieved from KTLX radar using GVAD method for (a) wind direction and (b) wind speed.

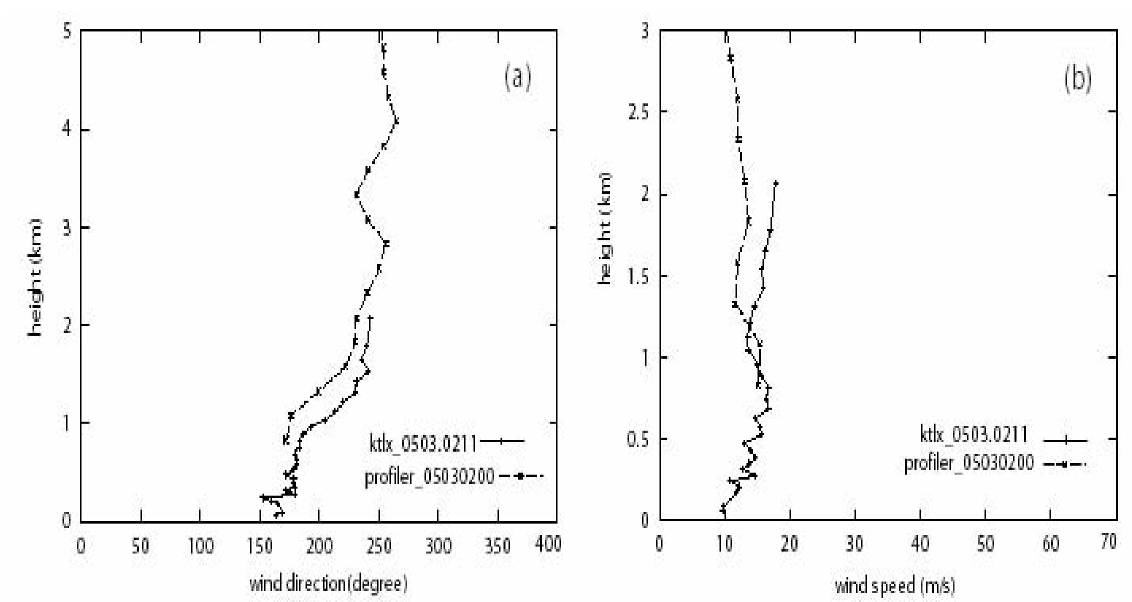

Fig. 2. Same as Fig. 1, but for 02 Z of 3 May 1999 when the radar operated in clear air mode.

2.3 Development of single-Doppler velocity retrieval techniques

In Shapiro et al (2003), an approximate (rapid-scan) dynamical model for single-Doppler retrieval of the vector wind field is investigated. This approximate model is based on the Lagrangian form of the radial component of the equation of motion, and is valid for retrieval time windows that are smaller than the effective time scale of the flow but larger than the product of the effective time scale and (nondimensional) relative error in the radial wind observations. The retrieval was tested with data gathered by two Doppler-On-Wheels mobile Doppler research radars of a cold front on 16 June 2000 near Grandfield, Oklahoma. Experiments focused on the impact of time resolution and the utility of a background constraint obtained from a VVP-like estimate of the wind field. Retrieval error statistics were substantially improved as the volume scan intervals decreased from 5 minutes (characterizing the current WSR-88D scan rates) down to 1 minute. Use of the background constraint also improved the results, with superior results obtained in the high temporal resolution experiments when the background constraint was selectively imposed.

Gao et al (2003b) describes a three-dimensional variational analysis scheme for retrieving three-dimensional winds from single Doppler observations that uses a simple conservation equation as a dynamic constraint in the cost function. The cost function also includes the usual observation and background terms, as well as smoothness, and mass continuity constraints. The method was tested against a simulated data set as well as with real radar observations of supercell storms. In both cases, detailed structures of the storms were well retrieved in comparison with the model truth or dual Doppler analysis.

2.4 Development and testing of 3DVAR systems for Doppler radar assimilation

In Gao et al (2003c), a new method of dual-Doppler radar wind analysis based on a 3DVAR approach is described. The 3DVAR system includes the mass continuity equation as a weak constraint and the background error covariance matrix is modeled using a recursive filter. The minimization problem is preconditioned by the square root of the background error covariance matrix. The method is applied to Doppler radar observations of a supercell storm and the analysis results are compared to a conceptual model and previous research. It is shown that the horizontal circulations, both within and around the storms, as well as the strong updraft and the associated downdraft, are well-analyzed. Because no explicit integration of the anelastic mass continuity equation is involved, error accumulation associated with such integration is avoided. As a result, the method is less sensitive to the vertical boundary uncertainties. An example of the wind analysis using the system is given in Fig. 3.

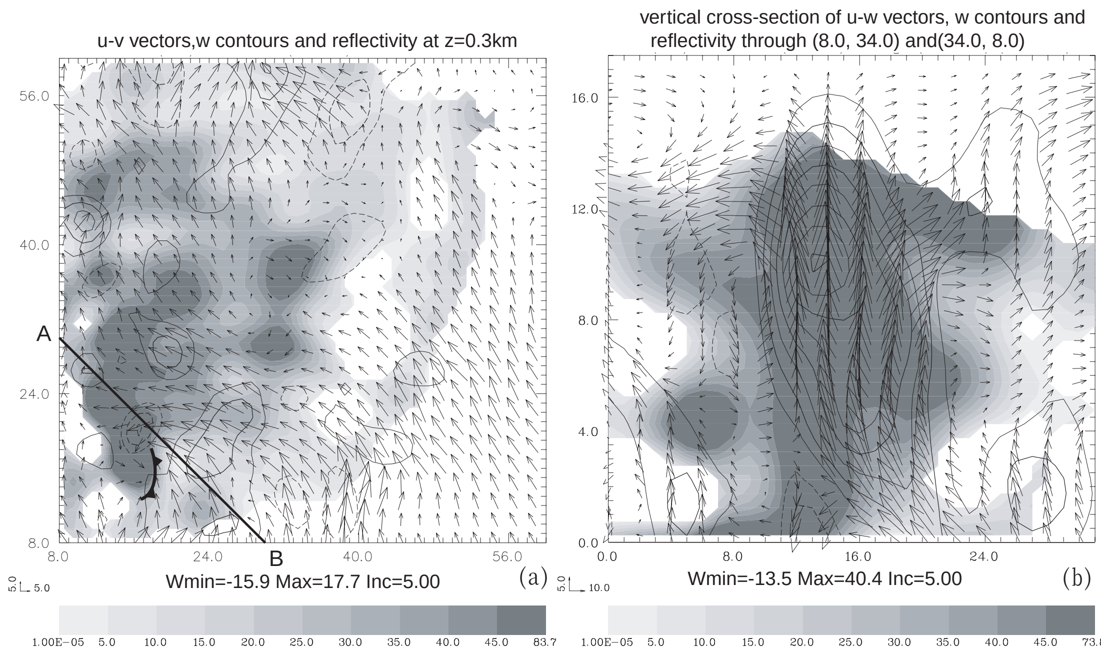

Fig. 3. Wind vectors, vertical velocity (contours) analyzed from data sampled by two Doppler radars (located at Norman and Cimarron of Oklahoma) using the 3D variational method with recursive filter for the Arcadia, OK tornadic storm at 16:34 CST, 17 May 1981. Also shown are shaded contours of the reflectivity field. a) Horizontal cross-section at z = 0.3km; b) Vertical cross-section through A-B line in panel a). Rear flank gust front at this level is indicated by the cold front symbol in a). Radar observations are only available where there is reflectivity shading. Recusive filter and mass-continuity constraint were used (from Gao et al 2003a).

2.5 3DVAR analysis of water vapor field from GPS slant-path and surface network data

Ph.D. student, H. Liu, developed a 3D variational (3DVAR) system for analyzing the three-dimensional water vapor structure from GPS slant-path water observations. A set of Observing Simulation System (OSS) experiments were completed. The ARPS mesoscale model was used to produce a "true" atmospheric moisture field for an IHOP 2002 case that contained a dryline. The system uses a spatial filter to model the background error covariances and is formulated in a terrain following coordinate. The results illustrate that this variational retrieval method can properly recover mesoscale three-dimensional moisture structure and accurately capture major features of water vapor field simulated by the model in the presence of surface observations (Liu and Xue 2004). In addition, sensitivity experiments are conducted to test the effects of surface moisture observations and a vertical filter on the retrieval. Further experiments will involve the use of flow-dependent spatial filters and assimilation of real GPS data collected during IHOP 2002 and will examine the impact of the data on mesoscale forecasts. Fig. 4 shows an example of the 3DVAR analysis increment as compared to the 'true' increment valid at 1500 UTC June 18, 2002. It can be seen that most of the details in the moisture fields are well recovered by the analysis.

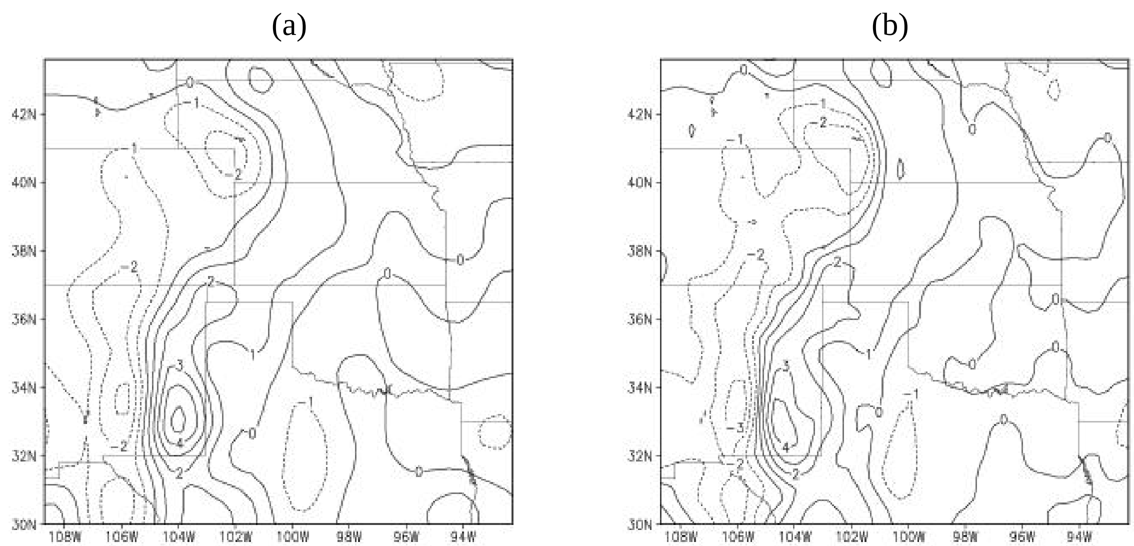

Fig. 4. The increment fields of specific humidity in g kg^{-1} at the second model level (~30m) above ground for the analysis (a) and the 'truth' (b) at 1500 UTC June 18, 2002, at which time a dryline extends north-south from eastern New Mexico through Kansas-Colorado border and into western Nebraska.

2.6 Precipitation verification of CAPS IHOP forecasts

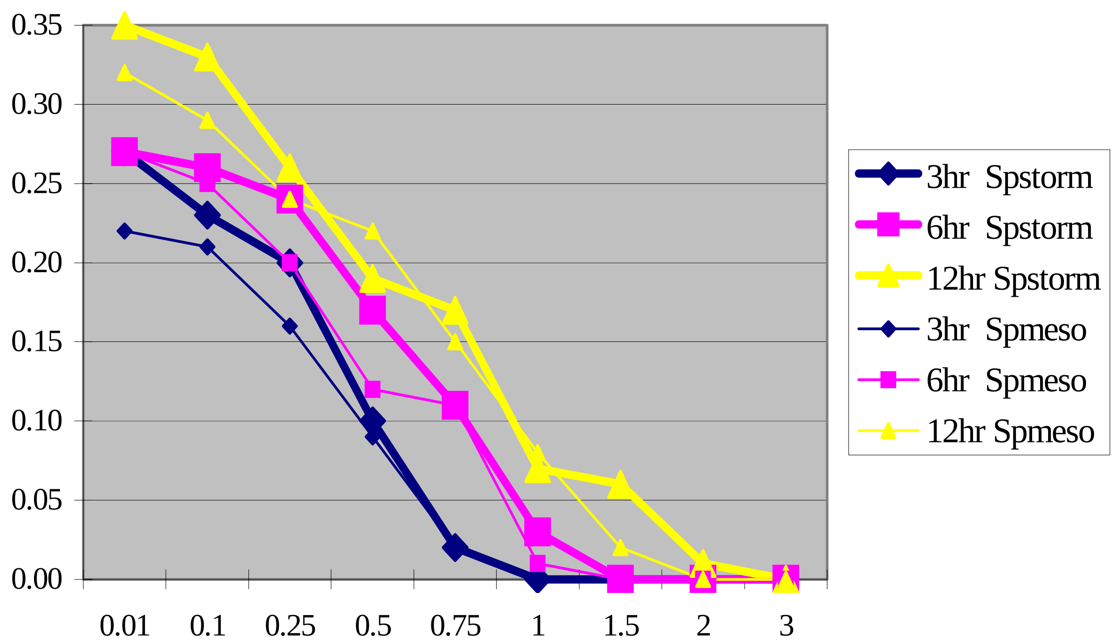

Fig. 5. Equitable threat score (ETS) of the 9km (Spmeso) and 3 km (Spstorm) CAPS IHOP forecasts verified against gauge data in the common 3 km forecast domain. It is clear that the 3 km grid (thick lines) consistently outperforms the 9 km grid (thin lines) for all three forecast ranges.

Working with M. Xue, visiting scientist Dr. J. Min developed a code and performed detailed precipitation verification studies of CAPS IHOP_2002 real time forecasts (see http://ihop.caps.ou.edu) on 27, 9 and 3 km grids against both NCEP Stage IV gridded and rainfall gauge data. Standard threat scores and Hövmöller diagrams were examined (Xue and Min 2003). The results were presented at the Spring IHOP Science meeting in Boulder CO in March 2003. Contrary to the findings of some other work, the results clearly show improved precipitation forecast skills as the grid resolution increases (Fig. 5). A complete re-run of IHOP forecasts is planned that will examine systematically the impact of cloud analysis using radar data on the precipitation forecast.

2.7 Analysis of convective initiation for an IHOP case

Masters student G. Stano performed detailed analysis of the convective initiation processes in the 24 May 2002 case observed during the IHOP field experiment (Stano 2003). At 2000 UTC on 24 May 2002, a strong line of storms developed in the Texas panhandle area and moved across the state of Oklahoma and northern Texas. The study investigated the causes for convective initiation on 24 May 2002 using gridded fields produced by the ARPS Data Analysis System (ADAS) as well as by examining raw observations. Special IHOP data sets, including those from regional and mobile, surface and upper-air networks and those from many remote sensing platforms, were used in the objective analysis. It was shown that the initial storms developed due to the interaction of the surface cold front and the dryline. The initiation region was favored over locations further to the northeast along the surface cold front due to strong surface heating, a weakening of the stable layer above the boundary layer, and by more effective upper-level support. Further high-resolution model simulations starting from the detailed analyses are being performed that will provide a more continuous description in both space and time of the convective initiation processes and further improve our understanding of the physical mechanisms of initiation.

2.8 High-resolution simulation and data impact study of an IHOP case

Masters student D. Dawson has conducted a set of large domain, high-resolution experiments with the June 15, 2002 bow echo/MCS case, examining the impact of resolution, special observational data including radar, and the data assimilation strategy on the prediction of convective events that organized into an intense MCS/bow echo. As the grid resolution increases, the position as well as the structure of the predicted bow echo was progressively improved. The use of surface data from special networks and the impact of cloud analysis were found to be most significant in the first 6 hours of forecast (Dawson and Xue 2004). A 1 km forecast is planned and further improvement in the position forecast is expected as the low-level cold pool and gust fronts are better resolved. Precipitation power spectra are calculated and will be compared with those from observations. The model simulated events will be analyzed to understand the dynamic processes involved. Fig. 6 presents an example of the 3 km forecast as compared to the radar observations.

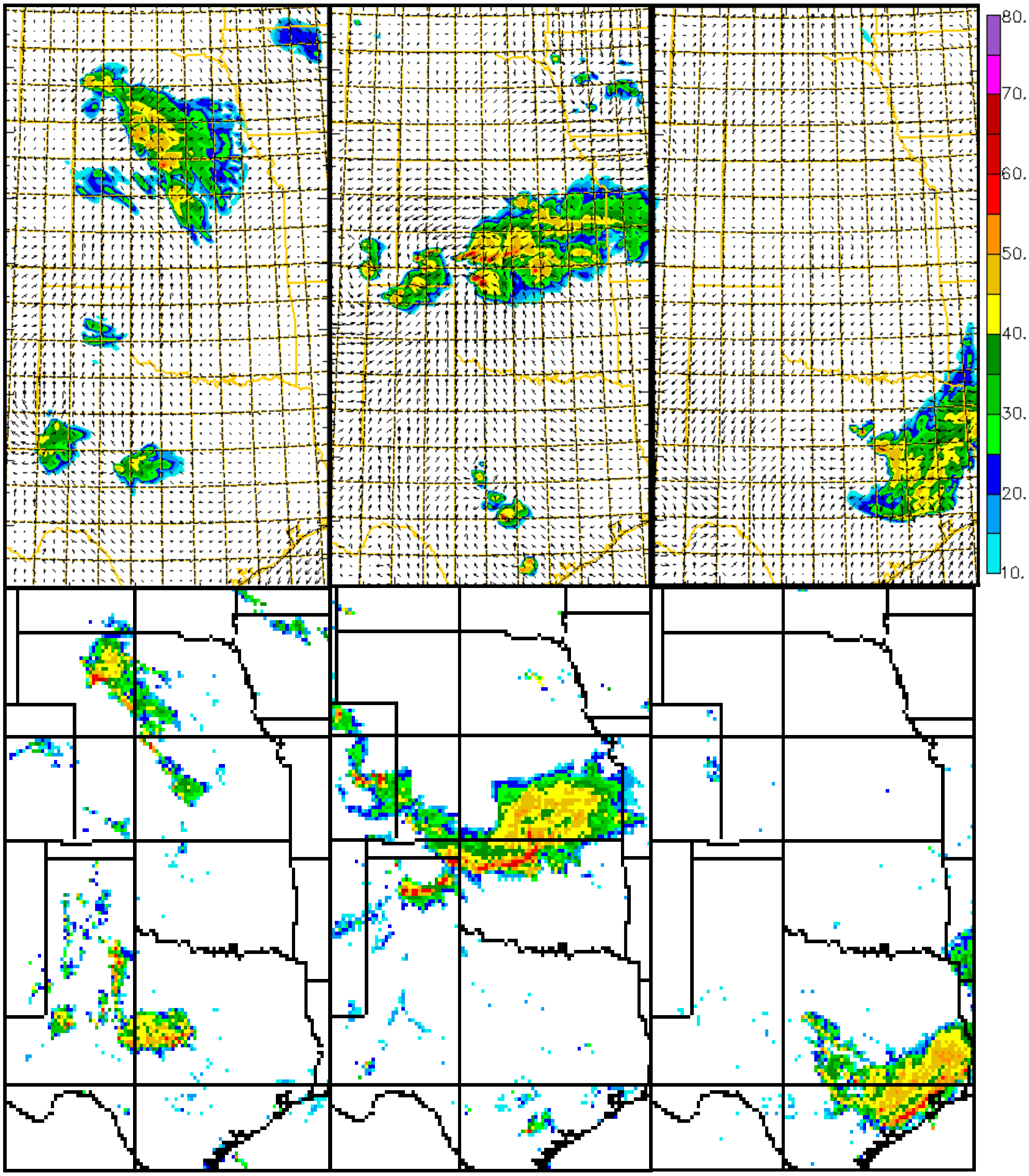

Fig. 6 Simulated composite reflectivity for 3km resolution simulation at 15 Z 15 June 2002 (3 hr forecast, top left), 0Z 16 June 2002 (12 hr forecast, top center), and 12Z 16 June 2002 (24 hr forecast, top right). Observed NEXRAD composite reflectivity at the corresponding times is shown in the bottom row.

2.9 Impact of lateral boundary conditions on ensemble forecasts

Working with Drs. M. Xue and D. Stensrud, P. Nutter completed his Ph.D. dissertation (Nutter 2003) and submitted two papers to Mon. Wea. Rev. (Nutter et al., 2003a,b), examining the effect of lateral boundary conditions (LBCs) on limited-area ensemble forecasts. Through a set of carefully designed nested ensemble forecast experiments, the specific effects of the lack of fine-scale structures and/or high-frequency signals in the LBCs on the error growth and dispersion of nested limited-area ensemble forecasts were clearly documented. A new method was developed to apply statistically consistent LBC perturbations at each time step that remain spatially and temporally coherent while passing through the boundaries. The LBC perturbations were shown to capably restore error variance growth and LAM ensemble dispersion without compromising the integrity of the individual solutions.

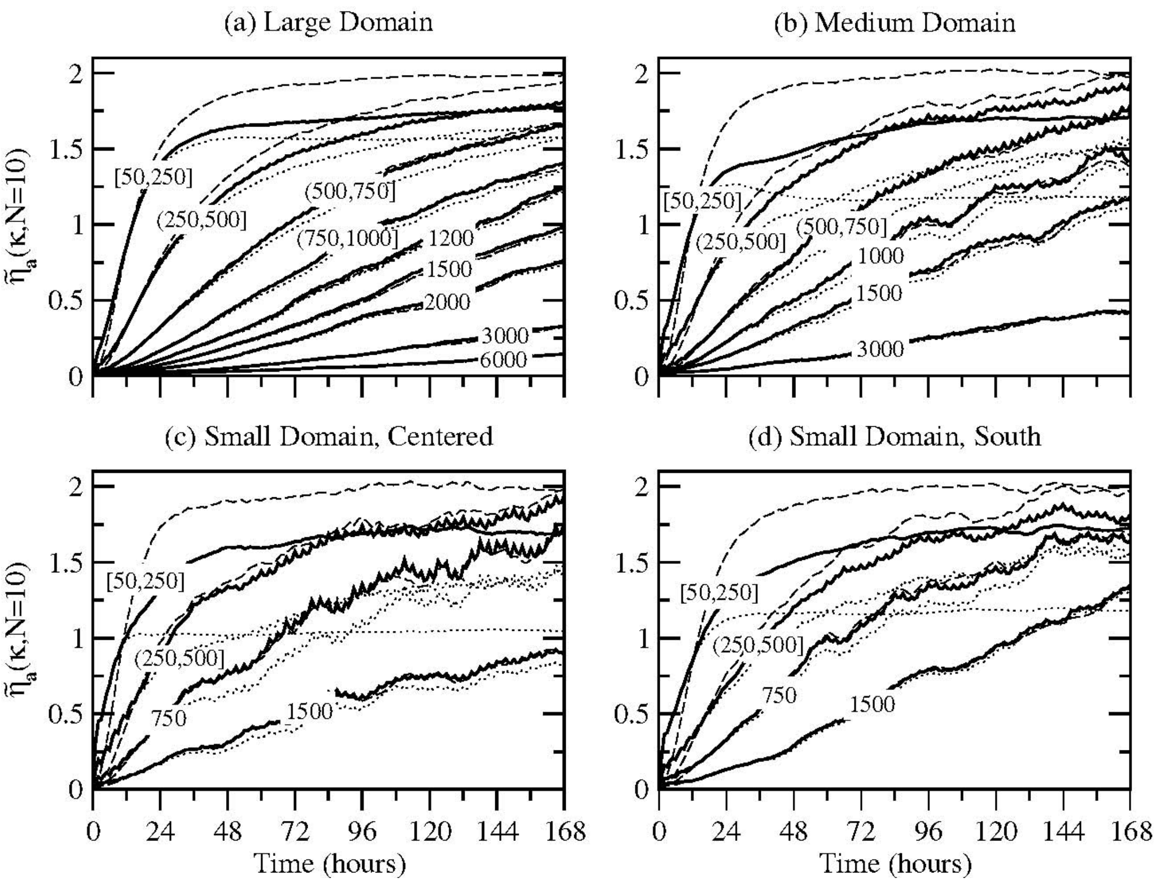

Fig. 7. Normalized vorticity error variance, averaged over 100 independent 10-member LAM ensemble simulations having perturbed, 3hourly updated, low-pass filtered LBCs (150 km wavelength cutoff). Line labels (km) indicate wavelength(s) contributing to error variances. Dashed reference lines show error variances from subsets of global ensemble simulations and dotted lines show error variances from corresponding LAM ensemble simulations run without LBC perturbations.

Fig. 7 shows that the application of LBC perturbations completely restores error variances at wavelengths longer than about 500 km to values obtained from the control simulations run on the global domain. The LBC perturbations are less effective for smaller scales, where the proportion of error variance restored depends on domain size. For example, on the large domain (Fig. 7a), the LBC perturbations restore about 1/3 of the error variance lost at saturation in the smallest scales. Compare this to the small, centered domain (Fig. 7c), where the LBC perturbations restore more than 3/4 of the error variance lost in the unperturbed LAM simulations.

2.10 Ensemble Kalman filter data assimilation

Ph.D. student, M. Tong, with initial contributions from W. Martin, developed an ensemble Kalman filter (EnKF) system based on a compressible model, the ARPS, and applied it to the assimilation of radar radial velocity and/or reflectivity data at the convective scale (Tong and Xue 2004). Based on a set of OSS experiments, it was shown that not only can the wind and thermodynamic fields be retrieved accurately, all five categories of hydrometeors employed by the ice microphysics scheme can also be retrieved successfully. Fig. 8 shows two examples of assimilation experiments in which radial velocity of different spatial coverage were assimilated.

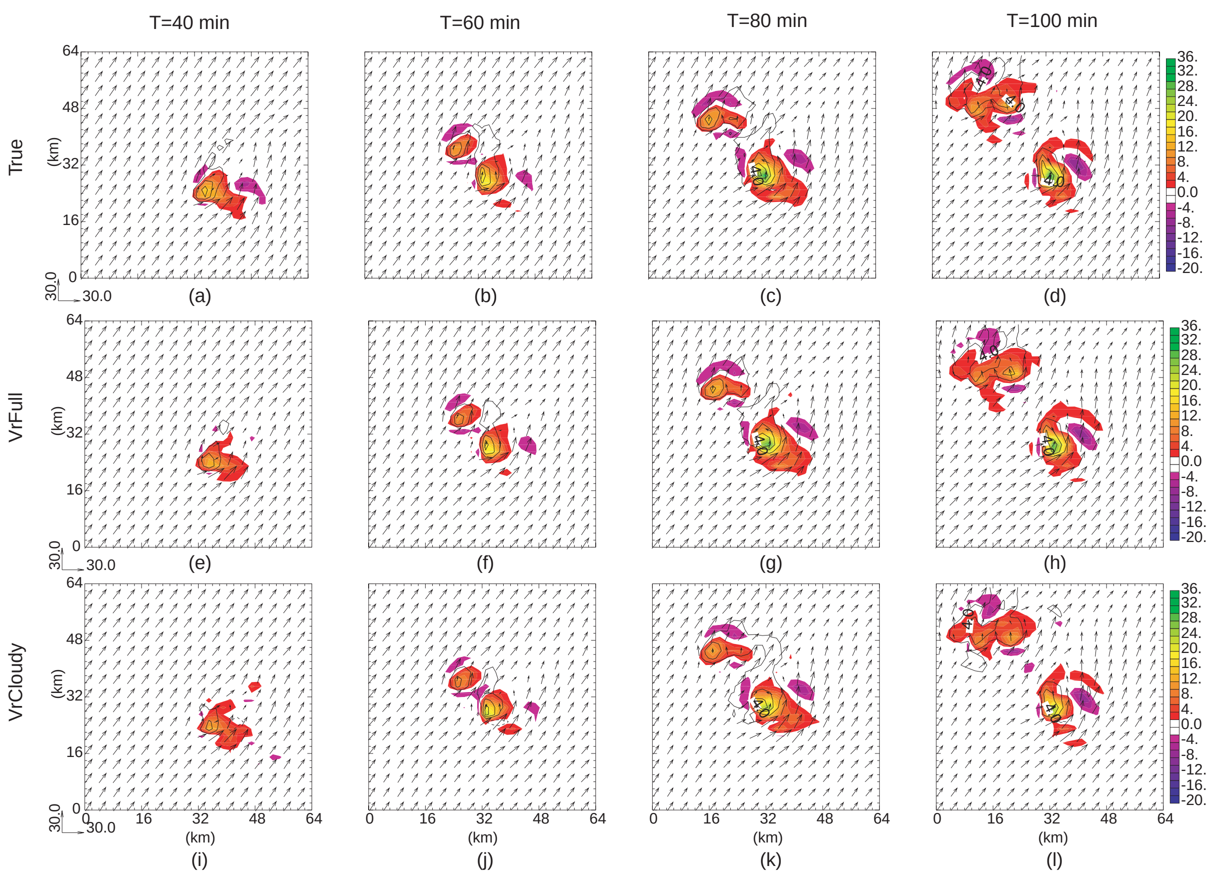

Fig. 8. Vertical velocity (m s^{-1}; shaded), horizontal wind vectors (m s^{-1}), and perturbation potential temperature θ' (K; contour) at z=6 km for truth simulation (a)~(d), assimilation experiment VrFull that assumed radial velocity is available in the entire domain (e)~(h) and for VrCloudy that assumes radial velocity data are available when reflectivity is larger than 10 dBZ (i)~(l), at T=40, 60, 80 and 100 min for a supercell storm. Assimilation of radial velocity data only started at 25 mins.

2.11 Study on squall line dynamics

M. Xue conducted basic research examining the role of environmental vorticity on squall line dynamics. In this work, the role of environmental shear in the initiation and maintenance of intense long-lived squall lines is studied using a vorticity-based numerical model with parameterized microphysics. The initial distributions of vorticity in different layers as well as the generation of vorticity by baroclinic process are partitioned and evolved separately in the model. The results extend widely established theories on long-lived squall lines. A presentation was given on the findings at the 15th AMS Conference on Mesoscale Processes and a manuscript is being prepared for journal publication.

2.12 Development of adjoint of a complete nonhydrostatic model for sensitivity and data assimilation studies

To perform the proposed adjoint sensitivity experiments, we are developing a new version of the adjoint code based on the latest version of the ARPS. This is being done with the help of an automatic adjoint code generator, TAF (Transformation of Algorithms in Fortran) which is the commercial version of the popular TAMC program (Tangent-linear and Adjoint Model Compiler). In 2003, some funds from this project was used to purchase the license for TAF. So far, the full-physics ARPS adjoint except for those for the full radiation and Kain-Fritsch cumulus parameterizations passed initial validation tests. Sensitivity experiments will soon begin.

2.13 Initial condition sensitivity studies using very large ensembles

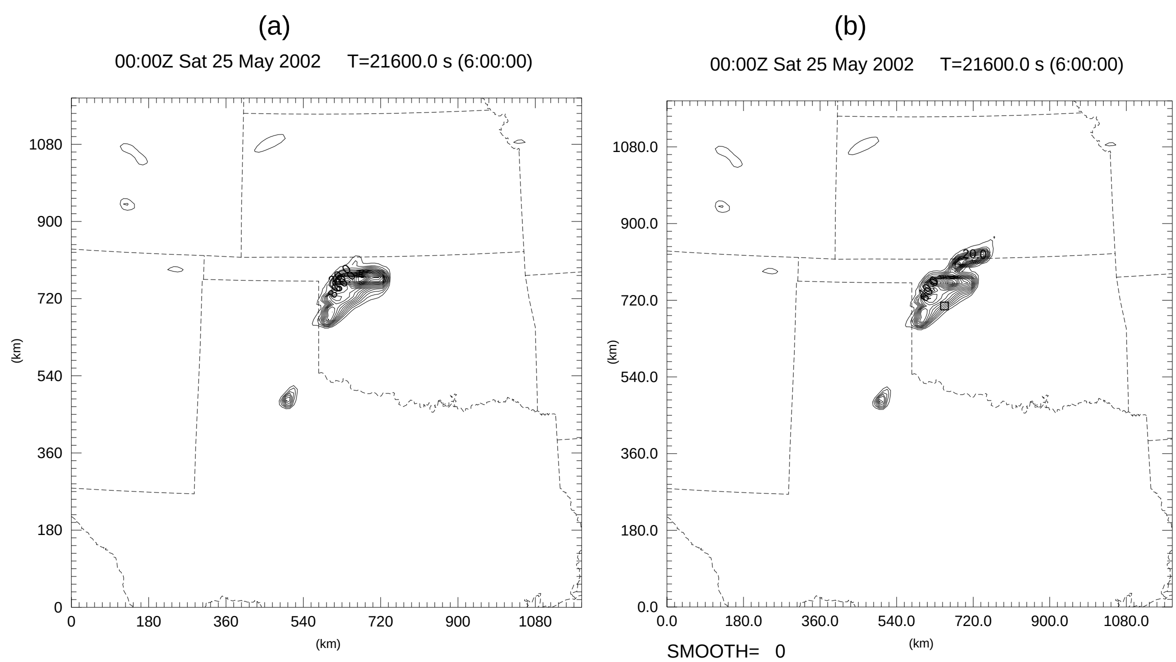

Fig. 9. Six-hour forecast of accumulated precipitation from control run (a) and from a model run with an initial 1 g/kg surface moisture perturbation at the location indicated by a small box in northwest Oklahoma (b). The extra local

maximum in the precipitation along the Kansas-Oklahoma border of the perturbed run (b) is 120 mm.

Dr. W. Martin completed a preliminary set of experiments in which ensembles of very large sizes (on the order of thousands) were performed for the May 24, 2002 IHOP case in which convection was initiated along a dry line and a cold front (Martin and Xue 2004). For each ensemble member, the initial low-level moisture field in a finite patch of the computational domain was perturbed. Sensitivity fields of the forecast precipitation and other output variables to the initial low-level moisture were constructed. Some strong nonlinear sensitivity was found near the cold front. In one case, a 1 g kg^{-1} perturbation at the lowest 1 km depth over a 27x27 km^2 area triggered an entire new storm along the cold front (Fig. 9), a sensitivity that is larger than what has been documented in the literature.

The large-ensemble-based sensitivity experiments will complement our adjoint-based sensitivity studies as both have advantages and disadvantages.

2.14 Retrieval of soil model initial state using 4DVAR method and improvement of land-surface model

Ren and Xue (2003a), under partial support of this project, proposed an important improvement to the temperature prediction equation used in land-surface models based on the force-restore model. It was shown that the improved system produced much better predictions of deep-layer soil temperatures, and the modification was found important for the 4DVAR-based soil temperature and moisture retrieval work of Ren and Xue (2003b, 2004). In another work (Ren et al 2003), hydraulic lift was introduced into a multi-layer soil-hydrology model that enabled that model to correctly predict daytime moistening and night-time drying in near surface soil under dry conditions.

3 Education and Training

During 2003, this research grant provided support for 3 Ph.D. students (H. Liu, M. Tong, and P. Nutter) and two M.S. students (D. Dawson and G. Stano). The participation of the latter two leveraged significantly on their fellowships, the National Defense Science and Engineering and the Williams Fellowship, respectively. The grant also supported the research of a post-doctoral scientist W. Martin and a visiting scientist J. Min. Under the partial support of this project, two Ph.D. students (Nutter and Martin) and one Master student (Stano) completed their degrees in 2003. This project also provided training opportunities for five graduate students in fall 2003, who utilized the data achieved by this project to perform numerical experimentations using the ARPS model as part of their term project of Computational Fluid Dynamics course taught by the PI. All supported graduate students submitted journal and/or conference papers for publication during the year. Further, Dr. F. Carr gave an invited presentation at Reading University, England, on the "The Future of Mesoscale Observations and data Assimilation" in June 2003. He also co-organized (with W. Dabberdt and T. Schlatter) the USWRP Mesoscale Observing Workshop to be held De. 8-10, 2003.

Overall, the project provided training for graduate students and post-doctoral scientists in the area of numerical modeling, advanced data assimilation methods and understanding of mesoscale processes, and enabling them to gain improved abilities for performing scientific research and publishing scientific findings.

4 List of Publications under the Full and Partial Support of the Current Grant

4.1 Refereed Publications

Dowell, D. C. and A. Shapiro, 2003: Stability of an Iterative Dual-Doppler Wind Synthesis in Cartesian Coordinates. *Journal of Atmospheric and Oceanic Technology*, **20,** 1552-1559.

Gao, J., K. K. Droegemeier, J. Gong and Q. Xu, 2003a: Retrieval of vertical wind profiles from Doppler radar radial velocity data, *Mon. Wea. Rev. C*onditionally accepted.

Gao, J., M. Xue, K.K. Droegemeier, A. Shapiro, 2003b: A three-dimensional variational single-Doppler velocity retrieval method with single conservation equation constraint, Q. J. Roy. Meteor. Soc., Under review.

Gao, J.-D., M. Xue, K. Brewster, K.K. Droegemeier, 2003c: A Three-dimensional variational data analysis method with recursive filter for Doppler radars, J. Atmos. Ocean Tech., Accepted.

Nutter, P., D. Stensrud, and M. Xue, 2003a: Effects of coarsely-resolved and temporally-interpolated lateral boundary conditions on the dispersion of limited-area ensemble forecasts, *Mon. Wea. Rev.*, Conditionally accepted.

Nutter, P., M. Xue, and D. Stensrud, 2003b: Application of lateral boundary condition perturbations to help restore dispersion in limited area ensemble forecasts. *Mon. Wea. Rev.***,** Submitted.

Ren, D., M. Xue and A. Henderson-Sellers, 2003, The effects of hydraulic lift in simulating superficial soil moisture for vegetated surfaces under dry conditions, J. of Hydrometeorology, Conditionally accepted.

Ren, D., and M. Xue, 2003a: An improved force-restore model for land-surface modeling, J. App. Meteor., Conditionally accepted.

Ren, D., and M. Xue, 2003b: 4DVAR assimilation of ground temperature for the estimation of soil moisture and temperature, Submitted to Mon. Wea. Rev.

Shapiro, A., P. Robinson, J. Wurman, and J. Gao, 2003: Single-Doppler Velocity Retrieval with rapid-scan radar data, *J. Atmos. Oceanic. Technol.* (In press).

Sharif, H. O., F. L. Ogden, W. F. Krajewski, and M. Xue, 2003: Statistical Analysis of Radar-Rainfall Error Propagation. *J. Hydrometeor*. In press.

Souto, M. J., C. F. Balseiro, V. Pérez-Muñuzuri, M. Xue, and K. Brewster, 2003: Importance of cloud analysis and impact for daily forecast in terms of climatology of Galician region, Spain. *J. App. Meteor*., **42,** 129-140.

Xue, M., 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.

4.2 Conference papers

Brewster K., A. Shapiro, J. Gao, E. M. Kemp, P. Robinson, and K. Thomas 2003: Assimilation of radar data for the detection of aviation weather hazards, Preprints, *31 Conf. on Radar Meteorology,* Amer. Meteorol. Society. 339-342.

Dawson, D. T., II and M. Xue, 2004: Impact of mesoscale data, cloud analysis on the explicit prediction of a MCS during IHOP 2002. *Extended Abstract, 20th Conf. Wea. Analy. Forecasting/16th Conf. Num. Wea. Pred.,* Amer. Meteor. Soc., Seattle, WA.

Gao, J., K. K. Droegemeier, J. Gong and Q. Xu 2003d: A wind profile retrieval method from azimuthal gradients of radial velocity, Preprints, *31th Conf. on Radar Meteorology,* Amer. Meteorol. Society. 339-342.

Gao, J., M. Xue, K. Brewster, and K. K. Droegemeier 2003e: A 3DVAR method for Doppler radar wind analysis with using recursive filter, Preprints, *31th Conf. on Radar Meteorology,* Amer. Meteorol. Society. 339-342.

Liu, H. and M. Xue, 2004: 3DVAR retrieval of 3D moisture field from slant-path water vapor observations of a high-resolution hypothetical GPS network. *Extended Abstract, 20th Conf. Wea. Analy. Forecasting/16th Conf. Num. Wea. Pred.*, Amer. Meteor. Soc., Seattle, WA.

Martin, W. J. and M. Xue, 2004: Initial convection sensitivity analysis of a mesoscale forecast using very-large ensembles. *Extended Abstract, 20th Conf. Wea. Analy. Forecasting/16th Conf. Num. Wea. Pred.*, Amer. Meteor. Soc., Seattle, WA.

Nutter, P., M. Xue, and D. Stansrud, 2004: On the need for perturbed LBCs in limited-area ensemble forecasts. *Extended Abstract, 20th Conf. Wea. Analy. Forecasting/16th Conf. Num. Wea. Pred.*, Amer. Meteor. Soc., Seattle, WA.

Ren, D. and M. Xue, 2004: 4DVAR assimilation of ground temperature for the estimation of soil moisture and temperature. *Extended Abstract, 20th Conf. Wea. Analy. Forecasting/16th Conf. Num. Wea. Pred.*, Amer. Meteor. Soc., Seattle, WA.

Tong, M. and M. Xue, 2004: Ensemble Kalman filter assimilation of Doppler radar data with a compressible nonhydrostatic model. *Extended Abstract, 20th Conf. Wea. Analy. Forecasting/16th Conf. Num. Wea. Pred.,* Amer. Meteor. Soc., Seattle, WA.

Xue, M. and J. Min, 2003: Precipitation verification on CAPS Real-time forecasts during IHOP 2002, Presentation, IHOP Spring Science Meeting, March 2003, Boulder CO.

Xue, M., 2003: Vorticity dynamics of long-lived squall lines, Presentation at the 10th Conf. on Mesoscale Processes, Amer. Meteor. Soc., Portland, OR.

Xue, M. and D. Ren, 2004: Testing of several recent modifications to ARPS land surface model. *18th Conf. Hydro.*, Amer. Meteor. Soc., Seattle, WA.

4.3 Thesis and Dissertation Completed

Nutter, P., 2003: Effects of nesting frequency and lateral boundary perturbations on the dispersion of limited-area ensemble forecasts, Ph.D. Dissertation, University of Oklahoma, 156 pp.

Martin, W. J., 2003: Measurements and modeling of the Great Plains low-level jet. Ph.D Dissertation, University of Oklahoma.

Stano, G., 2003: A case study of convective initiation on 24 may 2002 during the IHOP field experiment, M.S. Thesis, University of Oklahoma, 106 pp.

5 List of project participants

Ming Xue, Principal Investigator (PI)
Jidong Gao, Co-PI
Keith Brewster, Co-PI
Alan Shapiro, Co-PI
Fred Carr, Co-PI
Willam Martin, Post-doctoral scientist
Jinzhong Min, Visiting research scientist
Paul Nutter, Ph.D. student, completed.
Geoffrey Stano, M.S. student, completed.
Mingjing Tong, Ph.D. student, current
Haixia Liu, Ph.D. student, current
Dan Dawson, M.S. student, current