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P9.8 A 3DVAR Application to Several Thunderstorm Cases Observed During VORTEX2 Field Operations and Potential for Real-Time Warning

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1. Introduction

As found by several studies (e.g., Burgess 1976; Burgess and Lemon 1991; Bunkers et al. 2006, 2009), the determination of whether or not a thunderstorm is a supercell thunderstorm is very important to accurate and timely severe weather warning operations. These studies revealed that over 90% of supercells are severe (i.e., produce tornadoes, large hail, or severe surface winds). Therefore, the proper early identification of a supercell thunderstorm, or a supercell imbedded in a cluster of storms, is critical to the issuance of public warnings for severe weather.

One of the most important indicators of a supercell is the existence of a mid-level mesocyclone. In this sense, *mesocyclone* is a radar term, defined as the Doppler radar velocity signature of a storm-scale (2–10-km diameter) vortex (Burgess, 1976) which corresponds to the rotating updraft–downdraft couplet of a supercell thunderstorm. Mesocyclones in the United States are often cyclonic and may also contain the more intense tornado vortex. In last twenty years, several criteria have been established for mesocyclone recognition based on a wealth of Doppler radar observations, especially after the implementation of WSR-88Ds (Burgess et al. 1976, 1982, 1991, 1993; Stumpf et al., 1998). Based on these criteria and other conceptual models (i. e., Lemon and Doswell 1979), a mesocyclone detection algorithm (MDA) was developed that helps meet the needs of the meteorologists who have to make warning decisions (Stumpf et al., 1998). Although this approach has met with great success, some shortcomings exist. Most importantly, the method uses the data only from a single Doppler radar; it does not incorporate information contained in other nearby WSR-88Ds. In other words, it does not take the full advantage of information contained within the WSR-88D network. In addition, the method does not naturally combine other available information into the system, such as operational analysis and forecast products and routine surface observations (including those provided by mesonet networks, such as the Oklahoma Mesonet).

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The other hallmark characteristics of supercells, such as the depth and persistence of the circulation, the strength of updraft, and the maximum vertical vorticity magnitude, are very difficult to identify with the MDA method based upon radar observations alone. While forecasters make their warning decisions based on all available information, the workload and timeliness requirement may limit their ability to effectively use all available information. This situation has led to the call for an exploration of the use of fast data assimilation methods as potential solutions for merging all available information together as quickly as possible for the human decision makers.

In this study, we investigate the possibility of identifying supercells using a three-dimensional variational data assimilation method (Gao et al. 2004) developed for Advanced Regional Prediction System (ARPS, Xue et al. 2000, 2001, 2003) at the Center for Analysis and Prediction of Storms (ARPS 3DVAR). The system is used to produce physically-consistent high-resolution analyses based on all available information. The data sources used in the ARPS 3DVAR include observations from several nearby WSR-88Ds, operational North American Mesoscale (NAM) model 12 km grid spacing analysis and forecast products, and surface observations. This analysis system has potential to make better use of observations from the WSR-88D network, along with operational model forecast products, and thereby can help to meet the needs of the meteorologists who have to make warning decisions. The method is applied to several severe storms cases obtained during VORTEX2 field operations in summer of 2009. Our principal goal is to evaluate the potential value of 3DVAR data assimilation system for real-time severe weather warning.

Section 2 provides an overview of the data assimilation (DA) system and the experiment design. Experiment results are assessed in section 3. We conclude in section 4 with a summary and outlook for future work.

2. The ARPS 3DVAR and Procedure Description

As introduced in the last section, the data assimilation method used in this study is a three-dimensional, variational DA system (Gao et al. 2002, 2003, 2004; Hu et al. 2006) that has been developed during the last several years. The ARPS 3DVAR system, designed especially for storm-scale data assimilation, uses a recursive filter (Purser et al. 2003) with a mass continuity equation and other constraints that are incorporated into a cost function, yielding physically-consistent three-dimensional analyses of the wind components and other model variables. Multiple analysis passes are used that have different spatial influence scales in order to accurately represent intermittent convective storms, while the quality control steps within the ARPS 3DVAR also are very important to improving the quality of the radial velocity and reflectivity data. There is also a cloud analysis system included within the ARPS 3DVAR which is not used here.

We propose to develop a real-time weather-dependent hazardous weather analysis and detection system based upon this 3DVAR method to identify supercells and other severe weather events using data from the WSR-88D network and from the NCEP NAM 12 km resolution analyses and forecasts. The steps needed to make such a system operationally in real time are as follows.

First, we obtain the Convective Outlook field from the National Weather Service (NWS), and find the location (longitude, latitude) at greatest risk for severe storms. This location is used as the center for the 3DVAR analysis domain. Parameters are then selected for this analysis domain, including the number of grid points, nx, ny, and nz in the three spatial directions and the grid spacings dx, dy, and dz. For the current study, we choose nx=ny=400, dx=dy=1 km. In the vertical, we use 31 terrain-following vertical layers, with nonlinear stretching, via a hyperbolic tangent function, yielding an average vertical grid spacing of 400 m. Once the domain is defined, we also need to interpolate the terrain data to the analysis grid. The challenge is selecting a domain that is large enough to contain the principal features of meteorological interest while maintaining an efficient computational advantage so that the analyses can be produced fast enough to be of use in operations.

Once the analysis domain is selected, the second step is to get the necessary background data. The NCEP operational NAM 12 km resolution analysis and forecast product is obtained and interpolated to the analysis grid in both space and time using existing software developed within the ARPS model. While the spatial interpolation is determined by the grid spacing of the 3DVAR analysis, the frequency of the time interpolation is determined by how often the end users wants analyses to be produced. Analyses could be produced every minute, although an analysis interval of perhaps 5 to 10 minutes is more reasonable and corresponds more closely to the 4-6 minute period required for the WSR-88D to complete a full volume scan.

The third step is to determine how many operational WSR-88Ds are present within the selected domain, get the WSR-88D data in real-time, perform quality control on the radar observations, and thin and interpolate the radar data onto the analysis grid (this interpolation may be skipped in the future).

The fourth step is to conduct the 3DVAR analysis using both the background field obtained from step two, and the WSR-88D data obtained from step 3. Any additional available real-time data, such as mesonet data can be also used within this analysis with little additional computational cost.

The final step is post processing of the resulting analyses, including identifying the position of supercells, vorticity centers, regions of upward and downward vertical velocity, and producing other products that can be effectively used by the forecasters who issue severe weather warnings.

The above 5-step procedure can be performed every 5 or 10 minutes depending on computational cost and users' needs. By carefully choosing the domain size and number of vertical levels, in relation to the available computer resources, we hope that each new analysis can be finished within 5 minutes or less. By using all available information simultaneously, it is possible to determine the 3D winds and other variables as accurately as possible, while also improving the quality of reflectivity data coverage. In the analyses that follow, we only focus on the 3D wind analyses and wind-derived variables such as vertical velocity and vorticity.

3. Some Preliminary Results

To assess the potential of the 3DVAR analysis to assist in warning operations, we apply the 3DVAR to several supercell cases observed during the 2009 VORTEX2 field experiment. We follow the procedure described in the last section except that the analysis domain location is centered on the observed storm.

The first case is a tornadic supercell event that took place on 5 June 2009 in Goshen County, Wyoming. The tornado was rated as an EF-2. It touched down near 2207 UTC and lasted about 13 minutes. The supercell that produced this tornado lasted for over 2 hours. The VORTEX2 project scientists observed this event from beginning to end. We use radial velocity and reflectivity observations from three nearby WSR-88Ds in the 3DVAR analysis. For this case, the radar observations are from the radars at Cheyenne, WY (KCYC), Denver, CO (KFTG), Rapid City SD (KUDX).

The evolution of the supercell storm as indicated by the analyzed radar reflectivity, horizontal winds, and vertical vorticity at the 3 km above ground level is shown in Fig. 1 from 2100 to 2240 UTC. The wind analysis at this level indicates a very strong mid-level

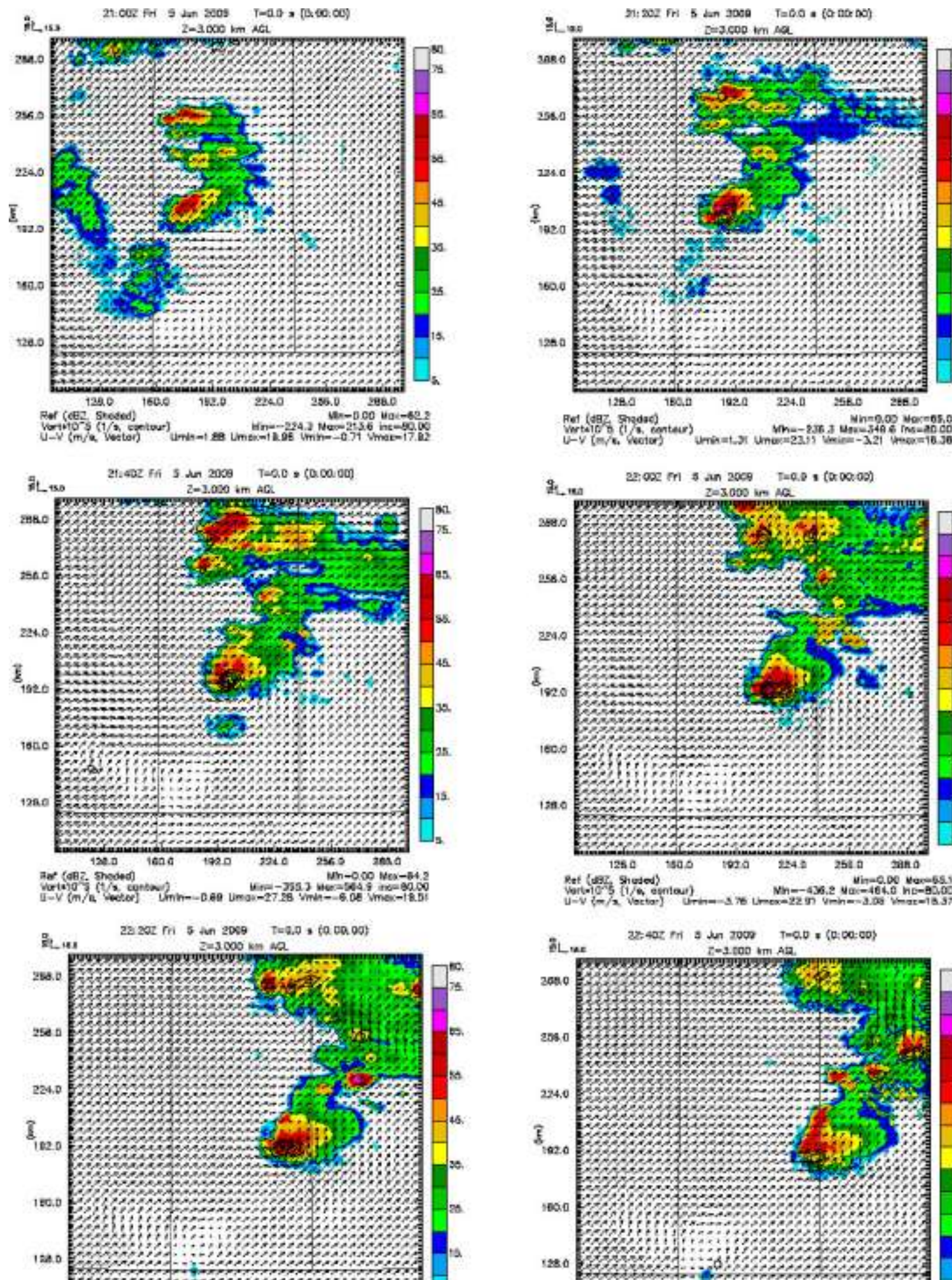

Fig. 1. The analyzed reflectivity, horizontal wind fields, and vorticity at z=3 km using data from KCYS, KUDX, and KFTG radars valid at (a) 2100 UTC, (b) 2120 UTC, (c) 2140 UTC, (d) 2100 UTC, (e) 2220 UTC, and (f) 2240 UTC, June, 05 2009 near Goshen, WY.

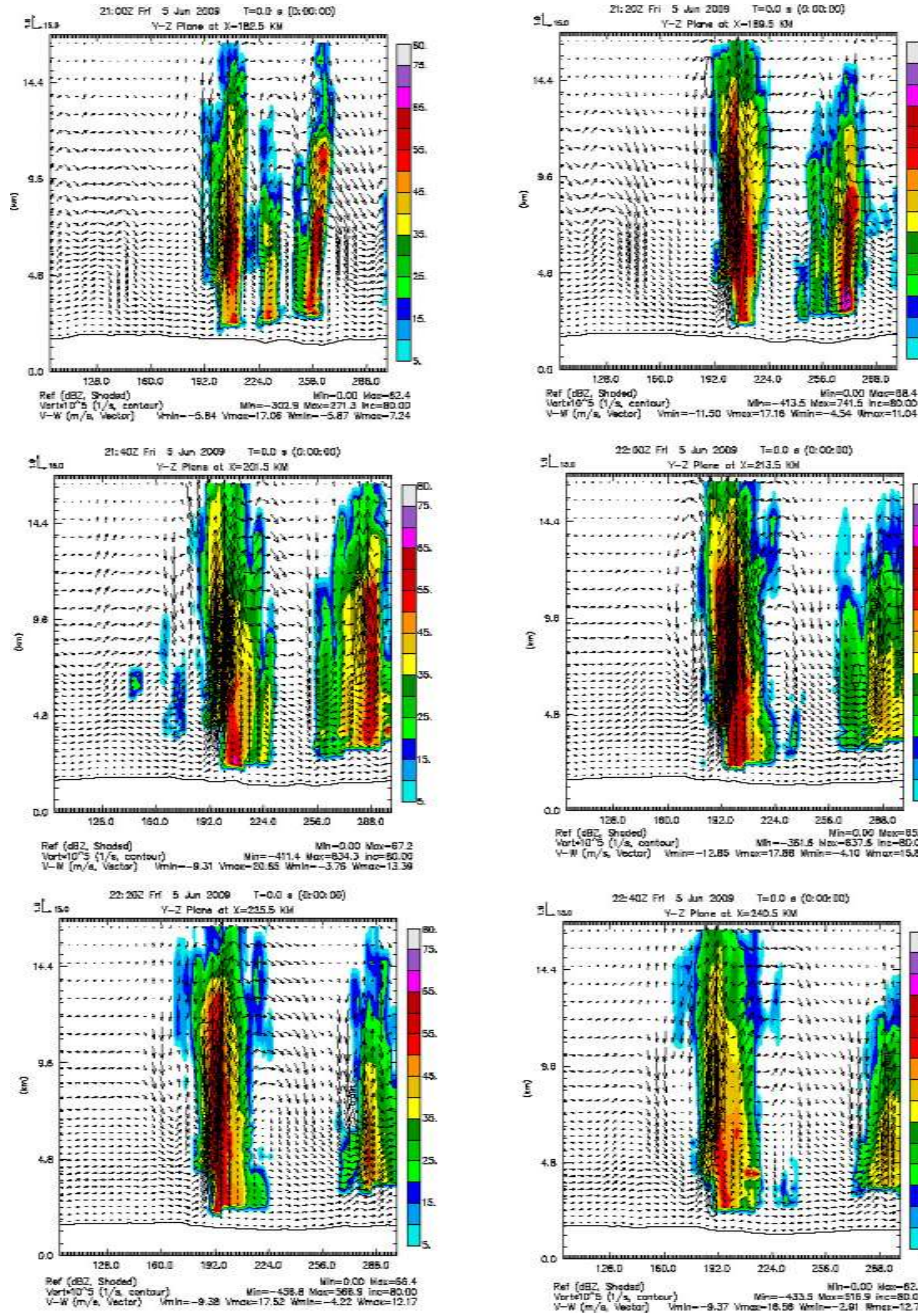

Fig. 2. Same as Fig. 1, but for vertical slice through the maximum vertical velocity.

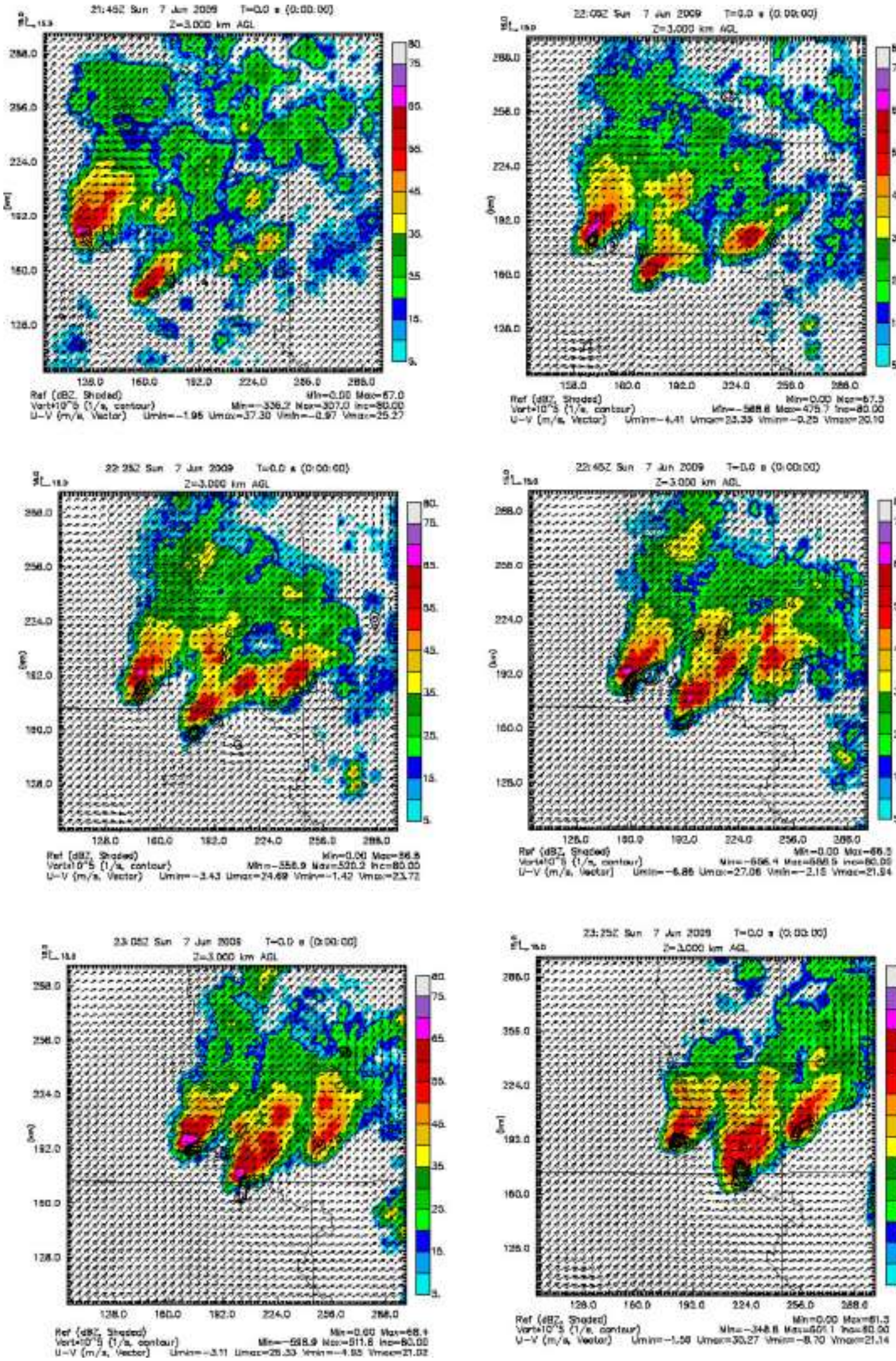

Fig. 3. The analyzed reflectivity, horizontal wind fields, and vortices at z=3 km using data from KTWX, KEAX, KOAX and KDMX radars valid at (a) 2145 UTC, (b) 2205 UTC, (c) 2225 UTC, (d) 2245 UTC, (e) 2305 UTC, and (f) 2325 UTC, June, 07 2009 near the joint boundary of three states NE, KS, MO.

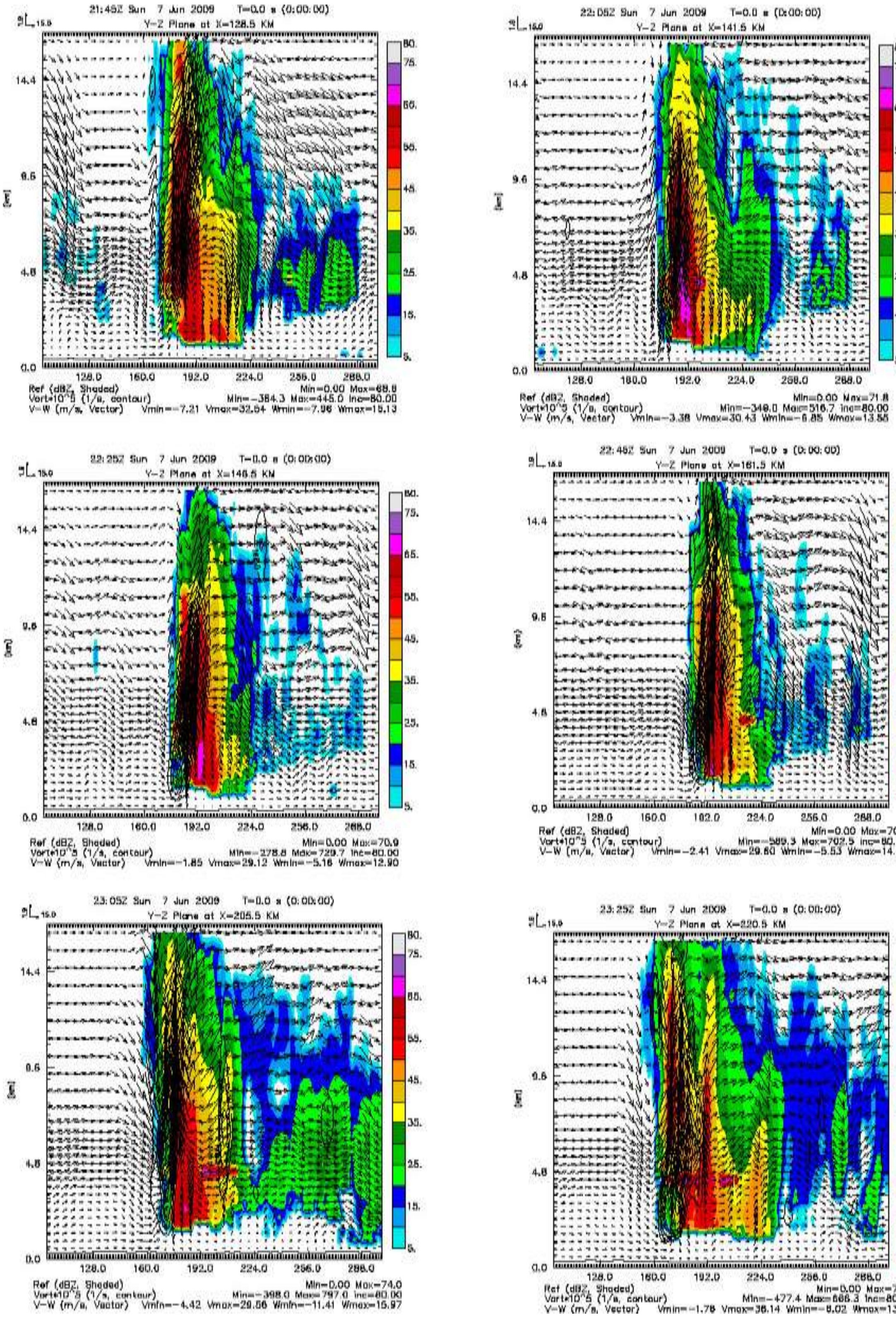

Fig. 4. Same as Fig.3, but for vertical slice through the maximum of vertical velocity.

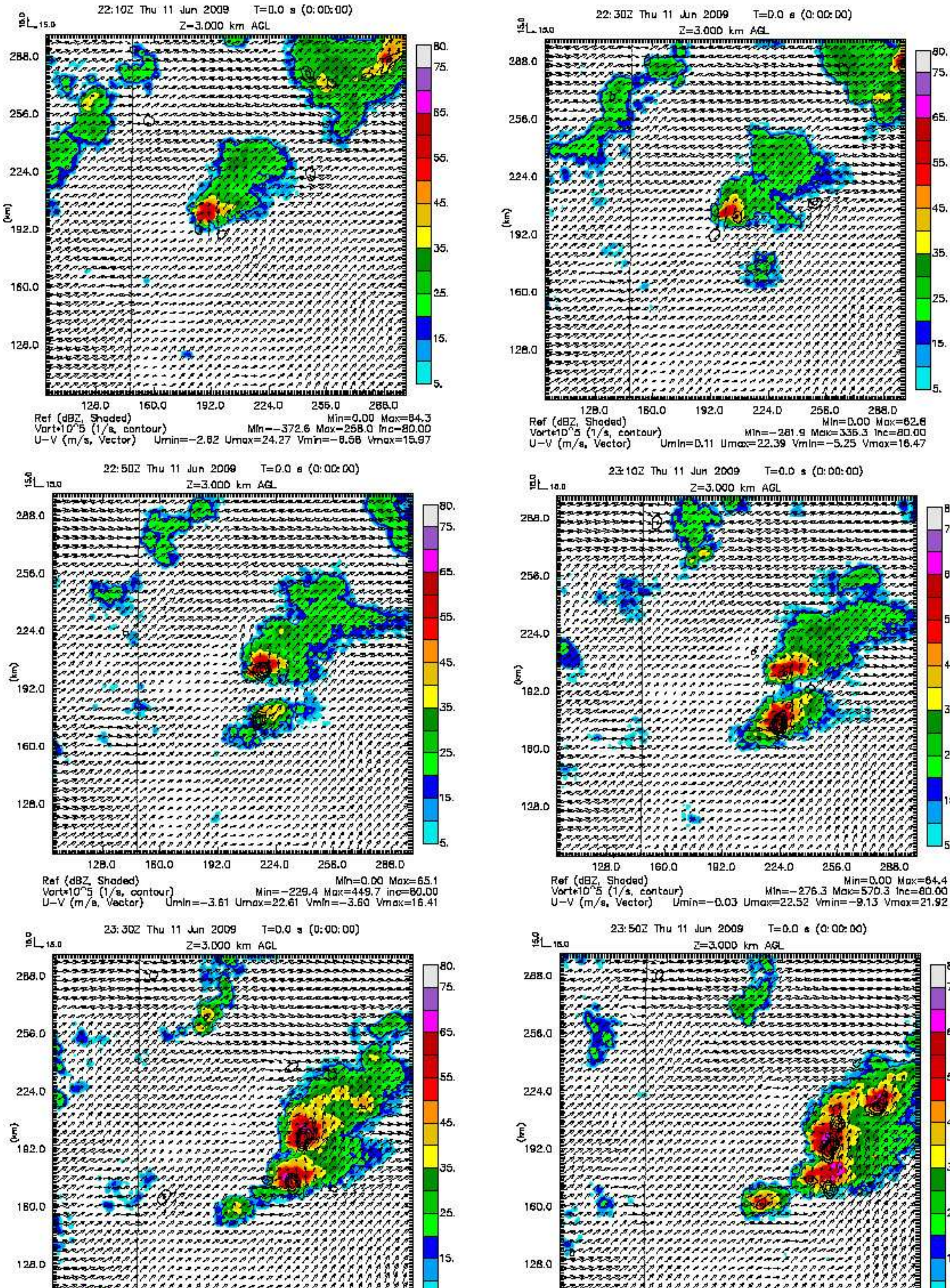

Fig.5.The analyzed reflectivity, horizontal wind fields, and vortices at z=3 km using data from KPUX, and KFTG radars valid at (a) 2210 UTC, (b) 2230 UTC, (c) 2250 UTC, (d) 2310 UTC, (e) 2330 UTC, and (f) 2350 UTC, June, 11 2009 near PUEBLO, CO.

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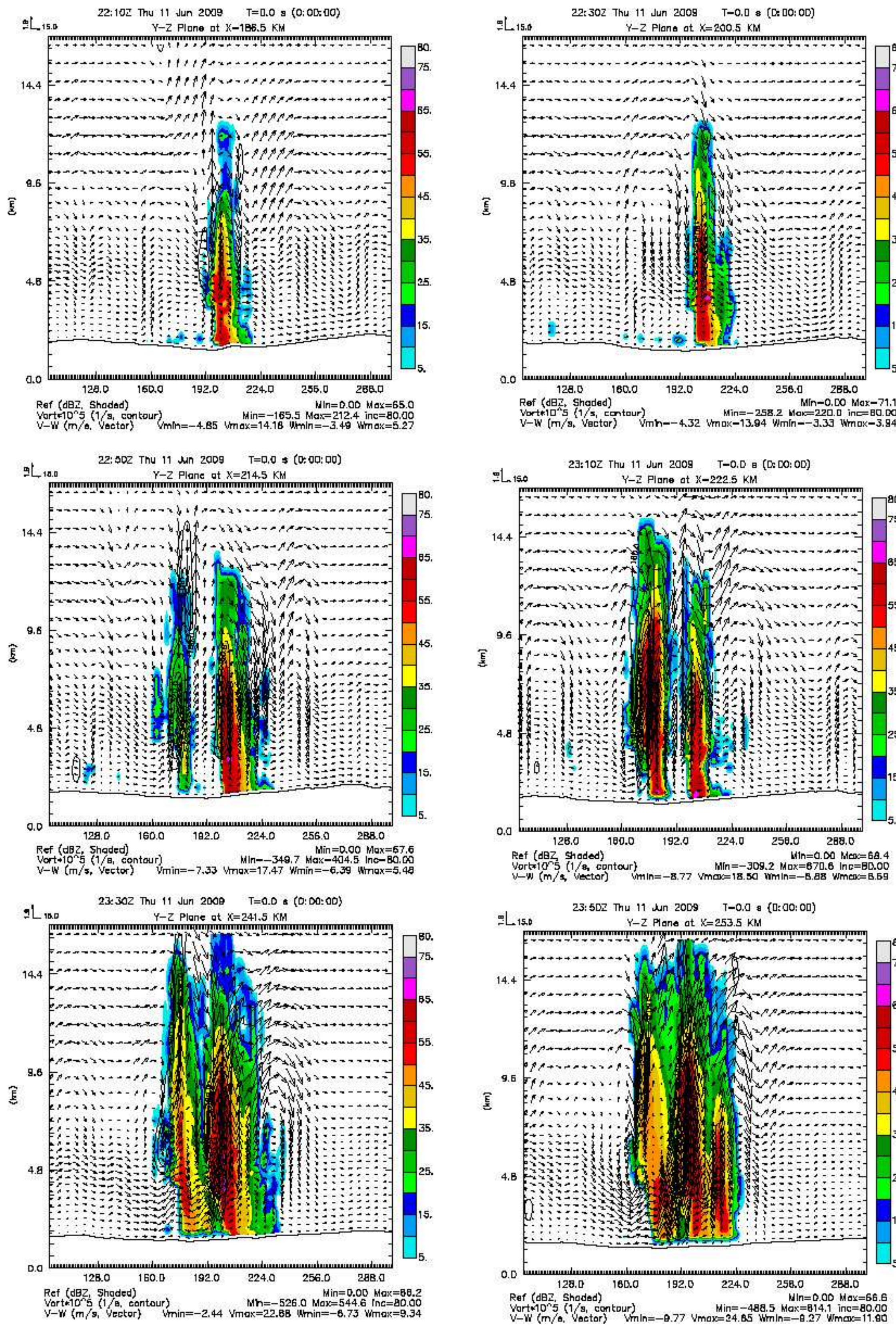

Fig. 6. Same as Fig.5, but for vertical slice through the maximum of vertical velocity.

cyclonic circulation beginning at 2120 UTC and persisted until the end of the analysis. The mesocyclone first developed in the mid levels and gradually extended downward and reached the ground at 2120 UTC. The mesocyclone maintained its strength and vertical extent until 2220 UTC. The development of weak echo region (WER) feature (though not very classic) within the supercell core was evident around 2120 UTC, and became much more clear by 2200 UTC when the tornado touched down (Fig 2). This storm moved gradually to the east. During this period, the storm produced large hail and the EF-2 tornado reached the ground around 2207 UTC in Goshen County. The supercell became weak after moving eastward into Nebraska (Fig 1f and 2f).

The second case examined is a nontornadic supercell event that took place in Bates and Mound County, Missouri (Figs. 3, 4). For this case, reflectivity and radial velocity observations from four nearby WSR-88Ds at Topeka, KS (KTWX), Kansas City, MO (KEAX), Omaha, NE (KOAX), and Des Moines, IA (KDMX) are used in the 3DVAR analysis system. The storm environment was very suitable for severe weather on this day. Several tornadoes and numerous reports of large hail are seen across the plains states. Several storm cells developed in southeast Nebraska and moved toward the joint boundary of the three states of Nebraska, Kansas, and Missouri from 2130 UTC, 7 June to 0000 UTC 8 June. At least two of these cells developed into supercells (Figs. 3 and 4). During this development process, the leftmost cell (located farthest to the west) first became supercellular. The hook echo appeared at 2145 UTC and its maximum vertical velocity reached above 15 ms^{-1} (Fig 3a, 4a). The WER was also evident near the area of maximum updraft below 4 km level. Vertical vortices were weak below 4 km level, but above 4 km the maximum vorticity was above 0.004 s^{-1} for this 1 km resolution analysis (Fig 4a). After this time, the mesocyclone gradually reached to the ground and maintained its strength until 2325 UTC (Fig. 4c, d, e, f). Both supercell storms were well organized on this day and rear flank downdrafts (RFDs) were also very clear at several analysis times (Fig 4c, d, e, f). During this time period, golf ball size hail was observed.

The third case is another nontornadic supercell event that took place in Larimer county, Colorado (Fig 5, 6). For this case, observations from only two WSR-88Ds are used. One is at Denver, CO (KFTG), and the other is at Pueblo, CO (KPUX). Two major supercells are present during this event, but they developed at different times. Comparing with the two previous cases, the primary storm updraft cores were not as deep and the maximum vertical velocity is less than 10 ms^{-1} most of time, but the intensity of circulations are almost identical to the two previous cases. The first cell (or north cell) developed around 2210 with very weak updraft just over 5 ms^{-1} (Fig. 6a). This storm cell moved slowly to the east and maintained its strength throughout the entire 90 minute analysis period. A second cell (or south cell) initialized at 2230 UTC and became a well organized supercell around 2310 UTC. The circulations for both supercells became strongest around 2330 UTC and large hail was reported before and around this time. Although no tornadoes were reported for this case, and the analyzed vertical velocities were much weaker, these two cells still exhibited the characteristics of supercell storms. The atmosphere also was quite instable around 2350 UTC, with new cells developing both southwest and northeast of these two supercells (Fig 6f).

The analyses for all three cases indicate no distinguishable analysis differences among tornadic and non tornadic supercells. This is not a surprise since the horizontal grid spacing of our analyses is only 1 km and is too large to resolve tornado-scale features. Although much higher resolution analyses can be performed, the radar data we used is also about same resolution. Other high resolution data may be needed to identify differences between tornadic and nontornadic supercells; hopefully the special observations collected during VORTEX2 will shed new light on this topic.

5. Summary

Radar is a fundamental tool for severe storm monitoring and nowcasting activities. Forecasters examine real-time WSR-88D observations, radar algorithm products, and use their considerable experience and situational awareness to issue severe storm warnings that help protect the public from hazardous weather events. However, there are situations for which even well-trained forecasters find it challenging to make a sound judgment based on information from only a single WSR-88D. To take more complete advantage of the full information content from the WSR-88D network and recently easy-to-access high resolution operational model analysis and forecast products, we propose a data assimilation method that mixes possible all available information together. The proposed method may have the potential to provide improved information for making severe weather warning decisions. The objectivity of the procedure ensures that (i) all available information, including nearby several WSR-88Ds and NAM high resolution analysis and forecast products, are used, (ii) physically-consistent gridded data are provided to forecasters to help make their decisions in a timely manner, and (iii) the problem of subjectivity, inherent to some arbitrary criteria (for example implemented in the MDA), is avoided. Furthermore, the analysis method can be run automatically and enables, for example, the study of a specific area in greater detail or the investigation of the evolution and lifetime of certain kinds of severe weather.

The potential of this method is shown by detecting the initiation and evolution of supercells from several case studies. This study represents the first step in the assessment of this type of analysis approach for use in severe weather warnings, such as tornadoes, large hail and strong damaging winds. While we recognize that the MDA is very useful for identifying supercell thunderstorms, analyses from a 3DVAR approach may provide more intuitive products that can be just as effectively used by forecasters, while also providing the benefits gained from using observations from multiple WSR-88Ds and other data sources. Alternatively, the output of a 3DVAR analysis can be inserted into MDA-like algorithm for use in warning operations. This will be our future work.

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REFERENCES

Bunkers, M. R. Hjelmfelt, and P. L. Smith, 2006: An observational examination of long-lived supercells. Part I: Characteristics, evolution, and demise. *Wea. Forecasting*, **21**, 673–688.

Bunkers, M. R., D. R. Clabo, and J. W. Zeitler, 2009: Comments on ‘‘Structure and Formation Mechanism on the 24 May 2000 Supercell-Like Storm Developing in a Moist Environment over the Kanto Plain, Japan’’. *Mon. Wea. Rev*., **137**, 2703–2711.

Burgess, D. W., 1976: Single Doppler radar vortex recognition: Part I—Mesocyclone signatures. Preprints, 17th Conf. on Radar Meteorology, Seattle, WA, Amer. Meteor. Soc., 97–103.

Burgess, D. W., V. T. Wood, and R. A. Brown, 1982: Mesocyclone evolution statistics. Preprints, 12th Conf. on Severe Local Storms, San Antonio, TX, Amer. Meteor. Soc., 422–424.

Burgess, D. W., and L. R. Lemon, 1991: Characteristics of mesocyclones detected during a NEXRAD test. Preprints, 25th Int. Conf. on Radar Meteorology, Paris, France, Amer. Meteor. Soc., 39–42.

Burguess, D.W., Doswell, C.A., 1993. Tornadoes and tornadic storms: a review of conceptual models. The Tornado: Its Structure, Dynamics, Prediction and Hazards. Geophys. Monogr., vol. 79. Amer. Geophys. Union, pp. 161–172.

Gao, J., M. Xue, K. Brewster, F. Carr, and K. K.Droegemeier, 2002: New Development of a 3DVAR system for a nonhydrostatic NWP model. Preprint, *15th Conf. Num. Wea. Pred.and 19th Conf. Wea. Anal. Forecasting*, San Antonio, TX, Amer. Meteor. Soc., 339-341.

Gao, J., M. Xue, K. Brewster, and K. K. Droegemeier, 2003: A 3DVAR method for Doppler radar wind assimilation with recursive filter. *31st Conf. Radar Meteor*., Seatle, WA, Amer. Meteor. Soc.

Gao, J., M. Xue, K. Brewster, and K. K. Droegemeier 2004: A three-dimensional variational data assimilation method with recursive filter for single-Doppler radar, J. *Atmos. Oceanic. Technol.* **21**, 457-469.

Hu, M., M. Xue, J. Gao and K. Brewster, 2006: 3DVAR and Cloud Analysis with WSR-88D Level-II Data for the Prediction of the Fort Worth, Texas, Tornadic Thunderstorms. Part II: Impact of Radial Velocity Analysis via 3DVAR. *Mon. Wea. Rev*.,**134**, 699-721.

Lemon, L. R., and C. A. Doswell III, 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev.*, **107**, 1184–1197.

Purser, R. J., W.-S. Wu, D. Parrish, and N. M. Roberts, 2003: Numerical aspects of the application of recursive filters to variational statistical analysis. Part I: Spatially homogeneous and isotropic Gaussian covariances. *Mon. Wea. Rev.,* **131,** 1524–1535.

Stumpf, G. J., A. Witt, E. D. Mitchell, P. L. Spencer, J.T. Johnson, M. D. Eilts, K. W. Thomas, D. W. Burgess, 1998: The National Severe Storms Laboratory Mesocyclone Detection Algorithm for the WSR-88D. *Weather and Forecasting*, **13,** 304-326.

Zrnić, D. S., D. W. Burgess, and L. D. Hennington, 1985: Automatic detection of mesocyclonic shear with Doppler radar. Journal of Atmospheric and Oceanic Technology, **2,** 425-438.

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

Xue, M., and Coauthors, 2001: The Advanced Regional Prediction System (ARPS)—A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part II: Model physics and applications. *Meteor. Atmos. Phys.*, **76,** 134–165.

Xue, M., D. Wang, J. Gao, K. Brewster, and K. K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. *Meteor. Atmos. Phys.*, **76,** 143–165.