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9B.2 Importance of Environmental Variability to Ensemble Storm-scale Radar Data Assimilation and Very Short Range NWP

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1. Introduction

Ensemble forecasting produces multiple, concurrently valid forecasts starting from slightly different initial conditions and/or somewhat different model configurations. For short-range forecasting, the ensemble member initial conditions typically are created using bred or singular vectors, while the forecasts are made using either the same model, the same model with different physics options, or from different models (so-called super ensemble). Lagged average forecasts have also been used in short-range ensemble forecasting. Over the past decade, ensemble forecasting has become more popular in both operational and research numerical weather prediction (NWP) as a method to provide probabilistic forecast guidance (Brooks et al. 1995; Stensrud et al. 2000; Du and Tracton 2001; Hamill et al. 2000; Hou et al. 2001; Krishnamurti, et al. 2001; Lewis 2005; Stensrud and Yussouf, 2007; Yussouf and Stensrud 2006). However, these ensemble applications have focused upon synoptic scale and mesoscale weather phenomena using model grid spacing that cannot explicitly resolve convective storms.

The deterministic and explicit numerical prediction of convective storms using fine-scale observations from Doppler radars and other sensing systems have been explored with nonhydrostatic cloud-resolving models over a decade (e.g., Lin et al. 1993; Sun and Crook 1998; Crook and Sun 1996, 2004; Xue et al. 2003; Alberoni et al. 2003). However, the considerable difficulties surrounding the production of accurate stormscale NWP, together with the large societal impacts of severe local weather, has led to the call for a considerable emphasis on probabilistic methods as the optimal strategy to provide user guidance. Since the Nation's current supercomputer systems are now capable of running many cloud models simultaneously, it is important to determine whether or not cloud model ensembles can provide beneficial insight into convective storm characteristics.

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Storm-scale ensemble forecasting via the use of cloud models initialized with horizontally homogeneous environments and thermal bubbles in a simple context has been studied in recent years by Elmore et al. (2002, 2003). Their results showed that when storm lifetimes of at least 60 min are used as a proxy for severe weather, the ensemble shows considerable skill at identifying days that are likely to produce severe weather. Using the Advanced Regional Prediction System (ARPS, Xue et al. 2000, 2001, 2003), full-physics storm-scale ensembles that include terrain, horizontally varying initial conditions, and the assimilation of real observations—particularly from Weather Surveillance Radar-1988 Doppler (WSR-88D) radar data—have been attempted by Kong et al. (2006, 2007). Though only five-member ensembles were employed using a scaled lagged average forecasting technique, they found that the ensembles with a 3-km grid spacing can capture explicitly the details of storm evolution in good agreement with observations than any single ensemble member when using a modeling system with explicit cloud microphysics that assimilated WSR-88D Level III radar data. The research indicates that the quality of the resulting storm-scale analyses and forecasts are sensitive to the storm environment, parameterized microphysics, the details of the assimilation methodology, the quality of radar data, and the method used to generate the initial ensemble members. In this study, we investigate the importance of environmental variability to storm-scale radar data assimilation (DA) and forecasting by including environmental variability within a variational data assimilation system (3DVAR) and a cloud analysis package developed at the Center for Analysis and Prediction of Storms (CAPS).

The ARPS 3DVAR system (Gao et al. 2004) is used to assimilate WSR-88D radar data from the case of May 2007 Greensburg, KS tornadic thunderstorm into the ARPS model. Both reflectivity and radial velocity data are assimilated. An ensemble approach for increasing initial condition complexity is used to examine the importance of mesoscale environmental variability on storm-scale radar data assimilation and prediction. Ensembles of 3DVAR analyses and forecasting are conducted using 1) a horizontally homogeneous environment initialized with an observed sounding from

Dodge City prior to the time of observed tornadic supercell, 2) 30 vertical soundings extracted from a 30-member mesoscale WRF-DART (the Data Assimilation Research Testbed) ensemble Kalman filter (EnKF) analysis system valid near Greensburg KS, and 3) 30 three-dimensional (3D) fields with heterogeneous environments extracted from the same WRF-DART analysis system. These 3DVAR analyses with rapid update cycles are created and examined. Forecasts are launched from these analyses to assess the relative importance of vertical and horizontal environmental variability to storm-scale radar DA and numerical weather prediction (NWP). Our principal goal is to quantify the value of the ensemble of 3DVAR analyses, and the assimilation of WSR-88D radar data, to improving the accuracy of stormscale forecasting from both deterministic and probabilistic viewpoints. A set of preliminary experiments have been completed and the results are reported here. Although a single case study does not provide sufficient information with which to draw general conclusions, the present work represents a first step. More experiments with an EnKF DA approach will be tested in the future.

Section 2 provides an overview of the tornadic storm case while section 3 describes the DA system and experiment design. Experiment results and qualitative performance are assessed in section 4. We conclude in section 5 with a summary and outlook for future work.

2. The Greensburg Kansas tornadic thunderstorm

We chose the 4-5 May 2007 Greensburg, Kansas (KS), tornadic thunderstorm case for our test because it is well documented and produced one of the strongest tornadoes in recent years. The storm complex produced 18 tornadoes in the Dodge City forecast area and 47 tornado reports in Kansas, Nebraska and Missouri. The tornado that started moving through Greensburg at 0245 UTC 5 May 2007 (21:45 CDT 4 May) and destroyed over 90 % of the town. The tornado damage was rated at EF5 - the highest rating on the Enhanced Fujita scale (McCarthy et al., 2007).

The synoptic setting for this event consisted of a deep long-wave trough over the western U.S., a surface low over eastern Colorado, and a quasi-stationary front extending from the low across northwest Kansas into northeast Nebraska (Fig. 1). A dryline was located across western Kansas into west Texas. A very moist and unstable air mass was present east of the dryline. A deep moist layer was advecting northward into central Kansas ahead of the dryline in the evening of 4 May 2007 as indicated by the OUN sounding (not shown). The forecast sounding valid at 03 UTC 5 May 2007 from the NCEP NAM model showed a quite favorable environment to support supercell storms development.

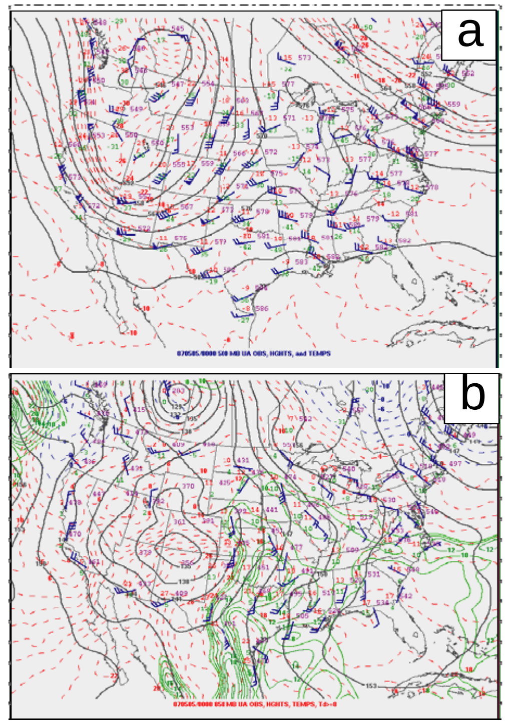

Fig. 1. NCEP NAM analysis valid at 00 UTC 5 May 2007 at (a) 500 hPa, (b) 850 hPa. Heights are shown as black contours (in decameters); and temperatures are shown by dashed red contours.

Initial storm development occurred over the northern Texas panhandle/Oklahoma border around 2210 UTC on 4 May 2007. A surface analysis at 2100 UTC shows this location to be in a favorable location on the surface dry line (not shown). The low-level jet (with speeds $\geq$ 25 ms^{-1}) from north central Texas through eastern Kansas enhanced moisture flux convergence through western Oklahoma into south central Kansas, just east of the dryline (Fig. 1b). Several additional cells developed over northwest Oklahoma around 00 UTC 5 May. The cell that eventually produced the Greensburg, KS tornado developed over north central Harper County, Oklahoma around 0050 UTC and was moving north-northeast at about 20 ms^{-1}. The cell first developed its hook signature by 0106 UTC over south-central Clark County at 0113 UTC. Between 0130 UTC and 0148 UTC, a strong middle-level mesocyclone was very clear and persistent in the data of Dodge City WSR-88D radar (not shown). As the storm approached Greensburg, it intensified rapidly. It began to take on a hook echo shape, and strength of its rotation increased dramatically. Forecasters were well aware of the likelihood of severe tornadoes, as the NWS Dodge City Weather Forecast Office issued a tornado warning 30 minutes ahead of time.

3. The ARPS 3DVAR, cloud analysis system and experiment design

The model and DA used in this study is a three-dimensional, nonhydrostatic compressible numerical weather prediction system (Xue et al. 2000, 2001) and its 3DVAR DA system that includes a complex cloud analysis package (Gao et al. 2002, 2003, 2004, Brewster 2005; Hu et al. 2006b). In this study we use 3-km grid spacing with 200x200 grid points in the horizontal. The domain is selected with sufficient coverage to contain the principal features of interest while maintaining some distance between primary storms and the lateral boundaries. The model uses 47 terrain-following vertical layers, with nonlinear stretching, via a hyperbolic tangent function, that yields a spacing of 100 m at the ground that expands to approximately 800 m at the top of the domain.

By using data from two or more Doppler radars scanning the same atmospheric volume simultaneously, it is possible to determine the 3-D winds from radial velocity data, and the quality of reflectivity data also can be greatly improved through quality control steps. The 3DVAR DA system uses a recursive filter (Purser et al. 2003a, b) and mass continuity equation and other constraints by incorporating them into a cost function, yielding the analyses of three wind components and other model variables.

In this study, the 3DVAR technique is used to do rapid analysis cycles for the Greensburg case. A cloud analysis package follows the 3DVAR analysis step that uses the radar reflectivity data and other cloud observations. The package is initially based on the Local Analysis and Prediction System LAPS (Albers et al. 1996) and subsequently modified for the ARPS system (Zhang et al. 1998; Brewstrer 2002; Hu et al. 2006a). In this study, the mixing ratio of precipitation (including rain water, snow, and hail) and potential temperature are adjusted within the cloud analysis based on reflectivity measurements, although the other hydrometeor variables are not adjusted to avoid negative impacts of these adjustments on the balance of model equations when rapid analysis cycles are applied.

Traditional approaches for creating ensemble initial conditions, such as the Monte Carlo (random perturbations) (e.g., Mullen and Baumhefner 1989), breeding of growing modes (e.g., Toth and Kalnay 1997), lagged average forecasting (e.g., Hoffman and Kalnay 1983), singular vectors (e.g., Hamill et al. 2000), physics perturbations (e.g., Stensrud et al. 2000), and ensemble Kalman-filter-based techniques (e.g., Houtekamer and Mitchell 1998) are not used here. Some of these methods may not be directly applicable to storm-scale NWP even though they have been applied to large-scale hydrostatic NWP models with much success. In this study, the ensemble initial conditions are produced by performing storm-scale 3DVAR analyses using different background environments.

For the first analysis and forecast experiment (named experiment ExDDC), the 0000 UTC Dodge City (DDC) sounding is used to define the horizontally homogeneous storm-scale analysis background or the storm environment. For the second set of ensemble experiments (named AnxSnd), 30 analysis and forecast experiments are performed, where the initial conditions are obtained using the ARPS storm-scale (3DVAR plus cloud analysis) analyses, with the analysis backgrounds defined, respectively, by 30 individual soundings extracted from 30 mesoscale WRF-DART EnKF analyses at a location near Greensburg. It is expected that these soundings provide a reasonable estimate of the environmental variability for the storm-scale forecasts. The third set of experiments (named Anx3D) is the same as the second set, except for the use of the 3-D mesoscale scale analyses from WRF-DART to define the storm-scale analysis background.

For all the experiments, the reflectivity and radial velocity from six radars at Dodge City (KDDC), (Vance AFB, OK (KVNX), Wichita Kansas (KICT), Oklahoma City (KTLX), Amarillo TX (KAMA) and Topeka Kansas (KTWX) are used in the 3DVAR and cloud analysis system. Each experiment consists of a 1-h DA period (from 0130-0230 UTC) and a 1-h forecast period (0230-0330 UTC). The assimilation period contains thirteen analysis cycles at 5-minute intervals, where a 5 minute ARPS forecast follows each analysis until the end of the 1-h assimilation period. From the final analysis, a 1-h forecast is launched.

4. Results

In this section, we present ensemble forecasts from each of the initialization strategies, and use analyses from WSR-88D data for verification. The evolution of the storm as indicated by the analyzed radar reflectivity, horizontal winds, and vertical vorticity at the 2 km level is shown in Fig. 2 from 0240 to 0320 UTC. The development of hook feature for the major supercell near Greensburg area around 0240 UTC is very clear. The wind analysis at this level indicates a very strong mid-level cyclonic circulation. This storm moved gradually in the northeast direction. During this period, the storm produced the most intense tornado that hit the town of Greensburg. The storm maintained a very strong circulation and continued to move to the northeast, and second tornado developed coincident with the end of Greensburg tornado just northeast of the town (McCarthy 2007).

Our first analysis and forecast experiment (ExDDC) that uses the Dodge City sounding at 00 UTC to define the storm-scale analysis background is able to

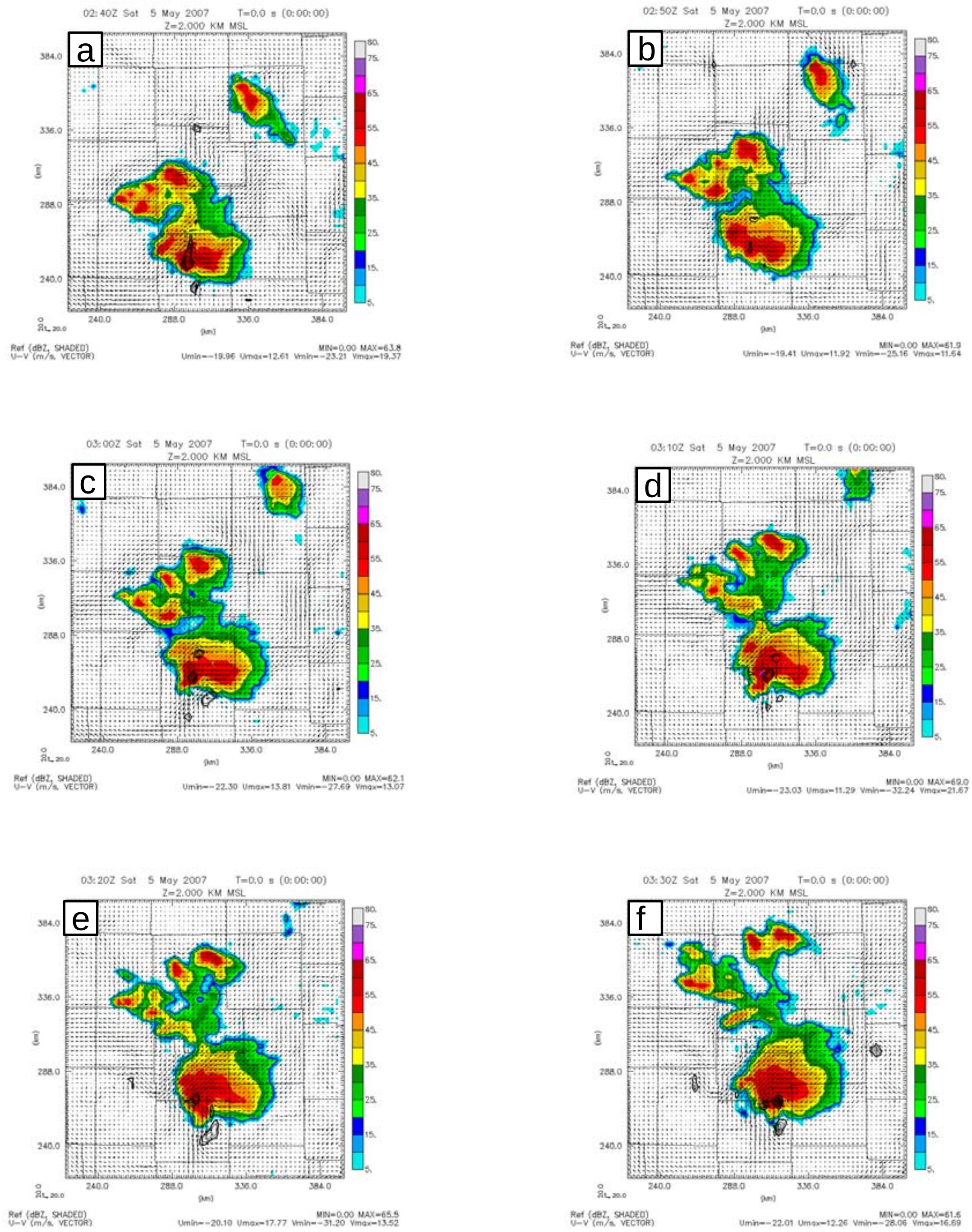

Fig. 2. The analyzed reflectivity, horizontal wind fields, and vorticity at z=2 km using data from KDDC, KICT, KVNX, KTLX, and KTWX radars valid at (a) 0240 UTC, (b) 0250 UTC, (c) 0300 UTC, (d) 0310 UTC, (e) 0320 UTC, and (f) 0330 UTC.

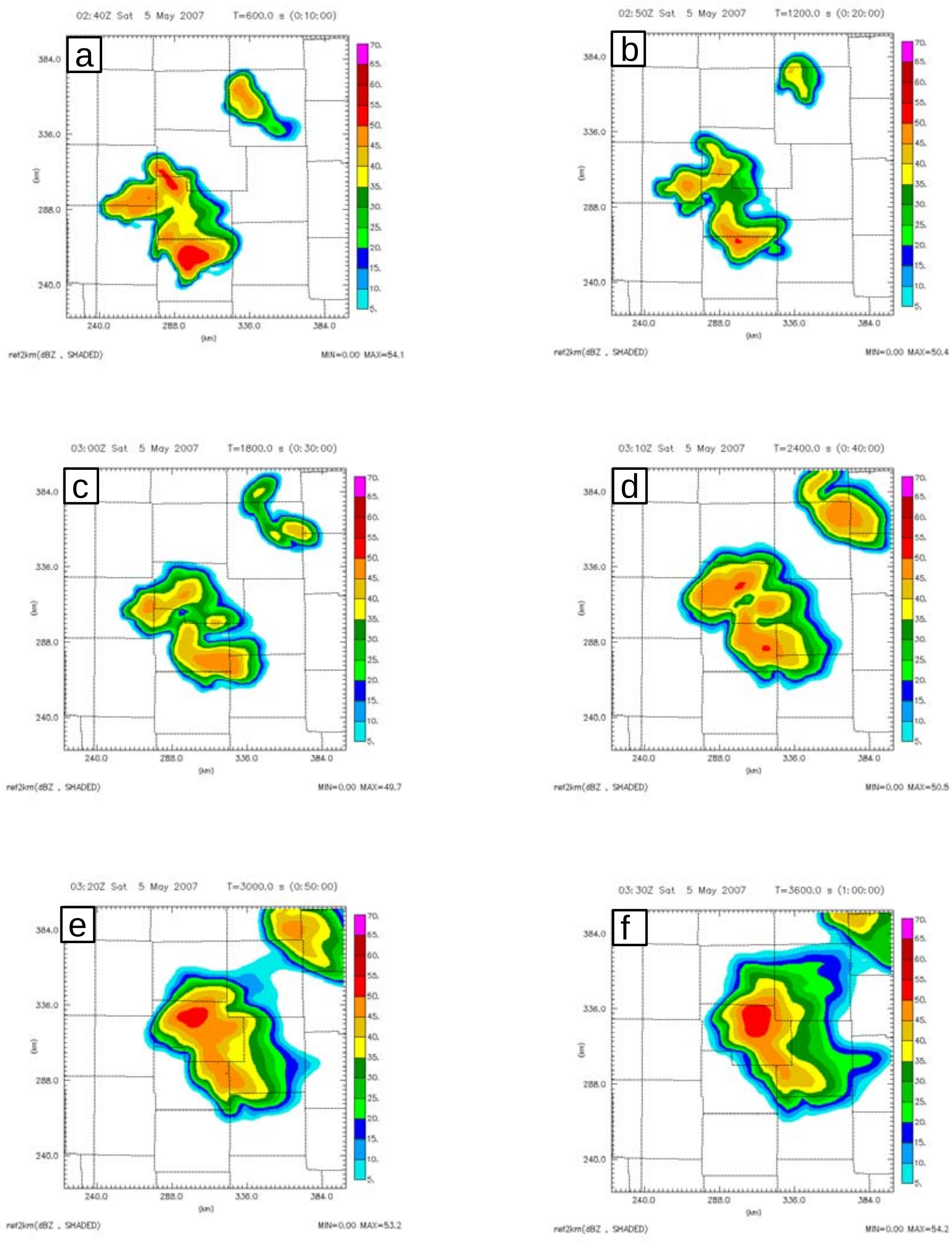

Fig. 3. Same as Fig. 2 (without wind vectors), but for the ensemble mean forecast produced from the ensemble, AnxSnd, starting from the 3DVAR analyses using the soundings extracted from the WRF-DART analyses to define the background.

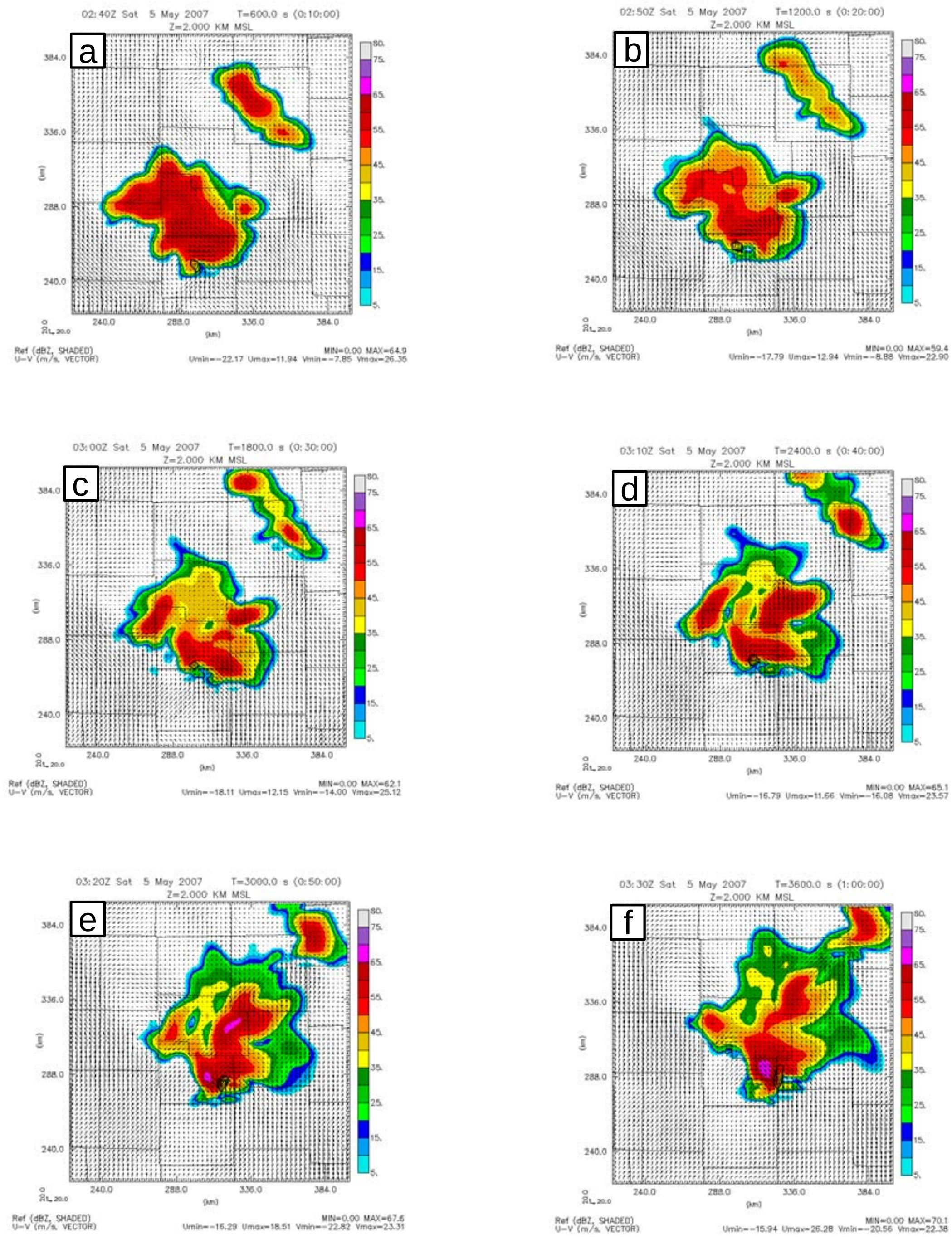

Fig. 4. Same as Fig. 2, but for the forecast of ensemble member 6 using one of the 3D WRF-DART analyses as our storm-scale analysis background.

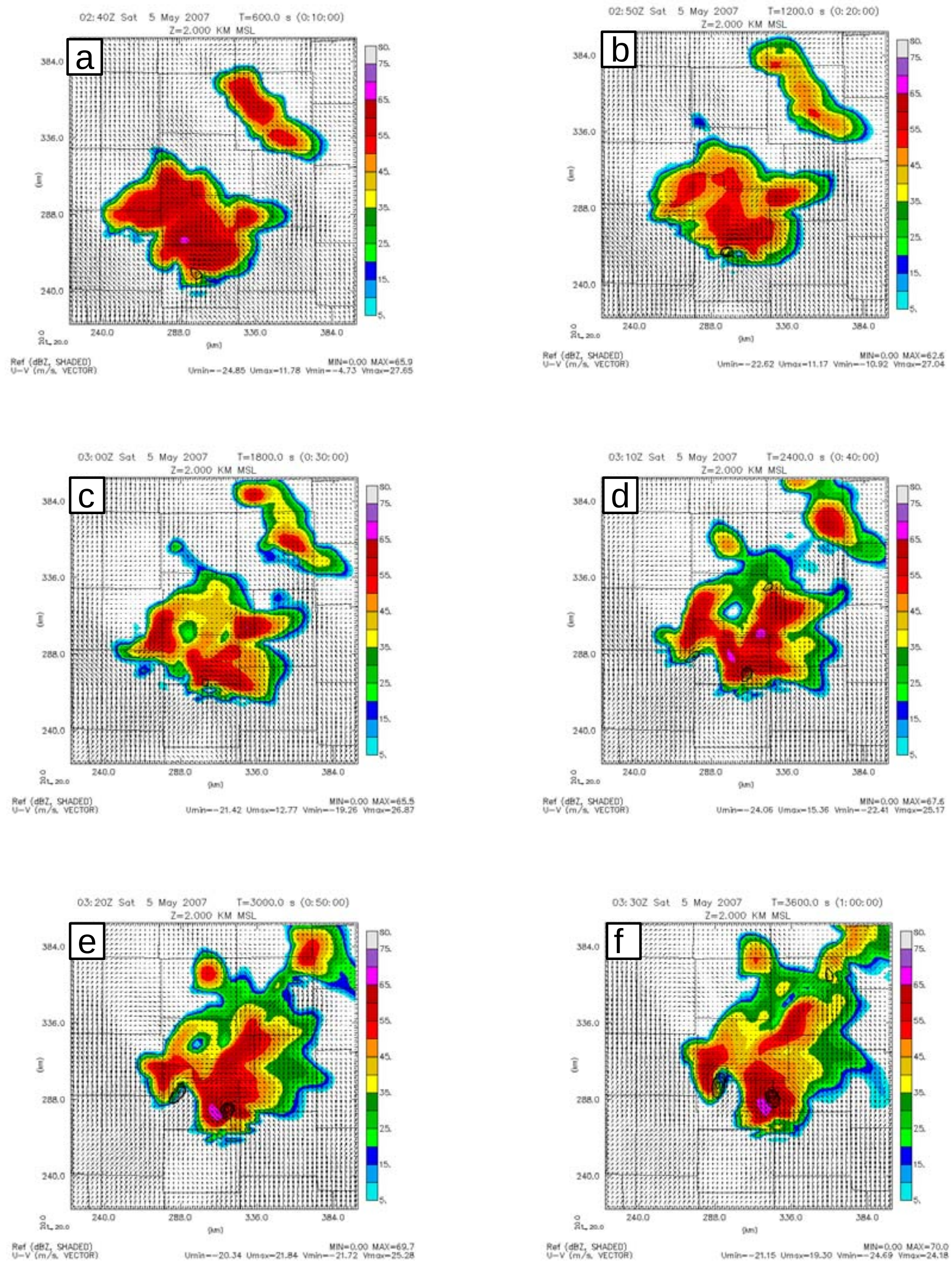

Fig. 5. Same as Fig. 2, but for the forecast from ensemble member 13 using another of the 3D WRF-DART analyses as the storm-scale analysis background.

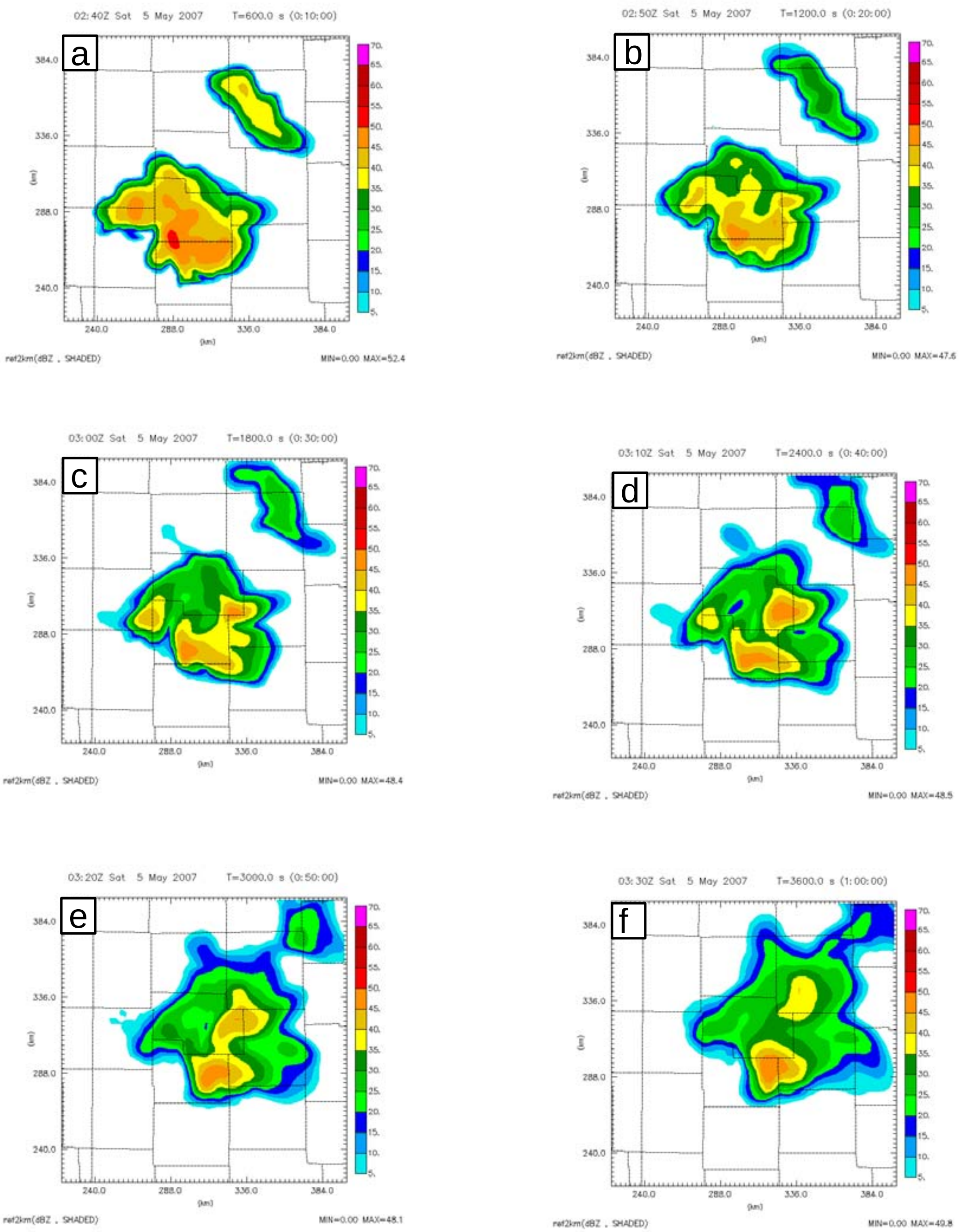

Fig. 6. Same as Fig 2 (without wind vectors), but for the ensemble mean forecast produced from the ensemble that uses the 30 3D WRF-DART analyses as the background of individual storm-scale analysis.zscN873

capture the right path of the storm that produced the Greensburg tornado. But the storm is generally very weak, and the associated hook echo is not very clear (not shown). In the second set of experiments (AnxSnd), 30-member ensemble forecasts are produced with initial conditions analyzed using extracted WRF-DART soundings to define the background. Some ensemble members produce reasonable forecasts of the storms, but most members predict a main storm that propagates too fast to the northeast. As indicated by the ensemble mean forecast in Fig. 3, the initially dominant cell on the right (south side) merges with some smaller cells to its north as it propagates to the northeast (also see Fig. 2 for comparison). By the end of the one hour forecast period, the cells to the north have grown stronger in most of the ensemble members, resulting in a reflectivity maximum that is too far to the north in the ensemble mean (Fig. 3f), as compared to the observation (Fig. 2f). While some of the individual ensemble members have more complex structures and suggest several cells at the end of the forecast period, there is a strong tendency among all the members to create a single large storm complex located north of the most intense observed cell near Greensburg. In general, the results from this set of experiments are not good.

Our focus is on the third set of experiments because in this case the storm environments include both horizontal and vertical variabilities. In this case, the forecasts from most of the ensemble members match the analysis much better than the previous cases. Figure 4 shows the forecast of ensemble member 6, valid at times shown in Fig. 2. The 10-minute forecast valid at 0240 UTC indicates an obvious hook echo near Greensburg accompanied by a strong mesocyclone (Fig. 4a). The storm moves slowly to the northeast and maintains its strength throughout the entire one-hour forecast period. Several small cells separate from the major storm do not merge with the major cell. With a slightly different storm environment, ensemble member 13 preduces somewhat different forecasts. Compared to the forecast from member 6 in Fig. 4, the reflectivity from member 13 indicates a cell with a strong circulation just west of the major storm, which is not supported by the analysis created from the radar observation (Fig. 5). The analysis of other ensemble members indicates the most of the forecasts are similar to the member 6, but several others are similar to member 13 with some kinds of variability.

Because of the spatially intermittent nature of deep convection, the ensemble mean reflectivity forecast is usually weaker than individual forecasts due to the averaging and smearing effects. But it still gives us useful information. Figure 6 shows the 1-h reflectivity forecasts from the ensemble mean. The mean compares reasonably well with the analyses in Fig. 2 in the structure, location and evolution of the major convective storm. Even though the smaller cells at several locations are missing, the location of main supercell that produced the Greensburg tornado is predicted reasonably well by the ensemble mean. This indicates that there is a high-level of consistency among the ensemble members for the forecast of the main cell.

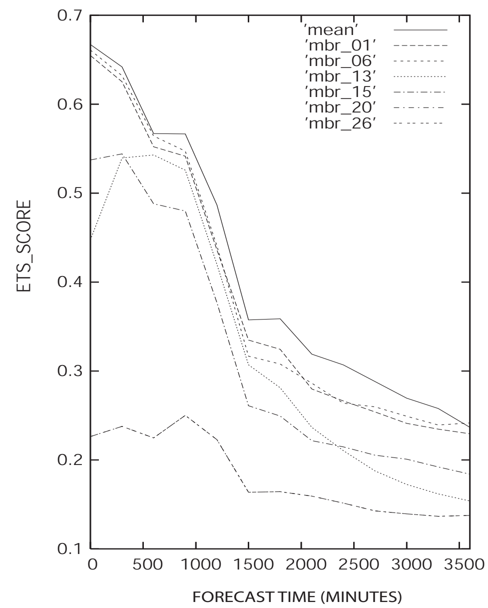

Fig. 7. ETS in the third experiment for reflectivity greater than 35 dBZ at z=2km for several ensemble members as well as ensemble mean.

A benefit of ensemble forecasting is the capability of generating probability products that quantify the relative frequency of occurrence of a weather event. This is even more valuable for explicitly resolved deep convective storms because probabilities highlight the likely occurrence of extreme or intense events (Kong et al. 2006). Thus, we also calculated the probability of composite reflectivity greater than 35 dBZ for the forecast period (not shown). In this case, the region of highest probabilities is generally in a good agreement with region of high observed reflectivity. Spuriously strong echoes found in some of the ensemble members have relatively low probability. Such probabilistic information should be very useful to forecasters.

To quantify forecast skill, we calculate the equitable threat scores (ETS) for randomly picked ensemble members and the ensemble mean, for reflectivity exceeding the 35 dBZ threshold. Figure 7 shows that the ETS scores for ensemble mean surpass those of several randomly picked individual members during the 1-h forecast period. Therefore, for this particular case, the ensemble mean has greater skill than the individual members when three-dimensional storm environments are defined by the mesoscale WRF-DART analyses. When either observed nearby sounding or soundings extracted from this set of mesoscale analyses are used, the forecast results are worse.

5. Summary

The assimilation of WSR-88D radar data into storm-scale weather prediction models for short-range forecasting represents a significant scientific and technological challenge. Numerical experiments over the past few years indicate that the quality of the resulting storm-scale analyses and forecasts are sensitive to the storm environment, parameterized microphysics, the details of the assimilation methodology, the quality of the radar data, and the method used to generate the initial ensemble members. In this study, we investigate the importance of mesoscale environmental variability to storm-scale radar data assimilation and subsequent forecasting by including explicit environmental information produced from a mesoscale ensemble data assimilation system.

The mesoscale environmental variability on storm-scale radar DA is provided by 1) a single Dodge City sounding, 2) 30 soundings extracted from mesoscale ensemble analyses, and 3) the 30 3-D mesoscale ensemble analyses directly. Such environments are introduced by using them as the analysis background for the storm-scale analyses with radar data. One-hour long analysis cycles at 5-minute intervals are performed in each case, followed by 1-hour long forecasts. It is shown that most of the forecasts initialized using the 3D mesoscale environment compared favorably to the observations in terms of radar reflectivity, with obvious rotation signatures in the forecasts. Most of these ensemble members predicted reasonably well the overall storm structure and movement, with large spread found in some areas of spurious cells in some members. However, the storm-scale forecasts produced using sounding-based environments fared much worse, with too weak mesocyclones, too much merging of individual convective cells, and resulting in the northern storm being dominant. Overall, the ensemble forecasts with horizontally inhomogeneous environments show greater skills and more operational value than a single deterministic forecast. The derived probabilities provide additional information about storm variability and forecast uncertainty. This result supports other studies noting the value of an ensemble strategy for intense local weather (e.g., Brooks et al. 1995; Elmore et al. 2002, 2003; Kong et al. 2007a). Another side conclusion is that with the assimilation of WSR-88D radar observations, the storm spinup time is much reduced.

Obviously, the single case study cannot lead us to draw general conclusions. Much more work is needed to understand ensemble forecasting of deep convection in real-time settings. Research is ongoing in this area (Xue et al. 2007, 2008; Kong et al. 2007b, 2008). Our efforts in the future will include examining the role of grid nesting, evaluating other techniques for generating initial perturbations, evaluating other DA techniques, such as storm-scale EnKF for convective ensemble forecasting. In addition, more quantitative measures of ensemble skill will be provided in future studies.

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