23.6 HIGH-RESOLUTION STORM-SCALE ENSEMBLE FORECASTS OF THE 28 MARCH 2000 FORT WORTH TORNADIC STORMS

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1. INTRODUCTION

Ensemble forecasting – or the creation of multiple, concurrently valid forecasts from slightly different initial conditions, from different models, or by using different options within the same model – has become the cornerstone of operational global numerical weather prediction (e.g., Kalnay 2003). Extensions to the regional scale have been underway for some time (e.g., Brooks et al. 1995; Hamill et al. 2000), though as for global models, mostly in a framework of hydrostatic dynamics and model grid spacings that do not explicitly resolve convective clouds.

During the past decade, increasing emphasis has been placed on the *explicit* prediction of storm-scale weather, especially deep convection, with the WSR-88D Doppler radar serving as the foundational observing system from which fine-scale wind, thermodynamic, and moisture fields can be observed directly or retrieved (e.g., Droegemeier 1997). Although storm-resolving (grid spacings of 1 km or less) non-hydrostatic models show considerable promise for practicable NWP (e.g., Xue et al. 2003), probabilistic, rather than deterministic forecasts, likely will be required (e.g., Brooks et al. 1992; Hou et al. 2001; Elmore et al. 2002a,b, 2003).

To begin exploring ensemble forecasting of deep convective storms in the context of full NWP (i.e., as opposed to a single-sounding cloud model), we apply herein the scaled lagged average ensemble forecasting (SLAF) technique (Ebisuzaki and Kalnay 1991) to the prediction of thunderstorms that occurred in north central Texas on 28 March 2000, and that produced a tornado in the Fort Worth metropolitan area (Xue et al. 2003). Our goals are to: a) investigate the viability of SLAF in limited-area, multi-resolution forecasting of storm-scale weather; b) examine the effectiveness of ensemble forecasting in comparison to deterministic forecasts of individual convective storms; and c) devise appropriate measures of forecast verification for highly intermittent convective events.

The experiments described herein, though admittedly simple in their use of SLAF, provide a baseline for other work at CAPS involving the structure and growth of errors at the convective scale and the specification of forecast model initial conditions that appropriately include them.

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2. FORT WORTH TORNADIC STORM CASE

On 28 March 2000, an F3 tornado moved through the Fort Worth metro area and later, another hit the Arlington/Grand Prairie area. According to the NCDC storm events data base, these events caused approximately $450 million in damage in the Fort Worth area alone, with five fatalities and 100 injuries associated with the tornado, hail, and flash flooding.

The conditions over north-central Texas were ideally suited for severe weather on the afternoon of 28 March 2000, with Gulf moisture sweeping northward and a dryline moving eastward across the area. Also present was a capping inversion which, coupled with moderate helicity and a low LCL, indicated the potential for severe convection and possibly tornadoes. Operational forecasters were well aware of this potential, though because of its grid spacing and other limitations, the operational Eta model predicted no precipitation south of the Red River in the 12 hours prior to the storms. In reality, a broken line of supercells (Figure 1) was present in this region.

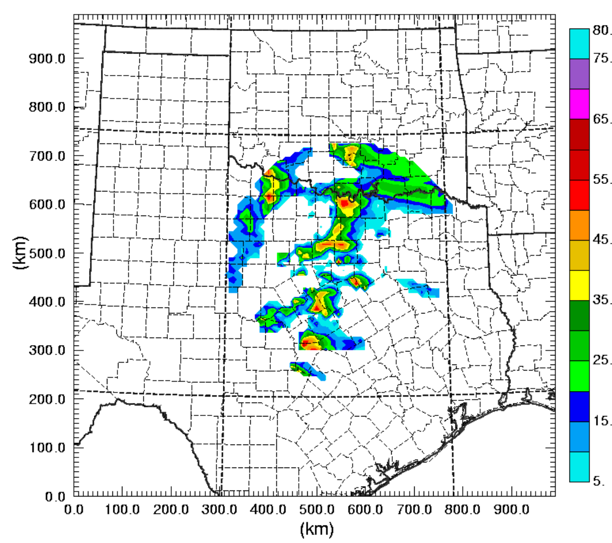

Figure 1. Fort Worth (KFWS) WSR-88D reflectivity at 0000 UTC on 29 March 2000 interpolated to the 9 km ARPS model grid. The altitude shown is 1 km.

3. METHODOLOGY

Storm-scale ensemble forecasting differs considerably from global ensemble forecasting in that a) storm-scale ensemble members cannot (yet) be run at grid spacings much coarser than that of the control forecast, which in this case is 3 km (admittedly coarser than desired); b) nested grids are required at the storm-scale, and their location depends upon the 'changing' weather of interest; thus, one does not have available a long time series of equivalent-resolution forecasts over the same region; and c) the highly local and intermittent nature of storm-scale weather events renders ineffective the application of some traditional ensemble processing and verification techniques (e.g., the mean of 5 forecasts, each containing thunderstorms displaced geographically from one another, will be a forecast having a broader area of storm coverage with reduced amplitude). Further, it is not clear whether theories of error growth (e.g., based upon singular vectors) at the global scale apply to the storm scale.

With these factors in mind, and guided by the methodology used by Xue et al. (2003) in their deterministic predictions of the Fort Worth storms, we utilize the ensemble configuration shown in Figure 2. Note that a virtually unlimited number of configurations is possible in light of the many options available for linking fine grid domains to the coarse grids that supply initial (background) and lateral boundary conditions. The configuration chosen here represents an attempt to utilize the SLAF methodology effectively, but by no means is purported to be optimal.

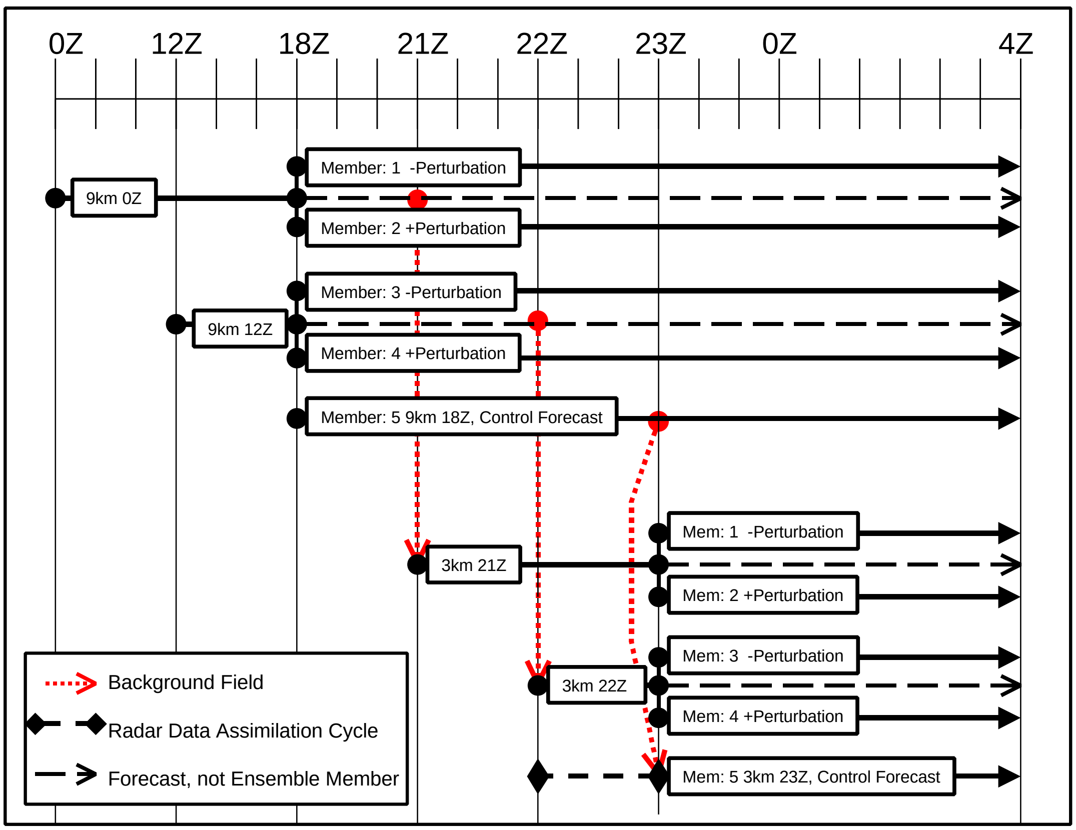

Figure 2. Ensemble forecast configuration for the 9 km (upper) and 3 km grid spacing experiments. The ensemble initial conditions are generated by adding (+ perturbation) and subtracting (- perturbation) the scaled difference between a previous forecast and the verifying analysis at the start of the forecast period. The background fields for the 9 km forecasts are based upon the NCEP Eta analysis at the time shown, while the background fields for the 3 km experiments (dotted lines) are generated by the 9 km ARPS forecasts.

A 9 km coarse-grid ensemble, designed to serve as the background for 3 km fine-grid nested ensembles, is generated by the ARPS model (Xue et al. 2001, 2002) using full radiation, surface, and explicit cloud microphysics. No cumulus parameterization is used at 9 km owing the absence of a clear theoretical basis for doing so (Molinari, 1993), and for the 3 km grid, we assume that relevant cloud-scale processes are handled by the cloud microphysics package (an assumption that would be more valid at 1 km grid spacing). The background state for all 9 km forecasts is the NCEP Eta analysis at 0000, 1200, and 1800 UTC (Figure 2). The ensemble initial conditions are generated by adding (+ perturbation) and subtracting (- perturbation) the scaled difference between a previous ARPS forecast and the verifying analysis at the start of the forecast period (e.g., the 1800 forecast and ensemble members in Figure 2 are based upon the ARPS forecast initiated at 0000 UTC). Boundary conditions also are perturbed in the same manner to avoid destroying the perturbations as the forecast proceeds.

The ARPS Data Assimilation System, ADAS (Brewster, 1996) is used to generate the gridded initial conditions. It utilizes a multi-pass Bratseth scheme (Brewster, 1996) in which the scale of influence changes for each pass (5 passes are used for the 9 km experiments). Hourly observations include surface reports, wind profiler and rawinsonde data, ACARS commercial aircraft wind and temperature data, GOES visible satellite data, and WSR-88D Level III reflectivity and velocity data (inserted only at the start of the forecast unless otherwise noted) from all radars within the computational domain. The vertical grid in the 9 km experiments contains 53 levels, with the spacing stretching from 20 m at the ground to approximately 800 m at the top of the domain.

We utilize the same concept for the 3 km ensembles as for their 9 km counterparts. The initial times for the 3 km background forecasts are 2100, 2200, and 2300 UTC on 28 March 2000, with all ensembles begun at 2300 UTC (Figure 2). At the latter time, differences between the two previous forecasts and the verifying analyses are scaled according to age and used to create four ensemble members. The 3 km forecasts are generated using the same model physics options as those at 9 km. ADAS (Brewster, 1998) again is used to generate the gridded initial conditions using the 9 km forecasts as the background field and a 6-pass Bratseth analysis.

Two additional 5-member, 3 km ensembles are created using a variation of the configuration just explained. The first involves using the 9 km, 1800 UTC forecast for all 3 km background fields. The second is exactly the same as the original 3 km ensemble, but with radar data assimilation cycling (Xue et al. 2003) at 15 minute intervals from 2200 to 2300 UTC (Figure 2). Owing to space considerations, we discuss only results from the latter.

4. 9 KM RESULTS

The principal role of the 9 km forecasts is to provide background and lateral boundary conditions for the 3 km nested ensembles. As noted above, 9 km grid spacing is problematic as it does not explicitly resolve the convective scales of interest, nor does there exist for it a closure assumption that allows convection to be represented implicitly. Despite these facts, and partly to reconfirm them in the context of ensemble forecasting, we analyzed the 9 km ensembles but show here only forecasts from individual members, as well as the mean.

The forecast radar reflectivity at 1 km altitude for the five ensembles, and for that of the mean forecast, is shown in Figure 3. In no case does the model produce convection having the structure and movement observed (compare Figure 1) – a result that is not surprising given the grid spacing used. The appropriateness of using these fields as background states for finer-scale forecasts thus is questionable, and perhaps even suggests the use of much coarser grid spacing (e.g., 25 km spacing) for which the use of cumulus parameterization is justified on theoretical grounds. Nonetheless, with the assimilation of new (especially radar) observations at 3 km, our results suggest some degree of value in using the 9 km background fields.

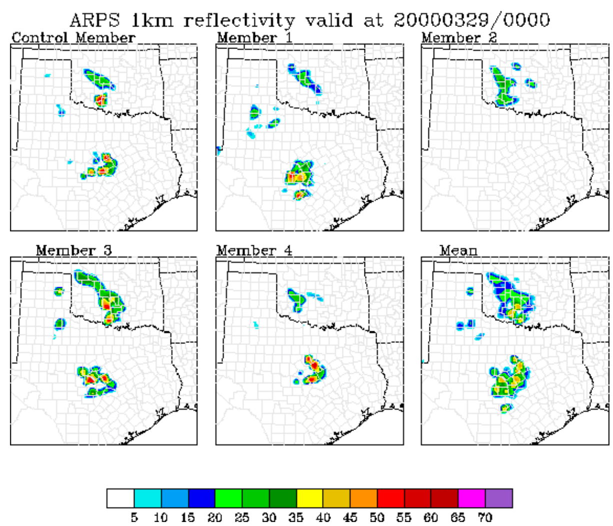

Figure 3. 6-hour forecast for the 9 km ensemble, and the mean, valid at 0000 UTC on 29 March 2000.

5. 3 KM ENSEMBLE RESULTS

As noted previously, the 3 km ensemble experiment begins at 2200 UTC, at which WSR-88D Level III radial velocity and reflectivity data are assimilated at 15-min intervals (those forecasts without radar data assimilation are uniformly less skillful) from all radars in the computational domain. The actual forecast begins at 2300 UTC and extends until 0400 UTC. We confine our analysis to the time of the Fort Worth tornado, which arrived in the metro area at approximately 0030 UTC.

Figure 4 shows the predicted radar reflectivity at 1 km altitude for each of the 3 km grid spacing experiments, along with the mean forecast. Not surprisingly, the finer grid spacing yields a more accurate forecast (compare with actual radar reflectivity in Figure 5), with the storms exhibiting stronger reflectivity than their 9 km grid spacing counterparts (Figure 3). The reflectivity in the mean forecast necessarily covers a much larger area

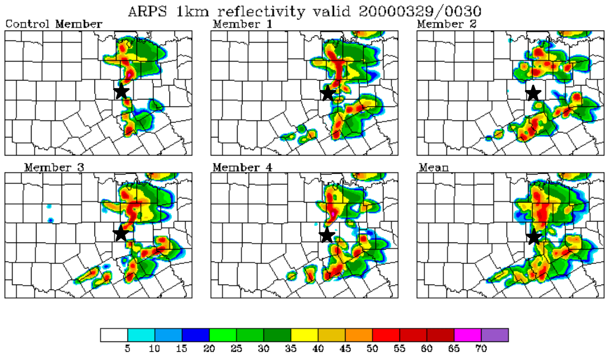

Figure 4. 90-minute forecast for all 3 km ensemble members, and the mean, valid at 0030 UTC on 29 March 2000 (approximate tornado time). Fort Worth is shown by the star.

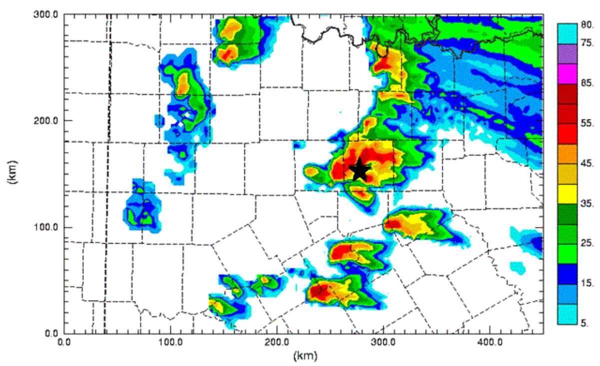

Figure 5. Fort Worth (KFWS) WSR-88D reflectivity at 0030 UTC on 29 March 2000 (approximate tornado time) interpolated to the 3 km ARPS model grid. The altitude shown is 1 km and Fort Worth is shown by the star.

and tends to merge individual storms into larger ones, thus being of questionable value.

Given the obvious limitations of an ensemble mean forecast for thunderstorms, we show in Figures 6 and 7 conditional probabilities of reflectivity for exceedance thresholds of 35 and 50 dBZ, respectively. In the context of thunderstorms, these plots focus attention on the more intense and rare events, indicating, presumably, where the atmosphere is most predictable. In both plots, the probability is notably high north of Fort Worth, which in general agrees with observations (Figure 5). However, the forecasts miss the high reflectivity over and to the west of Fort Worth. The storms southeast of Fort Worth are captured reasonably well, though none of the smaller cells to the northwest of Fort Worth are present in any of the forecasts (Figure 4).

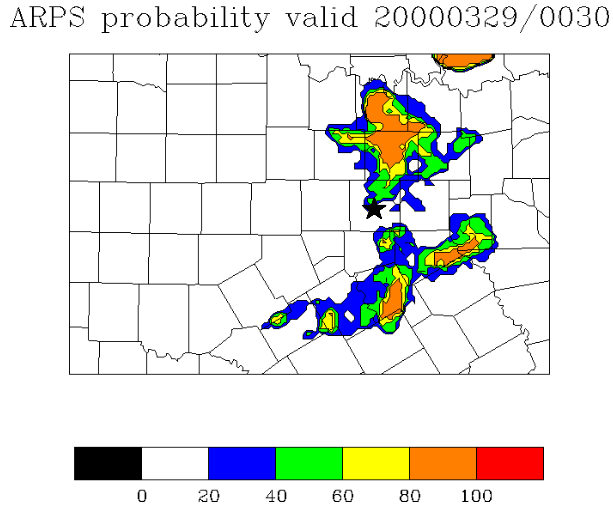

Figure 6. 90-minute forecast of the probability that reflectivity at 1 km altitude will be greater than or equal to 35 dBZ. Fort Worth is indicated by the star.

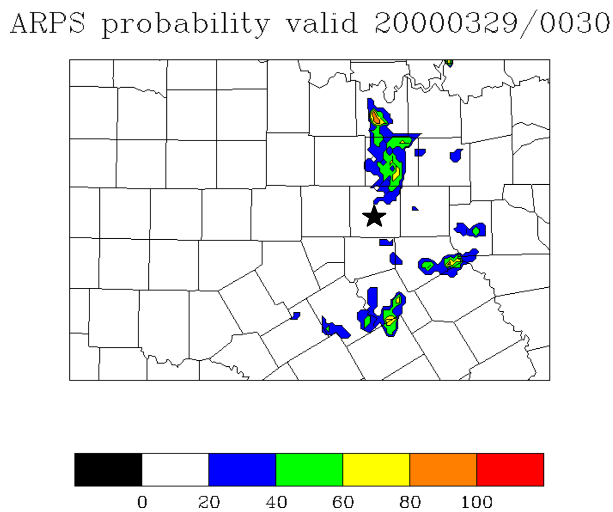

Figure 7. 90-minute forecast of the probability that reflectivity at 1 km altitude will be greater than or equal to 50 dBZ. Fort Worth is indicated by the star.

6. SUMMARY

These preliminary results show potential value in convective ensemble forecasts made using a full-physics NWP model initialized with fine-scale observations. Despite its simplicity, the SLAF method appears to work reasonably well in these simple experiments, though the ensemble spread appears to be less than desired. A suite of simulations more complete than shown here is being analyzed to address these issues as well as to understand error growth and structures, assess quantitative forecast skill, and calibrate the probability forecasts. Further, we are examining the suitability of scale recursive estimation as a means for creating high-resolution output from coarse-resolution ensembles (Kong et al. 2004),

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8. REFERENCES

Brewster, Keith, 1996: Implementation of a Bratseth analysis scheme including Doppler radar. Preprints, *15th Conf. on Weather Analysis and Forecasting*, Norfolk, VA, Amer. Meteor. Soc., 92-95.

Brooks, H. E., C. A. Doswell III, and R. A. Maddox, 1992: On the use of mesoscale and cloud-scale models in operational forecasting. *Wea. And Forecasting*, **8**, 120-132.

Brooks, H. E., M. S. Tracton, D. J. Stensrud, G. DiMego, and Z. Toth, 1995: Short-range ensemble forecasting: Report from a workshop (25-27 July 1994). *Bull. Amer. Meteor. Soc*., **76**, 1617-1624.

Droegemeier, K.K., 1997: The numerical prediction of thunderstorms: Challenges, potential benefits, and results from real time operational tests. *WMO Bulletin*, **46**, 324-336.

Ebert, E. 2001: Ability of a Poor man's Ensemble to Predict the Probability and Distribution of Precipitation. *Mon. Wea. Rev.*, **129**, 2461-2480.

Ebisuzaki, W. and E. Kalnay, 1991: Ensemble experiments with a new lagged average forecasting scheme. WMO Report #15.

Elmore, K.L., Stensrud, D.J., Crawford, K.C. 2002a: Explicit Cloud-Scale Models for Operational Forecasts: A Note of Caution. *Wea. and Forecasting*: **17**, 873–884.

Elmore, K.L., Stensrud, D.J., Crawford, K.C. 2002b: Ensemble Cloud Model Applications to Forecasting Thunderstorms. *Journal Appl. Meteorology*, **41**, 363 383.

Elmore, K.L., Weiss, S.J., Banacos, P.C. 2003: Operational Ensemble Cloud Model Forecasts: Some Preliminary Results. *Wea. and Forecasting*: **18**, 953–964.

Hamill, T.M., S.L. Mullen, C. Snyder, and Z. Toth, 2000: Ensemble forecasting in the short to medium range: Report from a workshop. *Bull. Amer. Meteor. Soc*., **81**, 2653-2664.

Hou, D., E. Kalnay, K.K. Droegemeier 2001: Objective verification of the SAMEX '98 ensemble forecasts. *Mon. Wea. Rev*., **129**, 73-91.

Kalnay, E., 2003: *Atmospheric Modeling, Data Assimilation and Predictability*. Cambridge Press, 341pp.

Kong, F., K. Droegemeier, V. Venugopal, and E. Foufoula-Georgiou, 2004: Application of scale-recursive estimation to ensemble forecasts: A comparison of coarse and fine resolution simulations of a deep convective storm. Preprints, *20th Conf. on Wea. Analysis and Forecasting/16th Conference on Num. Wea. Prediction*, American Meteor. Soc., this volume.

Molinari, J. 1993: An overview of cumulus parameterization in mesoscale models. *Meteorological Monographs*, **24**, 155-158.

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. *Met. Atmos. Phys.,* **76**, 143-165.