The Ensemble Kalman Filter Analyses and Forecasts of the 8 May 2003 Oklahoma City Tornadic Supercell Storm Using Single- and Double-Moment Microphysics Schemes

NUSRAT YUSSOUFF

Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, and NOAA/OAR/National Severe Storms Laboratory, Norman, Oklahoma

EDWARD R. RANSSELL AND LOUIS J. WICKER

NOAA/OAR/National Severe Storms Laboratory, Norman, Oklahoma

DUSTAN M. WHEATLEY

Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, and NOAA/OAR/National Severe Storms Laboratory, Norman, Oklahoma

DAVID J. STENSRUD

NOAA/OAR/National Severe Storms Laboratory, Norman, Oklahoma

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ABSTRACT

A combined mesoscale and storm-scale ensemble data-assimilation and prediction system is developed using the Advanced Research core of the Weather Research and Forecasting Model (WRF-ARW) and the ensemble adjustment Kalman filter (EAKF) from the Data Assimilation Research Testbed (DART) software package for a short-range ensemble forecast of an 8 May 2003 Oklahoma City, Oklahoma, tornadic supercell storm. Traditional atmospheric observations are assimilated into a 45-member mesoscale ensemble over a continental U.S. domain starting 3 days prior to the event. A one-way-nested 45-member storm-scale ensemble is initialized centered on the tornadic event at 2100 UTC on the day of the event. Three radar observation assimilation and forecast experiments are conducted at storm scale using a single-moment, a semi-double-moment, and a full double-moment bulk microphysics scheme. Results indicate that the EAKF initializes the supercell storm into the model with good accuracy after a 1-h-long radar observation assimilation window. The ensemble forecasts capture the movement of the main supercell storm that matches reasonably well with radar observations. The reflectivity structure of the supercell storm using a double-moment microphysics scheme appears to compare better to the observations than that using a single-moment scheme. In addition, the ensemble system predicts the probability of a strong low-level vorticity track of the tornadic supercell that correlates well with the observed rotation track. The rapid 3-min update cycle of the storm-scale ensemble from the radar observations seems to enhance the skill of the ensemble and the confidence of an imminent tornado threat. The encouraging results obtained from this study show promise for a short-range probabilistic storm-scale forecast of supercell thunderstorms, which is the main goal of NOAA's Warn-on-Forecast initiative.

1. Introduction

The assimilation of Doppler radar observations in an ensemble-based storm-scale numerical weather prediction (NWP) model is crucial for very short-range probabilistic forecasts of severe convective storms, and this is one of the major goals of the Warn-on-Forecast (WoF) initiative (Stensrud et al. 2009b, 2013). Almost a decade ago, Snyder and Zhang (2003) demonstrated the ability of an ensemble Kalman filter (EnKF) data-assimilation approach to successfully develop a storm within a storm-scale NWP model by assimilating synthetic Doppler radar observations. Despite many challenges (Stensrud et al.
2009b), progress has been made over the past decade in assimilating real radar observations of severe convective storms in storm-scale NWP models.

An EnKF approach using horizontally homogeneous and temporally constant environmental conditions can provide a good representation of the ongoing convection (e.g., Dowell et al. 2004a,b; Tong and Xue 2005; Xue et al. 2006; Aksoy et al. 2009, 2010; Yussouf and Stensrud 2010; Dowell et al. 2011; Dawson et al. 2012). However, the development and evolution of severe thunderstorm events are strongly tied to the environment, and therefore incorporating mesoscale environmental variability and its uncertainty is crucial for successful storm-scale data assimilation and forecasts (Aksoy et al. 2009, 2010). For example, Stensrud and Gao (2010) and Ziegler et al. (2010) illustrated the importance of incorporating the influence of horizontal environmental variability and mesoscale forcing on the storm-scale flows for the accurate prediction of tornadic supercell thunderstorms. In particular, when Stensrud and Gao (2010) used a more realistic inhomogeneous mesoscale environment as the initial and boundary conditions for their storm-scale three-dimensional variational data assimilation (3DVAR) and forecast system, substantial improvement in forecast accuracy was obtained over a similar storm-scale system using a homogeneous, single-sounding environment, which is typical of idealized storm modeling studies.

Several recent studies (e.g., Lei et al. 2009; Dowell et al. 2010; Jung et al. 2012) have been conducted that assimilate radar observations within realistic mesoscale environments and the results are encouraging. Lei et al. (2009) examine the value of assimilating real radar observations from the 8 May 2003 Oklahoma City, Oklahoma, tornadic supercell storm within a heterogeneous environment using the Advanced Regional Prediction System (ARPS) model and the EnKF data-assimilation approach and show that the assimilation of both radar and surface data through a nested-grid strategy were important for obtaining good forecast results. A deterministic forecast of the tornadic supercell is launched from the ensemble mean analysis and the forecast captures the evolution of the storm that matches the radar observations well. While the favorable results from the deterministic forecast of the 8 May 2003 supercell are very encouraging and illustrate the potential value of an EnKF data-assimilation approach, an ensemble forecast approach is needed to include the uncertainty in the tornadic supercell forecast. Dowell et al. (2010) assimilate Doppler velocity and “no precipitation” observations from six operational radars into a storm-scale EnKF-based system within a realistic mesoscale environment derived from a mesoscale EnKF analysis and forecast system for the 5 June 2009 Goshen County, Wyoming, tornadic supercell and the 11–12 June 2009 southeast Colorado nontornadic supercell. Results show good correspondence between the swaths of predicted high probabilities of rotating updrafts and swaths of severe weather reports from observed supercells.

In addition to Lei et al. (2009), Dowell et al. (2011) also simulated the 8 May 2003 Oklahoma City tornadic supercell storm but using an idealized horizontal homogeneous environment. They assimilated Norman, Oklahoma (KOUN), radar observations into a storm-scale NWP model using the EnKF data-assimilation technique and show that assimilating both reflectivity and radial velocity observations improves the quality of the analysis compared to assimilating only the reflectivity or radial velocity. Their study is limited to analyzing the quality of the analyses, however, and not the ensemble forecasts.

One important source of error in storm-scale modeling is the microphysical parameterization scheme, although other physics parameterizations can have substantial impacts as well. Several studies demonstrate significant differences in storm structure and evolution from using single- and multimoment bulk microphysics schemes (e.g., Milbrandt and Yau 2006; Morrison et al. 2009; Dawson et al. 2010). There are notable differences in storm behavior related to the selection of the microphysical parameters within a single-moment bulk microphysics scheme (e.g., Gilmore et al. 2004b; van den Heever and Cotton 2004; Snook and Xue 2008). Therefore, the choice of the parameterized microphysics and their parameters makes a significant impact on the quality of the EnKF storm-scale analyses and forecasts (Snyder and Zhang 2003; Dowell et al. 2004a; Kong et al. 2007; Aksoy et al. 2009, Yussouf and Stensrud 2012). Jung et al. (2012) demonstrate that EnKF analyses using a two-moment microphysics scheme results in significantly better agreement with the polarimetric radar signature compared to the analyses from a single-moment scheme, while Dawson et al. (2012) show that the probabilistic vortex swath from an EnKF data-assimilation and forecasts system using single-moment microphysics is clearly inferior compared to the simulations using a double-moment scheme.

In this study, we further investigate the impact of assimilating available observations in an ensemble-based data-assimilation system for very short-range forecasts of the 8 May 2003 Oklahoma City tornadic supercell storm. To evaluate the ensemble forecast of the tornadic supercell, an ensemble-based mesoscale and storm-scale data-assimilation and prediction system is developed using the Advanced Research core of the Weather Research and Forecasting Model (WRF-ARW; Skamarock et al. 2008) and the Data Assimilation Research Testbed.
2. Experiment design

a. Overview of the event

The 8 May 2003 Oklahoma City (OKC) tornado is one of the more destructive events that occurred during a period of active severe outbreaks of tornadoes across the central and eastern United States in early May 2003 (Hamill et al. 2005). Several studies have already focused on this particular storm (Burgess 2004; Dowell et al. 2004b; Hu and Xue 2007; Romine et al. 2008; Lei et al. 2009; Dowell et al. 2011). On 8 May a violent tornado passed through portions of Moore, Oklahoma, as well as the southeast OKC metropolitan area with a damage rating of category 4 on the Fujita scale (F4) along its path. Observations show that during the mid- to late afternoon, the synoptic-scale environment became increasingly conducive to severe tornadic thunderstorms. Several small cells started along the dryline in west-central Oklahoma around 2050 UTC, and by 2130 UTC one of the cells matured into an isolated supercell storm. The supercell moved northeastward and intensified significantly over the next hour. A violent tornado developed around 2210 UTC and tracked east-northeastward for about 30 km until it dissipated at around 2228 UTC, leaving a damage path stretching from Moore to Choctaw, Oklahoma. The National Weather Service office in Norman issued a tornado warning for the path of the storm, including Cleveland, McClain, and south Oklahoma Counties at 2149 UTC, with approximately 21-min lead time for Moore in Cleveland County and approximately 30-min lead time for Oklahoma County. Further details of the event can be found in Hu and Xue (2007) and Romine et al. (2008).

Multiple radars documented the life cycle of the 8 May 2003 tornadic supercell, including the operational Weather Surveillance Radar-1988 Doppler (WSR-88D) at Oklahoma City (KTLX), the terminal Doppler weather radar (TDWR), and the experimental polarimetric WSR-88D KOUN radar. These radars provide a unique dataset in which a series of storm-scale data-assimilation experiments are conducted to assess the impact of different microphysical and EnKF configurations on storm-scale ensemble forecasts of low-level rotation.

b. Mesoscale ensemble and data-assimilation system

An ensemble-based data-assimilation and prediction system is assembled using version 3.2.1 of the WRF-ARW and the Kodiak release branch of DART (revision 5038). The mesoscale model domain (Fig. 1a) covers the CONUS with a horizontal grid spacing of 18 km and 51 vertical grid levels, stretching from the surface to 50 hPa aloft. A 45-member ensemble is initialized at 1200 UTC 5 May 2003 (3 days prior to the event) using the 6-hourly National Centers for Environmental Prediction’s (NCEP) Global Forecast System (GFS) final analysis. A set of 45 random samples of the horizontal components of wind, water vapor mixing ratio, and temperature are drawn from a default background error covariance file estimated by the National Meteorological Center (NMC, now known as NCEP) method (Parrish and Derber 1992) using WRF data-assimilation (WRFDA) software. These samples are then added to each ensemble member to account for uncertainties in the initial and boundary conditions (Torn et al. 2006). The physics parameterization options used in the mesoscale ensemble system are the Kain–Fritsch scheme for cumulus (Kain and Fritsch 1993), the Mellor–Yamada–Janjić scheme (MYJ; Mellor and Yamada 1982; Janjić software system (DART; Anderson and Collins 2007; Anderson et al. 2009). The mesoscale ensemble system is designed based on studies done by Fujita et al. (2007), Torn and Hakim (2008), Stensrud et al. (2009a), Dowell et al. (2010), Wheatley et al. (2012), and Romine et al. (2013), while the storm-scale system is designed based on Aksoy et al. (2009, 2010) and Dowell et al. (2011). A 45-member mesoscale ensemble-based data-assimilation system with continuous cycling on a continental U.S. (CONUS) domain is conducted for 3 days. This mesoscale ensemble is used to provide the initial and boundary conditions for a one-way-nested storm-scale ensemble-based data-assimilation and prediction system centered on Oklahoma City. On the storm-scale domain, radar reflectivity including clear-air echo and Doppler velocity observations are assimilated rapidly every 3 min for a 1-h period and are used to start 1-h ensemble forecasts. As mentioned earlier, the selection of the microphysics scheme and the tunable parameters therein remains a substantial source of uncertainty at the storm scale and strongly influences the forecasts of storms. To explore the impact of different microphysics schemes, three different bulk microphysics scheme experiments are conducted at storm scale: a pure single-moment scheme, a partially two-moment scheme, and a fully two-moment scheme. The main objective of this study is to investigate the accuracy of the analyses and very short-range (0–1 h) ensemble forecasts of the Oklahoma City tornadic storm. A brief overview of the Oklahoma City tornadic supercell thunderstorm event followed by the experiment designs of both the mesoscale and storm-scale data-assimilation systems is discussed in section 2. Section 3 assesses the qualitative results of the analyses and forecasts of the ensemble. A final discussion is found in section 4.
for the planetary boundary layer (PBL), the Thompson method (Thompson et al. 2008) for microphysics, the Dudhia scheme (Dudhia 1989) for short-wave radiation, the Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997) for longwave radiation, and the Noah land surface model (Chen and Dudhia 2001) for the land surface parameterization.

Routinely available observations from the National Oceanic and Atmospheric Administration’s (NOAA) Meteorological Assimilation Data Ingest System (MADIS) are assimilated into the ensemble every 6 h starting at 1800 UTC 5 May 2003 out to the next 3 days using the ensemble adjustment Kalman filter (EAKF; Anderson 2001) within the DART system. Starting at 1200 UTC.
8 May 2003, MADIS observations are assimilated every 1 h instead of every 6 h, for a 12-h period out to 0000 UTC 9 May 2003 (Fig. 1a). A half-radius of 287 km in the horizontal and a half-radius of 4 km in the vertical are used for the covariance localization function [the fifth-order correlation function from Gaspari and Cohn (1999)]. In addition, at each assimilation cycle a spatially varying adaptive inflation (Anderson 2009) is applied to the prior state space before the observations are assimilated to counteract the tendency of ensemble underdispersion. The observations assimilated in the mesoscale ensemble are the altimeter setting, temperature, dewpoint, and horizontal wind components from land and marine surface stations, rawinsondes, and aircraft. The filter implements an additional observation quality control algorithm during assimilation such that if the magnitude of the squared difference between an observation and the prior ensemble mean exceeds 3 times the sum of the prior ensemble variance and observation error variance (outlier threshold of 3.0), that observation is rejected. The predicted variables updated by the data-assimilation scheme include the three wind components, perturbation temperature, perturbation geopotential, perturbation surface pressure of dry air, and potential temperature tendency due to microphysics, as well as water vapor and hydrometeors. Also updated are the 10-m wind fields, 2-m temperature and water vapor fields, and total surface pressure variables, which are diagnosed by the surface and boundary layer schemes using state variables on the model grid. Output from the mesoscale ensemble is then used to create the initial and boundary conditions for the storm-scale ensemble.

c. Storm-scale ensemble and data-assimilation system

A 45-member storm-scale ensemble is created from the mesoscale ensemble analyses at 2100 UTC nested down to 2-km horizontal grid resolution. The domain is centered on Moore and covers most of Oklahoma except for the panhandle on the west with a $225 \times 180 \times 50$ grid (Fig. 1b). Three different data-assimilation experiments are conducted using three microphysics schemes. The first experiment uses the Thompson et al. (2004, 2008) microphysics scheme (referred to as Thompson), which predicts the mixing ratios of five liquid and ice species: cloud water, rain, cloud ice, snow, and hail–graupel, as well as the number concentration of cloud ice and rain. This scheme is a single-moment scheme with the exception of the double-moment cloud ice and rain (i.e., the cloud ice and rain particle concentrations are predicted in addition to the masses of all species). The second experiment uses the National Severe Storms Laboratory NSSL fixed density (Ziegler 1985; Gilmore et al. 2004a; Mansell et al. 2010) single-moment bulk microphysics scheme (referred to as NFD-SM). This scheme is comparable to the Gilmore et al. (2004a) version of the Lin et al. (1983) method, with the main difference being the exclusion of the separate Bergeron parameterization for conversion of cloud ice to snow and instead allowing deposition growth and aggregation to determine conversions. The NFD-SM scheme predicts mass mixing ratios for two liquid (cloud droplets and rain) and three ice (cloud ice, snow, and graupel–hail) categories of hydrometeors. The third experiment uses the double-moment NSSL variable density microphysics scheme (referred to as NVD-DM), which features the prediction of average graupel particle density and allows graupel to span the range from frozen drops to low-density graupel. The scheme predicts the mass mixing ratios and number concentrations of six hydrometeor species: cloud droplets, cloud ice, snow, rain, graupel, and hail. The shape parameters of graupel and hail are $\alpha_1 = 0$ and $\alpha_2 = 2$, respectively. Details of this scheme are also discussed in Mansell et al. (2010). The fifth-order weighted essentially nonoscillatory (WENO) advection scheme (Shu 2003) is used for all three microphysics scheme experiments. The WENO advection scheme improves the coupling between microphysical moments within each bulk class (rain, ice, snow, etc.), particularly near cloud edges. The cumulus parameterization scheme is turned off for the storm-scale experiments. The remaining physics options for the storm-scale ensemble are identical to the parent mesoscale ensemble.

The single-moment NFD-SM scheme has fixed particle densities and size distribution intercept parameters. The particle size distributions are inverse exponential, and the intercept parameters used for the size distribution of rain, snow, and hail–graupel are $8.0 \times 10^3$, $3.0 \times 10^6$, and $4.0 \times 10^4 \text{m}^{-4}$, respectively, and the densities for snow and hail–graupel are 100 and 900 kg m$^{-3}$, respectively, which are the same as in Lin et al. (1983) except for the rain intercept. Compared to the well-known Marshall and Palmer (1948) rain intercept of $8.0 \times 10^6 \text{m}^{-3}$, a smaller rain intercept parameter of $8.0 \times 10^5 \text{m}^{-4}$ is used in this experiment to reduce the tendency of predicting a strong cold pool in single-moment schemes (Gilmore et al. 2004a). The hail in the NVD-DM scheme is produced only by the wet growth of graupel to try to represent the true hail rather than the high-density ice. The scheme also features adaptive sedimentation (Mansell 2010) to allow some size sorting but to also prevent spurious large particles (and radar reflectivity values) that can arise from two-moment microphysics, particularly for the larger precipitation categories (graupel, hail, and rain). The snow field in the Thompson scheme assumes a combination of two gamma functions (Field et al. 2005) and calculates the
size distribution moments based upon observed relationships between the predicted snow mass and air temperature unlike many single-moment microphysics schemes that use constant values of intercept parameters. The graupel intercept in the Thompson scheme is diagnosed from the graupel and supercooled liquid mixing ratios. The intercept is bounded between $1.0 \times 10^3$ and $1.0 \times 10^6 \text{ m}^{-4}$, but has a lower limit of about $1.1 \times 10^3 \text{ m}^{-4}$ if no supercooled liquid is present or the ambient temperature is greater than freezing. A supercooled liquid mixing ratio greater than about 0.1 g kg$^{-1}$ shifts the intercept toward typical values for hail ($1.0-4.0 \times 10^3 \text{ m}^{-4}$).

The observations assimilated into the storm-scale ensemble experiments are the Doppler velocity and reflectivity observations from the WSR-88D at Twin Lakes, Oklahoma (KTLX). The raw level II KTLX radar observations are obtained from the National Climatic Data Center (NCDC) and contain 14 scan angles (VCP 12 mode), completing each full-volume scan in approximately 4.5 min. The reflectivity observations are automatically edited using the Quality Control Neural Network (QCNN; Lakshmanan et al. 2003) method to remove nonteorological echoes from radar, anomalous propagation, and ground clutter. The Doppler velocity is dealiased using the method from Eilts and Smith (1990). The edited reflectivity and velocity observations are then objectively analyzed using the Observation Processing and Wind Synthesis (OPAWS; see Majcen et al. 2008; http://code.google.com/p/opaws/) software. The radar observations are analyzed onto a regularly spaced 4-km grid in the horizontal but on the original conical scan surfaces (Sun and Crook 2001; Dowell et al. 2004b; Dowell and Wicker 2009) using a two-pass Barnes (1964) scheme. Finally, the objectively analyzed radar observations are divided into 3-min bins and are assimilated at rapid 3-min intervals for a 1-h period starting at 2100 UTC (Fig. 1b). All observations within each 3-min window are assumed to be valid at the central time. Any values of reflectivity below 0 dBZ are assumed to be nonprecipitating and set to 0 dBZ. The nonprecipitating regions are assimilated to help suppress spurious convection that may develop in the model (Tong and Xue 2005; Aksoy et al. 2009; Dowell et al. 2011). Observation-error standard deviations are assumed to be 5 dBZ and 2 m s$^{-1}$ for reflectivity and Doppler velocity, respectively. Additional observation quality control using an outlier threshold of 3.0 is applied during assimilation similar to the mesoscale system.

In addition to the state variables that are updated in the mesoscale ensemble data-assimilation system as described in section 2b, all available hydrometeor fields from the microphysics scheme in the model also are updated in the storm-scale data-assimilation system. The covariance localization for the storm-scale ensemble is set to have a half-radius in the horizontal (vertical) of 12 km (6 km). To limit the number of observation assimilations in the highly dense storm area, an adaptive localization is used to dynamically shrink the horizontal localization cutoff in regions having dense observations. Adaptive inflation is applied to the prior state space at the beginning of each assimilation cycle to maintain spread in the storm-scale ensemble in addition to the spread that comes from the parent mesoscale ensemble. The tendency of high-density radar observations in storm locations to cause filter divergence due to ensemble underdispersion is more pronounced in the storm-scale data-assimilation system. Thus, additional spread to the storm-scale ensembles is provided by using the additive noise technique (Dowell and Wicker 2009). The additive noise technique is used to add random, smooth, local perturbations every assimilation cycle to each ensemble member’s horizontal wind components, temperature, and water vapor at locations where the observed radar reflectivity exceeds 25 dBZ (Dowell et al. 2011; Dawson et al. 2012; Jung et al. 2012). The additive noise is applied to the model state variables immediately before the updated ensemble is integrated forward in time. The perturbations have standard deviations of $0.50 \text{ m s}^{-1}$ for horizontal winds and $0.50 \text{ K}$ for temperature and dewpoint before smoothing. Perturbations are added to temperature and dewpoint temperature rather than to the potential temperature and water vapor mixing ratio and then converted back into the model state variables of potential temperature and water vapor mixing ratio. The spatial length scale for the perturbation smoothing function is 6 km in both the horizontal and the vertical. One-hour forecasts are launched from each of the 45 storm-scale ensemble analyses valid at 2200 UTC, which is ~10 min prior to tornadogenesis.

3. Results and discussion

a. Observation-space diagnostics

The observation-space diagnostic statistics (Dowell et al. 2004a; Dowell and Wicker 2009; Dowell et al. 2011) of the root-mean-square innovation (rmsi) and total ensemble spread (standard deviation) are calculated for the assimilated KTLX reflectivity and radial velocity observations during the 1-h assimilation period (Fig. 2) for the 8 May 2003 supercell. These metrics quantitatively evaluate the performance of the filter and configuration for real-data experiments. The rmi gives a measure of the overall fit of the observations to the forecasts and analyses, and the total spread gives information
about the degree of spread of the ensemble. The rmsi is defined as

$$\text{rmsi} = \sqrt{\langle d^2 \rangle},$$

where $d$ is the innovation (observation minus model state mapped to that observation location)

$$d = y^0 - H(x') \quad \text{or} \quad d = y^0 - H(x^a);$$

$y^0$ is the observation; $H$ is the forward operator that maps the model state vector to the observation location and type; $x'$ and $x^a$ are the model state vector forecast and analysis, respectively; the overbar represents the ensemble mean; and $(d)$ is the mean innovation averaged over all of the observations. The total ensemble spread (Dowell and Wicker 2009) is defined as

$$\text{total spread} = \sqrt{\sigma^2_{\text{obs}} + \left( \frac{1}{N-1} \sum_{n=1}^{N} [H(x_n) - H(x)]^2 \right)},$$

where $\sigma_{\text{obs}}$ is the observation error standard deviation, which is assumed to be 5 dBZ for reflectivity and 2 m s$^{-1}$ for radial velocity in these experiments; $N \approx 45$ is the number of ensemble members; and $n$ is the ensemble member index. The radial velocity statistics are calculated

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**FIG. 2.** Observation-space diagnostic statistics for assimilated KTLX (a) reflectivity (dBZ) and (b) Doppler velocity (m s$^{-1}$) every 3-min observations for the Thompson (green), NFD-SM (red), and NVD-DM (blue) experiments during the 1-h storm-scale data-assimilation period. Solid (dashed) lines indicate the root-mean-square innovation (total ensemble standard deviation). The reflectivity statistics are computed only where the assimilated observed reflectivity is >10 dBZ; no threshold is applied for Doppler radial velocity observations. The sawtooth patterns are due to the plotted forecast and analysis statistics.
only at the available observed locations within the domain and the reflectivity statistics are calculated for regions where the observed reflectivity is greater than 10 dBZ to isolate the performance measure around the main convective storm (Aksoy et al. 2009; Dowell et al. 2011; Dawson et al. 2012; Jung et al. 2012).

In general, both rmsi and the ensemble spread from the three microphysics scheme assimilation experiments are relatively similar in magnitude for both reflectivity and radial velocity observations (Fig. 2). The rmsi for reflectivity (Fig. 2a) indicates that after the first 20 min of the assimilation cycle, the rmsi error starts to decrease with time. The constant rmsi of approximately 12 dBZ during the first ~20 min of the assimilation is due to the “spinup” time taken by the storm-scale ensemble to initiate convection. The rmsi from the Thompson experiment is relatively smaller compared to the single- and double-moment experiments during the later 40 min of the assimilation period for reflectivity. The ensemble spread for reflectivity (Fig. 2a) is consistently smaller than the rmsi in all three microphysics experiments, suggesting ensemble underdispersion, which is a common problem in real radar observation assimilations at storm scale (Dowell and Wicker 2009; Aksoy et al. 2009; Dowell et al. 2011; Snook et al. 2011, 2012). In contrast, the ensemble spread for radial velocity (Fig. 2b) is comparable to rmsi, indicating that the forecast error is representative of the ensemble spread.

Another useful observation-space diagnostic measure to evaluate the performance of the assimilation system is the consistency ratio (Dowell et al. 2004a; Aksoy et al. 2009; Dowell and Wicker 2009). This ratio is defined as

$$\text{consistency ratio} = \frac{\sigma_{\text{obs}}^2 + \frac{1}{N-1} \sum_{n=1}^{N} [H(x_n) - \bar{H}(x)]^2}{\langle d^2 \rangle}.$$  \hspace{1cm} (4)

where a value of ~1.0 indicates that the ensemble variance is a good approximation of the forecast error variance for the assumed observation error. The consistency ratio for reflectivity is small in the early assimilation cycle, with a starting value of 0.18, and increases with time during the later part of the assimilation cycle (Fig. 3a) and has values ranging from 0.4 to 0.5 at the final assimilation cycle. The low consistency ratio suggests there is a deficiency in the ensemble spread and/or an assumed too small observation error variance or possibly that the initial storm echoes (Fig. 3b) are too few and small in size (relative to the grid spacing) to generate good statistics. Importantly, the filter shows no sign of forecast divergence during the 1-h assimilation period, indicating the robustness of the data-assimilation system. The radial velocity observations maintain more favorable consistency ratios, starting with 0.95 and ending within a range of 0.90–1.1 (Fig. 3c). The overall observation-space diagnostics as shown in Figs. 2 and 3 suggest that the configuration of the assimilation system is fairly reasonable for comparisons of the three microphysics experiments.

The reflectivity and radial velocity ensemble forecasts during the 1-h forecast period for the three experiments (Fig. 4) also are evaluated using observation-space diagnostics to see how the performance of the filter during assimilation is carried over to free forecasts. The time series of the rmsi and ensemble spread during the 1-h forecast period are binned every 5 min for plotting purpose only, so that each bin contains roughly one full volume scan of KTLX radar observations. The forecast errors for both reflectivity and radial velocity increase with time for all three experiments, as expected. However, for reflectivity forecasts, the rmsi for the NFD-SM experiment is larger than for the Thompson and NVD-DM experiments. The forecast rmsi and the ensemble spread for radial velocity are relatively similar in their magnitude from the three microphysics scheme experiments (Fig. 4b). The ensemble spread is consistently smaller than the rmsi for both reflectivity and radial velocity during the 1-h forecast period.

To evaluate the fit of the analyses and forecasts during the 1-h assimilation period with independent observations, the observation-space diagnostics are calculated with respect to KOUN radar reflectivity and radial velocity observations that are not assimilated and are shown in Fig. 5. The results indicate that the statistics are consistent when compared with the KOUN observations. The rmsi and total spread (Fig. 5a) compared to the KOUN reflectivity observations are very similar to those calculated from the assimilated KTLX reflectivity observations (Fig. 2a). However, the rmsi and ensemble spread for radial velocity are comparatively larger and the differences in the rmsi are more pronounced between the schemes after 2145 UTC (Fig. 5b) compared to that from the KTLX radial velocity (Fig. 2b) statistics. Overall, the error statistics verified reasonably well when compared with the KOUN radar observations.

b. Ensemble probabilistic forecast of low-level vorticity of the 8 May 2003 tornadic supercell

The 2-km model horizontal grid spacing used in this study is far too coarse to explicitly resolve any tornado circulation. To infer the relative threat of tornado potential from the ensemble forecast experiments, several studies (Stensrud and Gao 2010; Dawson et al. 2012; Stensrud et al. 2013) assume that the presence of low-level
rotation (vorticity) in the storm is representative of
a significant mesocyclone and is used as a proxy for a
forecast tornado probability. Recent studies (Markowski
et al. 2011; Marquis et al. 2012), however, suggest that
mesoscale vorticity is a proper metric for assessing the
location of a tornado but may not always correlate well
with tornado strength or even that a tornado exists. A
useful tool for quantifying the location and intensity of
low-level mesocyclone circulations using radar observa-
tions (Miller et al. 2013) is the Warning Decision Support
System–Integrated Information (WDSS-II; Lakshmanan
et al. 2007). The WDSS-II rotation track from the KTLX
radar observations at 0–2 km AGL of the 8 May 2003
OKC tornado is generated and compared with the
forecast probabilities of vorticity from the three micro-
physics experiments in Fig. 6. The vorticity probabilities
are calculated from the number of members exceeding
threshold values starting at 2201 UTC and ending at
2300 UTC (Figs. 6a–f). Each ensemble member forecast
is checked to see whether the vorticity exceeds thresh-
holds of 0.003 and 0.006 s$^{-1}$ at 150 m and 1 km AGL, re-
spectively. Instead of using model horizontal gridpoint

**Fig. 3.** The (a) consistency ratio and (b) number of observations assimilated during the 1-h
storm-scale data-assimilation period for the Thompson (green), NFD-SM (red), and NVD-DM
(blue) experiments for KTLX reflectivity (dBZ). (c),(d) As in (a),(b), but for the Doppler
velocity (m s$^{-1}$). The reflectivity statistics are computed only where the observed reflectivity is
>10 dBZ; no threshold is applied for Doppler radial velocity observations.
values, a 6-km radius around each grid point is used to calculate the probabilistic forecasts of vorticity to account for the small displacement errors across the ensemble members. Results indicate that the low-level mesocyclone persists during the forecast for all three experiments with higher probabilities of significant mesocyclones qualitatively correlating well with the rotation track (Fig. 6g). Maximum probabilities (100%) are seen at several grid points early in the forecast in all three experiments. Later in the forecast the probabilities remain above 50% for NFD-SM and NVD-DM but are above 95% for the Thompson experiment at several grid points along the observed maximum rotations, indicating that the mesocyclone circulation tilts in that direction in all three experiments (Figs. 6b, 6d, and 6f). The vorticity patches on the left and north-northwest of the main swath at 150 m AGL (Figs. 6a, 6c, and 6e) are associated with the small low-level circulation patterns on the storm's western gust front.

One of the goals of Warn-on-Forecast is to rapidly assimilate the most recent radar observations of the ongoing convection. To examine the impact of continuous every 3-min update cycles on the ensemble forecasts of the 8 May 2003 Oklahoma City tornadic supercell, additional radar data-assimilation cycles at 3-min intervals are performed for the Thompson and NVD-DM schemes. In addition, starting from as early as 2145 UTC (thereby assimilating radar observations for a shorter 45-min assimilation window), each of the 3-min update ensemble analysis forecasts are launched out to...
Similar to Fig. 6, neighborhood (within a 6-km radius) probability of vorticity swaths for thresholds exceeding values of 0.003 and 0.006 s\(^{-1}\) at 150 m and 1 km AGL, respectively, are generated from each of the 3-min update experiments and are shown for every 6-min interval (due to space constraint) in Fig. 7. The early lead-time forecast probability of vorticity from the 2145 UTC analyses show signs of a mesocyclone track near the surface. Compared to the Thompson experiment, the NVD-DM experiment shows more coherent and enhanced probability track forecasts near the surface (Fig. 7a) and the probabilities are as high as 30% in several grid points at 1 km AGL (Fig. 7c) for 2145 UTC forecasts. The forecast probability dissipates quickly with time at 1 km AGL with no signs of circulation patterns from the Thompson experiments along the observed damage track (Fig. 7d). With each additional assimilation cycle out to 2203 UTC, the forecast probabilities of a strong low-level mesocyclone are consistently enhanced and increased for both the Thompson and NVD-DM schemes.

The vorticity probabilities are usually highest early in each forecast, where they approach 100% at several locations and gradually decrease with time. Therefore, the 3-min updates of the ensemble from the radar observations during the last 18-min period enhance the confidence of the imminent tornado threat. The NWS Forecast Office in Norman issued the tornado warning for the 8 May 2003 Oklahoma City storm at 2149 UTC on that day. Indeed, the forecast probability of vorticity plots from the NVD-DM experiments demonstrates the possibility of a tornado threat as early as 25 min before tornadogenesis. Therefore, the continuously cycled NWP ensembles can potentially help operational forecasters improve tornado warnings by providing more quantitative probabilistic information regarding the evolution of storm-scale rotation on a 1-h time scale.

The probability forecasts of low-level circulation from the analyses at 2215 UTC and thereafter (Figs. 7u–af) also show coherent probability track forecasts that match the timing of the observed tornado track.
FIG. 6. Neighborhood ensemble probability of vorticity from the (top) Thompson, (middle) NFD-SM, and (bottom) NVD-DM experiments exceeding thresholds of (a),(c),(e) 0.003 s$^{-1}$ at 150 m (0.15 km) AGL and (b),(d),(f) 0.006 s$^{-1}$ at 1 km AGL during a 1-h forecast period starting from the analyses at 2200 UTC and ending at 2300 UTC. The portion of the domain shown here is 100 km x 60 km wide. (g) The WDSS-II-generated KTLX radar-observed low-level (0–2 km AGL) mesocyclone track during 2200–2300 UTC (MD indicates missing data). Overlain in each panel is the NWS-observed tornado damage track [black outline in (a)–(f) and green outline in (g)] that starts at 2210 UTC and ends at 2238 UTC.
Fig. 7. Neighborhood ensemble probability of vorticity forecasts for the NVD-DM and Thompson experiments exceeding thresholds of (first and second columns) $0.003 \, \text{s}^{-1}$ at 150 m (0.15 km) and (third and fourth columns) $0.006 \, \text{s}^{-1}$ at 1 km AGL. The forecasts are integrated out to 2300 UTC and are generated from rapid update analyses from 2145 to 2227 UTC. The portion of the domain shown here is 100 km $\times$ 60 km wide. Overlaid in each panel is the NWS-observed tornado damage track (black outline) that starts at 2210 UTC and ends at 2238 UTC.
spans approximately 2210–2238 UTC. However, a closer look shows a rapid decrease in the probabilities of rotation eastward down the observed tornado track compared to the probabilities from the 2209 UTC and earlier forecasts. Additional experiments with the assimilation of only radial velocity and no-precipitation observations later in the update cycle (starting at 2212 UTC) reveals that turning off the reflectivity assimilation later in the assimilation period provides some improvements in the forecast vorticity swaths (Figs. 8a–h). Dowell et al. (2011) noted that reflectivity assimilation by EnKF could intensify storm cold pools, particularly via covariances with potential temperature. A similar intensification is seen in 6-min forecasts of ensemble mean 2-m temperature (Figs. 8m–p) with reflectivity assimilation for the 2212 and 2215 UTC cycles compared to only radial velocity and no-precipitation observation assimilation experiments. Although the reflectivity-enhanced cold pools in the forecasts with reflectivity data assimilation have detrimental effects on the forecasts of vertical vorticity, other factors likely also play a role, such as errors in model physics and the suboptimal assimilation of radial observations into the storm-scale model, particularly within the context of a continuous rapid update cycle paradigm.

c. Reflectivity analyses and forecasts

The overall structure, location, and intensity of the simulated OKC supercell storm from the three experiments are examined using the reflectivity analyses and forecasts (Figs. 9–11). The reflectivity structures at 1 km AGL from the 10 randomly selected individual ensemble members at the end of the assimilation window reveal that an 1-h radar observation assimilation is able to reproduce the mature main supercell storm in the model (Figs. 9a–c). There are several spurious small cells with low-reflectivity cores west and southwest of the main supercell that are more evident in the Thompson solutions (Fig. 9a) than in the NFD and NVD solutions (Figs. 9b and 9c). These weak clouds produce more rain precipitation (and therefore higher radar reflectivity) in the Thompson scheme because it has a default assumption of low maritime-like cloud droplet number concentration (around 100 cm\(^{-3}\)), which tends to accelerate the collision–coalescence (warm rain) process. Moreover, the no-precipitation reflectivity observations fail to suppress those spurious cells in the Thompson experiments during assimilation due to the filter’s outlier threshold condition. The NFD and NVD simulations have default settings of more strongly continental droplet concentrations, about an order of magnitude higher, which reduces and delays warm-rain formation by comparison.

The 30-min forecast ensemble reflectivity as shown in Fig. 10 is also able to capture the evolution of the main supercell storm with time. However, the forecast supercell reflectivity loses the hook-echo structure over the forecast period while the actual storm maintains a narrow and less pronounced hook echo. Not surprisingly, at 2-km model horizontal grid spacing it is simply very hard to produce, let alone maintain, a hook-echo structure. The Thompson solution continues to generate spurious precipitation around the main supercell compared to the single- and double-moment schemes in addition to capturing the weaker cell to the southwest of the supercell (Fig. 10a). The NVD-DM members more consistently produce one isolated southwest cell compared to those from the Thompson members, even though the forecast reflectivity is lower compared to the observed weaker southwest cell (Fig. 10c).

To further investigate the differences in the three microphysics schemes in simulating the supercell storm, a single ensemble member from the 2200 UTC analyses and forecasts is selected for examination from each microphysics scheme. The ensemble member selected is the one closest to the ensemble mean from the 2200 UTC analyses and is chosen based on the normalized root-mean-square difference between the ensemble mean and each ensemble member of temperature, and the \(u\) and \(v\)-wind components. After 1 h of data assimilation, all three experiments place the main supercell storm at approximately the correct location, as well as the hook echo and strong low-level rotation at 1 km above ground, and compare well with the KTLX radar observations (Fig. 11d). The areal extent and the reflectivity distribution in the forward-flank region are closer to the size and shape of the observed forward-flank regions in the Thompson and NVD-DM schemes (Figs. 11a and 11c) compared to NFD-SM (Fig. 11b). This is mainly due to the greater flexibility in the graupel size distribution parameters in the Thompson and NVD-DM microphysics schemes. The distributions of the graupel/hail mixing ratios from the 2200 UTC analyses at around the melting layer corresponding to the reflectivity plots in Figs. 11a–c are shown in Fig. 12. The Thompson scheme diagnoses the graupel intercept parameter based on the graupel mixing ratio and the presence of supercooled liquid particles, and a smaller graupel mixing ratio leads to larger graupel intercept parameters (i.e., smaller mean diameters) and lower fall speeds, which spreads the smaller graupel mass farther downstream (Fig. 12a). The NVD-DM scheme also generates smaller, lower-density graupel aloft by predicting the graupel number concentration and riming density. This lower-density graupel has lower fall speeds, again leading to more mass farther down shear (Fig. 12c). This particular improvement is broadly consistent with recent studies demonstrating an improvement in storm structure and evolution.
FIG. 8. Neighborhood ensemble probability of vorticity forecasts (a)–(l) similar to Figs. 7u–af but generated from (top to bottom) the 2215–2227 UTC analyses. For this generation, radial-velocity (Vr) observation assimilation and 6-min ensemble-mean 2-m temperature forecasts (m)–(p) valid at 2221 UTC from 2215 UTC analyses were used for (m),(o) only Vr assimilation, and (n),(p) both Vr and dBZ assimilation experiments. The reference wind vectors are (m) 14.21, (n) 17.52, (o) 18.56, and (p) 17.83 m s\(^{-1}\). The black dots in (m)–(p) are the locations of the KOKC and KTIK ASOS stations, and the SPEN mesonet station.
when using a two-moment microphysics scheme (Mansell 2010; Dawson et al. 2010; Jung et al. 2012). The forecast supercell reflectivity loses the intensity of the precipitation signature and the hook-echo structure compared to the observations (Figs. 11h, 11l, and 11p) slowly over the 45-min forecast period with weakening vertical vorticity for the NVD-DM (Figs. 11g, 11k, and 11o) and Thompson (Figs. 11e, 11i, and 11m) schemes. In contrast, the NFD-SM...
The precipitation signature (Figs. 11f, 11j, and 11n) intensifies during the forecast over a comparatively larger area with values higher than 60 dBZ within the main reflectivity core and maintains the intensity longer in the forecast compared to the other two microphysics experiments. The lower intercept and higher-density parameters for hail in the NFD-SM scheme produce larger hail and thus high reflectivity in the core. The hail parameters could likely be tuned to achieve a more realistic result for this case, but the parameters used here are widely used (e.g., Dowell et al. 2011) and thus may serve as a control comparison with similar studies.
Fig. 11. The reflectivity (colors, 5-dBZ increment), wind vectors (reference vector $-28.0\,\text{m s}^{-1}$), and vertical vorticity (contours from 0.001 to 0.01 at 0.001 interval) at 1 km AGL for (first three columns) the experiments from the ensemble member that is closest to the ensemble mean in the 2200 UTC analyses. (top) The last analyses at 2200 UTC and (second–fourth rows) for 15-min forecasts valid at 2215, 2230, and 2245 UTC. The portion of the domain shown here is $90\,\text{km} \times 100\,\text{km}$ wide. (last column) The corresponding KTLX reflectivity observations.
Ensemble mean 2-m temperatures from the three microphysics experiments at the last analysis cycle and ensemble mean forecasts every 15 min out to 2245 UTC are shown in Fig. 13. The NVD-DM scheme generates a weaker and smaller cold pool (roughly the 25°C contour in Figs. 13c, 13f, 13j, and 13l) in the analysis and forecasts compared to the Thompson scheme even though the Thompson scheme is double moment for rain and ice crystals. The cold pool from the NFD-SM scheme is weaker than the cold pool from the NVD-DM scheme at the 15-min forecast time, with similar cold pool temperatures at later forecast times. For the Thompson scheme, the largest temperature deficits are collocated with the greatest graupel mixing ratios (8–9 g kg\(^{-1}\)) aloft (Fig. 12a), which leads to greater cooling by melting and subsequent rain evaporation as well as larger precipitation loading, resulting in stronger low-level downdrafts (Fig. 13a) compared to the other two schemes (Figs. 13b and 13c). The NFD-SM scheme has less graupel mass aloft than the Thompson result (Fig. 12b), producing not only less loading, but also less cooling by melting and evaporation, since the low graupel intercept promotes larger particles and fall speeds, allowing them to fall farther before completely melting, reducing the evaporation by limiting the depth over which rain exists.

While the three different microphysics scheme experiments show different low-level cold pool features, the analyses (Figs. 13a–c) all show a surface outflow boundary that turns north-northeastward along with updraft speeds exceeding 5 m s\(^{-1}\) at 500-m altitude. Within 15 min of forecast time, however, the forward-flank gust front surges from the northeast to create a more linear southwest–northeast-oriented boundary (Figs. 13d–f) though still maintaining a convergence signature. The updraft–downdraft interface (at 500 m AGL) also notably shifts its orientation to the northeast with weakening low-level updraft and vorticity. The 30- and 45-min forecasts (Figs. 13g–i) show continued weakening of the low-level updrafts for all of the schemes. The retrieval of near-surface features is difficult from the radar data assimilation using EnKF partly due to the lack of radar data near the surface, the earth’s curvature effect, and model errors associated with grid resolution and model physics (Dowell et al. 2004a, 2011), suggesting strong uncertainty in the analyzed cold pool.

The Will Rogers World Airport in Oklahoma City (KOKC) and Tinker Air Force Base, Oklahoma (KTIK), Automated Surface Observing System (ASOS) stations and the Spencer, Oklahoma (SPEN), mesonet station are the only three observation stations around the supercell storm and are shown by black dots in Fig. 13. The forecast
FIG. 13. The ensemble mean 2-m temperature (colors, 1°C increment), 10-m wind vectors (reference vectors are 21.0, 14.5, 13.5, and 12.0 m s\(^{-1}\) for first, second, third, and fourth rows, respectively), 500-m updrafts (black solid-line contours at 1, 3, 5, and 7 m s\(^{-1}\)) and downdrafts (black dashed-line contours at 2 and 3 m s\(^{-1}\)), 500-m vorticity (pink contours at 0.03, 0.06, and 0.09 s\(^{-1}\)), and gust fronts (green line) at (top) the last analysis time at 2200 UTC and (second–fourth rows) for 15-min forecasts valid at 2215, 2230, and 2245 UTC. The portion of the domain shown here is 70 km × 60 km wide. The black dots in each panel show the locations of the KOKC and KTIK ASOS stations, as well as the SPEN mesonet station.
4. Summary and conclusions

A WRF-ARW model-based mesoscale and storm-scale EnKF data-assimilation and forecast system is evaluated for the 8 May 2003 Oklahoma City tornadic supercell storm event. Traditional atmospheric observations of altimeter setting, temperature, dewpoint, and horizontal wind components from land and marine surface stations, rawinsondes, and aircraft are assimilated into a 45-member mesoscale ensemble system over the CONUS domain at 18-km horizontal grid spacing. Observations are assimilated every 6 h starting 3 days prior to the event at 1200 UTC 5 May 2003 using the EAKF data-assimilation technique from the DART software package. Observations are assimilated more frequently at every 1-h cycle starting at 1200 UTC on the day of the event out to 0000 UTC 9 May 2003. A storm-scale ensemble is nested within the mesoscale ensemble centered on the tornadic event at 2-km horizontal grid spacing on the day of the event at 2100 UTC. The mesoscale ensemble is used to create the initial and boundary conditions for the storm-scale ensemble. Doppler radial velocity and reflectivity observations from the operational KTIX WSR-88D are assimilated into the storm-scale ensemble every 3 min for a 1-h period to initialize the storm into the model. Three experiments are conducted at the storm scale using three different bulk microphysics schemes: the single-moment NFD-SM approach, the partially double-moment Thompson method, and the fully double-moment NVD-DM scheme. Finally, forecasts are launched from the analyses every 3 min starting at 2145 until 2230 UTC and cover the entire lifetime of the observed tornado.

Observation-space diagnostic statistics reveal that the filter shows no sign of forecast divergence during the 1-h assimilation period, indicating the robustness of the data-assimilation system. For radial velocity observations, the rmsi and ensemble spread are of comparable magnitude, indicating that the forecast error is representative of the ensemble spread for the three microphysics schemes. The reflectivity rmsi errors decrease with time and the ensemble spread for reflectivity is consistently smaller than the rmsi in all three microphysics experiments, suggesting ensemble underdispersion, which is commonly observed in real data-assimilation studies at the storm scale. All three microphysics schemes generate reasonably good analyses and forecasts that capture the movement of the main supercell storm, as well as the establishment of a hook echo, and match reasonably well with the radar observations. However, the areal extent and the distribution of the reflectivity in the forward-flank region of the simulated storm are better represented in the NVD-DM and Thompson simulations compared to the NFD-SM experiment. The NFD-SM precipitation signature intensifies during the forecast with high-reflectivity cores.

The neighborhood probability of vorticity forecasts reveals that a low-level mesocyclone persists during the forecast for all three experiments with higher probabilities of significant mesocyclones qualitatively correlating well with the observed rotation track. The consistent and gradual increase in probabilities of low-level mesocyclone forecasts from the continuously cycled data-assimilation system is very encouraging. However, results suggest that the continued assimilation of radar reflectivity observations after storm maturity may have detrimental effects on the analyses and forecasts (e.g., undue cold pool intensification). Further research is needed on assimilation strategies, particularly for reflectivity observations, as well as the identification of possible model biases and errors that may cause poor assimilation performance. Despite these issues, the rapid update cycle demonstrates how probabilistic storm-scale information can provide operational forecasters with situational awareness and confidence in the imminent tornado threats, potentially helping improve tornado warnings by providing more quantitative information regarding the evolution of storm-scale rotation on a 1-h time scale.

One possible approach to help alleviate the ensemble underdispersion in storm-scale data assimilation is to perturb the parameterized physics options used in the ensemble system. Varying the microphysical parameters
FIG. 14. The 1-h forecast time series of (a)–(c) ensemble mean 2-m temperature, (d)–(f) 2-m dewpoint temperature, (g)–(i) 10-m wind speed, and (j)–(l) 10-m wind direction from the Thompson (green), NFD-SM (red), and NVD-DM (blue) experiments at (from left to right) KOKC, KTIK (both ASOS stations), and SPEN (mesonet station). The surface observations are shown in black.
within the same microphysics scheme (Yussouf and Stensrud 2012) or using physics diversity across the ensemble (Snook et al. 2011, 2012) at storm scale can help with the spread problem and are worthwhile endeavors to include and test for future storm-scale data assimilation methods. Moreover, depending on the location of the developing storm, more than one radar can scan the same storm from different viewing angles and distances. Therefore, assimilating storm observations from multiple radars provides additional information of the storm particularly associated with the three-dimensional wind components and will likely improve the analyses and forecast (Snook et al. 2011, 2012). Future work will include assimilating storm observations from multiple radars. Although not computationally feasible for this study, experiments with horizontal grid spacing of 1 km or less may be needed to better quantify the impact of the differences in the microphysics schemes for convective storms (Dawson et al. 2010; Bryan and Morrison 2012). In addition, Bryan et al. (2003) and Bryan and Morrison (2012) show rather noticeable differences in their squall lines structures when simulated with a horizontal grid spacing varying between 250 m and 1 km. The computational demands associated with such small grid spacings are significant but with the continued rapid increase in computing power, future work will focus on more sophisticated microphysics schemes, like the triple-moment scheme for storm-scale data-assimilation and forecast systems.

The results obtained from this study indicate that a properly designed EnKF-based system that combines mesoscale and storm-scale ensembles seems to work well for very short-range ensemble forecasts of supercell thunderstorms. Admittedly the conclusions drawn here are based on a single tornadic supercell event. The system should be applied and tested across a variety of storm modes to determine its robustness before making any concrete conclusions on its applicability in operational settings.

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