Impact of Phased-Array Radar Observations over a Short Assimilation Period: Observing System Simulation Experiments Using an Ensemble Kalman Filter

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ABSTRACT
The conventional Weather Surveillance Radar-1988 Doppler (WSR-88D) scans a given weather phenomenon in approximately 5 min, and past results suggest that it takes 30–60 min to establish a storm into a model assimilating these data using an ensemble Kalman filter (EnKF) data assimilation technique. Severe-weather events, however, can develop and evolve very rapidly. Therefore, assimilating observations for a 30–60-min period prior to the availability of accurate analyses may not be feasible in an operational setting. A shorter assimilation period also is desired if forecasts are produced to increase the warning lead time. With the advent of the emerging phased-array radar (PAR) technology, it is now possible to scan the same weather phenomenon in less than 1 min. Therefore, it is of interest to see if the faster scanning rate of PAR can yield improvements in storm-scale analyses and forecasts from assimilating over a shorter period of time. Observing system simulation experiments are conducted to evaluate the ability to quickly initialize a storm into a numerical model using PAR data in place of WSR-88D data. Synthetic PAR and WSR-88D observations of a splitting supercell storm are created from a storm-scale model run using a realistic volume-averaging technique in native radar coordinates. These synthetic reflectivity and radial velocity observations are assimilated into the same storm-scale model over a 15-min period using an EnKF data assimilation technique followed by a 50-min ensemble forecast. Results indicate that assimilating PAR observations at 1-min intervals over a short 15-min period yields significantly better analyses and ensemble forecasts than those produced using WSR-88D observations. Additional experiments are conducted in which the adaptive scanning capability of PAR is utilized for thunderstorms that are either very close to or far away from the radar location. Results show that the adaptive scanning capability improves the analyses and forecasts when compared with the nonadaptive PAR data. These results highlight the potential for flexible rapid-scanning PAR observations to help to quickly and accurately initialize storms into numerical models yielding improved storm-scale analyses and very short range forecasts.

1. Introduction
A recent research application of the radial velocity and reflectivity observations provided by the Weather Surveillance Radar-1988 Doppler (WSR-88D) is their use in the initialization of storm-scale numerical prediction models using an ensemble Kalman filter (EnKF) data assimilation approach (Snyder and Zhang 2003; Zhang et al. 2004; Dowell et al. 2004a,b; Tong and Xue 2005, 2008; Caya et al. 2005; Xue et al. 2006; Jung et al. 2008; Aksoy et al. 2009). Many of these studies use observing system simulation experiments (OSSEs) to explore the data requirements needed to obtain accurate analyses of convective storms using an EnKF data assimilation method, and a consensus appears to be emerging on two data needs. First, the use of both radial velocity and reflectivity observations, including reflectivity observations in nonprecipitating regions that are used to suppress spurious regions of convection, yield more accurate analyses (Tong and Xue 2005; Aksoy et al. 2009). Second, approximately 10 complete volume scans of WSR-88D

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observations are needed to produce accurate analyses. Snyder and Zhang (2003) and Zhang et al. (2004) suggest that accurate analyses can be produced using 6–8 radar scans, but the synthetic observations used in these studies are available at the model grid points and do not mimic real radar observations. Using a radar emulator to generate synthetic radar observations on the radar elevation levels for each of the model horizontal grid points, Xue et al. (2006) show that 10–20 radar scans are needed to produce accurate analyses. Caya et al. (2005) indicate that an EnKF assimilation produces more accurate analyses than a four-dimensional data assimilation scheme after assimilating 8–10 radar scans. Thus, it appears reasonable to expect that at least 10 radar scans are needed to produce reasonable analyses of storms.

The conventional WSR-88D typically takes slightly over 5 min to scan a thunderstorm, indicating that at least 45 min of data (10 volume scans) are needed to obtain an accurate analysis of a storm. In an operational environment, however, National Weather Service (NWS) forecasters do not have the luxury to wait for 45 min of radar data to be collected after a thunderstorm’s first echo before making warning decisions. A shorter assimilation period is needed if EnKF analyses are to be useful in NWS operations. One way to reduce the assimilation time is to provide observations more frequently. Xue et al. (2006) and Lei et al. (2007) show that the assimilation of synthetic 1-min radar data leads to analyses that more closely approach the truth solution than do the analyses created using synthetic 5-min radar data when examined over a 1-h period. A number of storm features evolve on a time scale of minutes and are better sampled with 1-min data. Thus, rapid-volume-scan radar observations yield improved storm analyses using an EnKF data assimilation method, although the ability of these observations to quickly and accurately initialize a storm in a numerical model is unknown.

Because the conventional WSR-88D is approaching the end of its engineered-design 20-yr life span, the radar research community is exploring replacement radar technologies that could fulfill multiple mission requirements (Weber et al. 2007). One promising alternative is the phased-array radar (PAR) developed in the mid-1960s for use by the U.S. military (Skolnik 2001). Two unique features of PAR are its agile and fast electronic beam steering and its ability to use a beam multiplexing technique to further optimize scan rate without sacrificing data quality (Yu et al. 2007). A new experimental research PAR built in 2003 at the National Weather Radar Test Bed (NWRT) located in Norman, Oklahoma (Forsyth et al. 2004), provides unique opportunities for meteorologists to study rapidly evolving convective weather phenomena using more frequent volume updates. Indeed, the emerging PAR rapid-scanning technology can scan a thunderstorm in less than 1 min (Heinselman et al. 2008). Thus PAR can produce 10 complete volume scans of radar data in 10 min or less. Therefore, it is reasonable to expect that PAR observations can generate accurate storm analyses in a shorter period of time than is possible from WSR-88D observations. Therefore, even though the PAR is in the early stages of development, its adaptive, rapid-scan, and multifunction capabilities make it a promising replacement candidate for the WSR-88D (Weber et al. 2007; Yu et al. 2007; Zrnic et al. 2007).

To assess quantitatively the impact of assimilating high-temporal-frequency PAR observations on storm-scale modeling and to determine how quickly and accurately a storm can be represented in the analyses, an obvious first step is to use an OSSE approach prior to working with real PAR observations. Therefore, several different OSSEs are conducted using a simulated supercell storm as the reference, or truth, simulation. Synthetic observations of radial velocity and reflectivity are constructed from the reference solution in native radar coordinates using a realistic volume-averaging technique similar to the approach of Lei et al. (2007), and two sets of experiments are conducted. One experiment assimilates synthetic WSR-88D observations, in which a volume scan is conducted every 5 min, whereas the other experiment assimilates synthetic PAR observations, in which a volume scan is conducted every 1 min. The EnKF is used as the data assimilation method for both experiments with identical settings. Other OSSEs also are conducted to quantify the value of the adaptive scanning capability of PAR. However, unlike other recent research efforts (Dowell and Wicker 2009; Aksoy et al. 2009), this study assimilates radar data for a relatively short period of time (only 15 min). The storm-scale model, simulated radar dataset, and experimental design are described in section 2. Section 3 presents the results obtained from the EnKF analyses and forecasts, followed by a final discussion in section 4.

### 2. Assimilation system and experiment design

The Collaborative Model for Multiscale Atmospheric Simulation (COMMAS; Wicker and Skamarock 2002; Coniglio et al. 2006) is used in this study to assess the impact of high-temporal-frequency PAR observations on EnKF (Dowell et al. 2004a,b; Whitaker and Hamill 2002) analyses and forecasts. The COMMAS model is a nonhydrostatic compressible numerical cloud model with prognostic variables that include the three velocity components $u$, $v$, and $w$; pressure in the form of the perturbation Exner function $\pi$; potential temperature $\theta$;
turbulent mixing coefficient \( k_m \); and six categories of water substance: water vapor \( q_v \), cloud water \( q_c \), rain-water \( q_r \), ice \( q_i \), snow \( q_s \), and hail/graupel \( q_h \) (Dowell and Wicker 2009). The truth simulation and EnKF analyses both use the same 1-km horizontal grid resolution. The Gilmore et al. (2004) version of the Lin–Farley–Orville (Lin et al. 1983) single-moment bulk microphysics scheme is used for precipitation processes with four hydrometeor classes: rain, ice crystals, snow, and hail/graupel. The values of the intercept parameters for rain, snow, and hail/graupel are \( 8 \times 10^6 \), \( 3 \times 10^6 \), and \( 4 \times 10^4 \) m\(^{-4} \), respectively, and the densities of snow and hail are specified as 100 and 900 kg m\(^{-3} \), respectively. Moreover, the radar is stationary while the model domain moves with the simulated storm; all experiments in this study are conducted using a single radar to observe the supercell storm.

The EnKF data assimilation scheme used in the study is based on the ensemble square root filter (EnSRF) of Whitaker and Hamill (2002). A compactly supported fifth-order correlation function following Gaspari and Cohn (1999) is used for the covariance localization. The cutoff radius for covariance estimation of the filter is 4 km in both the horizontal and vertical directions. The reflectivity and radial velocity observations are assimilated in the filter serially. Each time an observation is assimilated, the ensemble mean and each of the ensemble members are updated for each model variable at each grid point within 4 km of the observation. Details of the EnSRF system used in this study can be found in Dowell et al. (2004b). To reduce the computational costs, the observation operator \( H \) uses a trilinear interpolation instead of the simplified volume-averaging technique to relate the forecast model variables at the model grid point to the observation location and type. The \( H \) operator for the radial velocity \( V_r \) is defined as

\[
V_r = u \sin(\phi)\cos(\theta) + v \cos(\phi)\cos(\theta) + (w + V_f) \sin(\theta),
\]

where \( u, v, \) and \( w \) are the wind components; \( V_f \) is the terminal fall speed of hydrometeors; and \( \theta \) and \( \phi \) are the elevation and azimuth of the radar beam, respectively, all trilinearly interpolated from the model grid point to the observation location. The \( H \) operator for reflectivity follows the relationships of Ferrier (1994) and is as follows:

\[
Z_{dB} = 10 \log_{10}(Z_{er} + Z_{es} + Z_{eh}),
\]

where \( Z_{er}, Z_{es}, \) and \( Z_{eh} \) are the equivalent reflectivity factors for rain, snow, and hail, respectively. In this study, a 40-member ensemble is used, and the number of observations assimilated during each 1-min assimilation period ranges from 400 to 377 500, depending on the location of the radar relative to the supercell, height of radar scans, and supercell intensity.

Unlike previous OSSE studies that made simplifying assumptions regarding the radar observations (Snyder and Zhang 2003; Tong and Xue 2005), this study follows Lei et al. (2007) and uses a radar emulator that generates radial velocity and reflectivity observations from the reference simulation in native radar coordinates using a simplified version (Fig. A1 of the appendix) of a realistic volume-averaging technique (Wood et al. 2009). The \( Z, u, v, \) and \( w \) wind components at model grid points within the beamwidth are scanned with the radar emulator to produce both WSR-88D and PAR reflectivity and radial velocity observations (Fig. 1). Details of the radar emulator are discussed in the appendix. To reduce the heavy computational burden of observation assimilation, the reflectivity and radial velocity observations used in this study are created at a coarser 1.0-km range sampling interval instead of the 0.25-km interval available from the radars. Although the experimental PAR located at NWRT has a beamwidth of 1.5° in the direction perpendicular to the antenna face and increases to 2.1° as it moves 45° from the perpendicular, the ultimate goal of PAR technology is to make the beamwidth match or exceed that of the WSR-88D, and therefore both WSR-88D and PAR antenna half-power beamwidths are assumed to be 0.89° for this study with 1.0° azimuth interval and a 1.39° effective beamwidth (EBW). The effects of the earth’s curvature and bending of the radar beam far from the radar location (Doviak and Zrnić 2006) also are taken into consideration in calculating the radar observations. The synthetic radar observations are generated using the volume coverage pattern (VCP)-11 precipitation-mode scanning strategy consisting of 14 elevation angles (Table 1). To assimilate the WSR-88D observations more realistically, the WSR-88D observations are generated for 2–3 sweeps every minute rather than assuming the entire volume is collected simultaneously. Out of the 14 sweeps, the lower 12 sweeps of observations are generated for 3 sweeps per minute for the first 4 min with the remaining upper 2 sweeps valid for the fifth minute of the volume scan. Observations for PAR data are generated instantaneously every minute for a complete volume scan. To account for the measurement and sampling errors for radial velocity and reflectivity observations, random numbers are drawn from a Gaussian distribution of zero mean and standard deviations of 2 m s\(^{-1} \) and 2 dBZ, respectively, and are added to the observations. The radar reflectivity observations assimilated include nonprecipitating observations, whereas the radial
velocity observations are assimilated only where the observed reflectivity values are greater than 10 dB Z. Previous studies (Tong and Xue 2005; Aksoy et al. 2009) show that assimilating clear-air reflectivity observations helps to suppress the spurious convective cells around the main storm. A more complete description of the volume-averaged reflectivity and radial velocity value calculation within the effective beamwidth is found in the appendix.

a. The truth simulation and synthetic radar observations

The 2-h-long truth simulation uses the classic Weisman–Klemp analytic sounding (Weisman and Klemp 1982). The vertical wind shear profile uses a quarter-circle hodograph. The shear vector turns through 45° over the lowest 2 km, and then the wind is linear from 2 to 6 km. At 6 km above ground, the values of \( u \) and \( v \) are 39.55 and 9.55 m s\(^{-1}\), respectively, and the winds remain constant above 6 km at the 6-km magnitude. An ellipsoidal thermal bubble of 2.5 K with 10-km radius in the horizontal direction and 1.4-km radius in the vertical direction is placed at the center of the domain to initiate a supercell thunderstorm at \( t = 50 \) min. The model domain is 100 km wide in the horizontal direction and 18 km tall in the vertical direction. The domain is vertically stretched from 100-m vertical spacing at the bottom to 700-m vertical spacing at the domain top. The ellipsoidal thermal bubble develops into a convective cell within the first 30 min of the simulation, and the first echo is seen by the radar emulator at around \( t = 25 \) min. Over the next 30 min, the convective cell splits into two cells, one moving right toward the southeast and the other moving toward the northwest. During the second hour of the simulation, the right-moving cell tends to dominate the system, with a few short-lived smaller cells developing in between the two main cells. The domain grid is translated at \( u = 17 \) m s\(^{-1}\) and \( v = 7 \) m s\(^{-1}\) to keep the main storm near the center of the model domain.

### Table 1. Enhanced VCP-11 scan strategy for scanning storms within ~70 km and beyond ~70 km from the radar location.

<table>
<thead>
<tr>
<th>No. of angles</th>
<th>VCP 11</th>
<th>Enhanced VCP 11 (~70 km)</th>
<th>Enhanced VCP 11 (≥70 km)</th>
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<td>0.50</td>
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<tr>
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<td>—</td>
<td>23.70</td>
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</tbody>
</table>
b. The ensemble configuration and OSSE design

Each member of the 40-member ensemble uses the same classic Weisman–Klemp sounding with quarter-circle hodograph in a horizontally homogeneous environment to define the initial environmental condition. To facilitate the development of storms, seven thermal bubbles (i.e., 1.5 K maximum ellipsoidal \( \theta \) perturbations) with 7.5–km radius in the horizontal direction and 2.0–km radius in the vertical direction at random locations within the 30–70–km portion of the domain in \( x \) and \( y \) directions and within 0.25–2.25 km in \( z \) direction are introduced at the initialization time (\( t = 0 \)) to each ensemble member, following the methods of Snyder and Zhang (2003) and Dowell et al. (2004a,b). This method of initialization is very helpful, because the thermal bubbles initiate convective cells and produce the covariance information needed for the ensemble to assimilate the radar data successfully. Moreover, the assimilation of clear-air observations suppresses the unwanted spurious convective cells around the main supercell. The ensemble members thus differ from each other in the location and magnitude of the thermal bubbles but have an identical base environment. After initializing the ensemble members at \( t = 0 \), the members are integrated forward in time for 25 min before the assimilation of first observations. During this period, the \( \theta \) perturbations within the center 40 km \( x \) \( \times \) 40 km area of the domain initiate convective cells in the ensemble members (Snyder and Zhang 2003; Dowell et al. 2004a,b; Aksoy et al. 2009). However, problems can arise if these convective cells are collocated over the radar location. For lower-elevation scans, a number of radar observations within \( \sim \)11–km range of the radar are below the lowest model vertical level at 100 m, causing a problem with the trilinear interpolation observation operator. To avoid this problem when the radar location is very close to the storm, the thermal bubbles during initialization are placed at random locations but within a narrower 45–70–km area of the domain in the horizontal directions. The vertical area remains the same. It is found that this reduced bubble area of 25 km \( x \) \( \times \) 25 km does not affect the overall quality of the EnKF data assimilation (shown later).

The observations valid within 1 min of the current time are assimilated, followed by advancing the ensemble members 1 min to the next observation time. To help maintain the storm and ensemble spread during the assimilation cycles, ellipsoidal thermal (\( \theta \)) perturbations are added to the members instead of applying covariance inflation that can degrade the results (Snyder and Zhang 2003; Dowell and Wicker 2009). Thermal perturbations are added near the locations where the difference between the observed and ensemble-mean reflectivity field exceeds 30 dBZ. The perturbations have a temperature excess of 1.5 K at the center of the ellipsoid that decreases to zero at a horizontal radius of 7.5 km and vertical radius of 2 km. The thermal perturbations are added every 5 min for WSR-88D observations assimilation and every 2 min for PAR observations assimilation. Similar assimilation results are obtained when thermal perturbations are added every 2 min for the WSR-88D experiments (not shown). The domain size and grid resolution for the ensemble members are identical to the truth run. The domain of the ensemble also moves at \( u = 17 \text{ m s}^{-1} \) and \( v = 7 \text{ m s}^{-1} \) following the truth run to keep the storm inside the domain. Thus, we are assuming that the model is perfect and the environmental condition is perfectly represented. Moreover, although previous studies make a short-term forecast initialized from the ensemble-mean analysis at the last assimilation cycle (Snyder and Zhang 2003; Tong and Xue 2005), this study uses all of the 40 ensemble members at the last assimilation cycle to make an ensemble of forecasts. Three sets of OSSEs are implemented in this study to assess the benefits and challenges of flexible and rapid-update volumetric PAR data.

1) 60-MIN ASSIMILATION

To document the stability of the EnKF scheme that is used in this study and to compare results with previous studies, a 60-min data assimilation experiment is conducted. The assimilation of 12 volume scans of storm observations from a WSR-88D and 60 volume scans from a PAR, both using VCP-11 precipitation-mode scanning strategy with 14 elevation angles, are compared. The 1-h assimilation period starts at \( t = 25 \) min and ends at \( t = 84 \) min. The radar is located inside the model domain during the first volume scan, southwest relative to the convective cell. However, because the storm motion is away from the radar, the radar is located outside the computational domain to the west-southwest of the supercell during the last volume scan.

2) 15-MIN ASSIMILATION

The objective of this experiment is to evaluate whether accurate analyses can be produced much more rapidly than has been shown previously. Unlike the first experiment, this experiment assimilates radar observations for a brief 15-min period starting at \( t = 25 \) min and ending at \( t = 39 \) min. During this assimilation period, 15 volume scans of PAR observations and 3 volume scans of WSR-88D observations are assimilated. After 15 min of data assimilation, the ensemble members are used to produce a 50-min forecast. The radar is located at \( x = -3.6 \text{ km} \) and \( y = -4.9 \text{ km} \) from the
southwest corner of the domain during the first volume scan, unlike the previous experiment in which the radar is located inside the model domain during the first volume scan. The initialization and other ensemble configuration details are identical to the previous experiment.

3) **Enhanced Scanning Strategies**

The new PAR technology is capable of adjusting its scanning mode to scan the storm top that may otherwise belong to the "cone of silence" in the WSR-88D VCP modes. In traditional WSR-88D VCP modes, the upper elevation angle of 19.5° often undershoots storm-top height when a storm is very close to the radar location (≤30 km). Moreover, the spacing between elevation angles above 6° (especially with VCP-11 scanning mode) often undersamples the vertical structure of storms. This is due to the vertical data gaps in radar coverage above 6° (Fig. 2a). In contrast, when the storm is far away from the radar (>70 km), scanning up to 19.5° from VCP-11 mode overshoots the storm top, whereas the lower levels of the atmosphere remain undersampled, even though there are no gaps in radar data coverage at low levels. This is due to the earth-curvature effect that prevents the radar from seeing the lower levels of the atmosphere when the radar is far away from the storm. Moreover, when the radar is far away from the storm location, the radar sampling resolution is lower because of beam broadening. With the PAR adaptive scanning capability, however, it is possible to enhance the scanning angles in real time when the storm is either close to or far away from the radar. In an effort to determine how well the PAR adaptive scanning capability can be utilized to yield a better depiction of the storm evolution, two enhanced VCP-11 scanning strategies with improved vertical sampling similar to the 2008 National Severe Storms Laboratory Real-Time PAR Experiment (Heinselman 2008) are used. The first enhanced scanning strategy adds six additional scans to the VCP-11 mode with elevation angles as high as 23.70° above ground when a storm is located very close to the radar location (Fig. 2b). These higher elevation angles sample the storm top that is unobserved when using the VCP-11 mode. The second enhanced scanning strategy includes additional lower-elevation scans in the lower level of the atmosphere while removing higher-elevation scans when the storm is far away from the radar (Fig. 2c). Thus, these enhanced VCP-11 scan strategies take advantage of the operational VCP 11’s accuracy while improving the vertical sampling based on whether storms are near or far away from the radar. However, the collocation of the radar with the bubble area can cause problems, as mentioned in section 2b. Therefore, to avoid bubbles close to the selected radar location

![Figure 2](https://journals.ametsoc.org/mwr/article-pdf/138/2/517/4251435/2009mwr2925_1.pdf)
within the domain, a reduced 25 km × 25 km horizontal area within the domain is used for the enhanced-scanning-strategy experiment when the radar is very close to the storm (≤30 km). Other than the reduced bubble area, the ensemble initialization and other configuration details of the ensemble members are identical to the 60-min assimilation experiment. A list of the scan angles for the enhanced VCP-11 scanning is given in Table 1.

3. Analysis results

The accuracy of the analyses during the assimilation period and the short-term forecasts from PAR and WSR-88D observation assimilations are evaluated using both statistical and graphical comparisons of the ensemble-mean analyses and forecasts with the truth run. Because the objective is to evaluate how well the supercell is captured in the analyses and to determine forecast accuracy when using the analyses as initial conditions, the analyses and forecasts errors are calculated only in areas where there is convection. Statistical measures include the root-mean-square (rms; Wilks 1995) error of the unobserved variables, calculated as the difference between the reference simulation and the ensemble mean averaged over only those reference simulation grid points for which the total precipitation mixing ratio (sum of rain, snow, and hail mixing ratios) is greater than 0.10 g kg⁻¹. Moreover, the rms errors are calculated from the ensemble-mean analyses during the observation assimilation period and from the ensemble-mean forecasts during the 50-min forecast period. Error prior to any data assimilation is identical in the various runs.

a. 60-min assimilation

The rms errors of the ensemble-mean analyses from assimilating PAR observations have a larger decrease in the rms errors for \( u, v, \) and \( w \) wind components; temperature; and total precipitation mixing ratios when compared with the WSR-88D observation assimilation during the first 30-min of the assimilation period (Fig. 3). This result is not surprising, because the PAR assimilation is using 5 times as many observations over the same time interval. By the end of the 60-min assimilation cycle, the magnitudes of the rms errors from both assimilations become close to each other and are similar to the values from Snyder and Zhang (2003). Horizontal plots of reflectivity and vertical vorticity at the last assimilation cycle (\( t = 84 \) min) from PAR and WSR-88D observation assimilation show that both observations capture the split supercell structure and the developing hook echo accurately (Fig. 4). The maximum reflectivity and vertical vorticity and its extent also are comparable between the two and closely match the truth. The 60-min-long assimilation cycle suppresses almost all spurious convection in the ensemble members through the assimilation of nonprecipitating observations for both PAR and WSR-88D observation assimilation. Overall, the results from the longer 60-min assimilation experiment suggest that the EnKF technique is stable and supports the conclusion drawn in earlier studies that 10 or more volume scans of radar observation assimilation generate very accurate analyses of severe-storm events (Tong and Xue 2005; Xue et al. 2006). After the first 15-min of assimilation period, the rms errors for \( u, v, \) and \( w \) wind components; temperature; and total precipitation mixing ratio approach 2 m s⁻¹, 2.6 m s⁻¹, 2.8 m s⁻¹, 1.2 K, and 0.60 g kg⁻¹, respectively, for PAR observation assimilation. For WSR-88D observation assimilation, the values approach 3.8 m s⁻¹, 3.4 m s⁻¹, 4.4 m s⁻¹, 1.5 K, and 0.9 g kg⁻¹, respectively.

b. 15-min assimilation

The rms errors of both PAR and WSR-88D observation assimilations are seen to decrease rapidly for all variables (Fig. 5). However, the faster volume scan of PAR observation generates significantly smaller rms error than does the WSR-88D assimilation for all variables. The increase and decrease (zigzag pattern) in the error curve from assimilating WSR-88D observations are more distinct than in the PAR error curve and correspond to the error from assimilating observations during the 5-min-long volume scans. At the end of the 15-min assimilation period, the rms errors for the horizontal wind components and temperature approach 2.5 m s⁻¹ and 1.15 K, respectively, for PAR observation assimilation, in reasonable agreement with the values of 3.5 m s⁻¹ and 1.4 K from Xue et al. (2006). Although the consistency ratio (Dowell et al. 2004b) should be approximately 1, for reflectivity observations it decreases from 2.5 to 0.9 during the assimilation period and for radial velocity observations it decreases from 0.80 to 0.40, suggesting that the ensemble spread is too small for both PAR and WSR-88D observations assimilations. Improved ensemble spread can be obtained from applying the more robust “additive noise” method (Dowell and Wicker 2009). The reflectivity and vertical velocity structure of the supercell storm in midlevels from PAR observation assimilation more closely resembles the truth than does that of the WSR-88D observation assimilation (Fig. 6). The PAR ensemble-mean analyses capture the location, structure, and the strength of the two main precipitation cores as in the truth, whereas the WSR-88D analyses fail to capture the high-reflectivity core of the northern cell and barely capture the high-reflectivity core of the southern cell. In addition, although
Fig. 3. The rms errors of ensemble-mean analyses vs time(s) for the 60-min assimilation experiment starting at \( t = 25 \) min and ending at \( t = 84 \) min for (a) \( u \) (m s\(^{-1}\)), (b) \( v \) (m s\(^{-1}\)), (c) \( w \) (m s\(^{-1}\)), (d) \( T \) (K), and (e) total precipitation mixing ratios (g kg\(^{-1}\)) for PAR (black lines) and WSR-88D (gray lines) observations assimilation. Values are averaged over the domain at grid points where the total precipitation mixing ratios (sum of \( q_r \), \( q_h \), and \( q_s \)) in the truth run is greater than 0.10 g kg\(^{-1}\). Note that 300 s = 5 min.
a number of spurious cells still surround the main supercell in the WSR-88D analyses, the more frequent observations assimilation from PAR suppresses most of the spurious convection. This result reinforces the conclusion that the frequent assimilation of reflectivity observations from clear air is indeed very helpful in suppressing spurious convection (Tong and Xue 2005; Aksoy et al. 2009). Furthermore, the two strong updrafts
FIG. 5. As in Fig. 3, but for the experiment with 15-min assimilation period starting at $t = 25$ min and ending at $t = 39$ min.
in excess of 16 m s\(^{-1}\) from the northern and southern cells (Fig. 6b) in the truth are well represented in the PAR analyses (Fig. 6d), whereas the WSR-88D analyses (Fig. 6f) fail to capture the location, structure, and strength of the updrafts. Although the maximum updraft from the WSR-88D assimilation is 14.28 m s\(^{-1}\), the maximum updrafts from PAR observation assimilation and the truth are 31.26 and 28.02 m s\(^{-1}\), respectively. Similar results also are found for other variables at other vertical levels of the model domain. These results clearly highlight the benefits of assimilating faster volume-scan observations when using a short assimilation period to accurately capturing the split supercell structure of the storm in the analyses.

c. **Enhanced PAR scanning analyses**

To evaluate whether the accuracy of the analyses can be improved with the enhanced scanning ability of PAR, the analyses with the enhanced scanned PAR observations are compared with those using the regular VCP-11 scanned PAR observation assimilation for a 15-min assimilation period. Results indicate that, when the storm is very close to the radar, the assimilation of enhanced PAR observations generates rms errors for
FIG. 7. As in Fig. 5, but for PAR observation assimilation when the storm is very close to the radar location for regular (gray lines) and enhanced (black lines) scanning strategies.
winds, temperature, and precipitation variables that are smaller than the rms errors from VCP-11 scanned PAR data (Fig. 7). The reflectivity plots at 6.1 km AGL and valid at the last assimilation cycle at \( t = 39 \) min show that both regular and enhanced PAR analyses capture the split cell structure of the developing supercell (Fig. 8).

When the storm is far away from the radar location, the rms error for the enhanced PAR assimilation is slightly smaller in general than the regular PAR assimilation at the last assimilation cycle (Fig. 9). However, the differences in the errors are small, likely because of the similarities of the sampling strategies (cf. Fig. 2). The reflectivity contours (Fig. 10) at 2.1 km AGL at the last assimilation cycle \( (t = 39 \) min) from regular (Fig. 10b) and enhanced (Fig. 10c) PAR observation assimilation show that the location, structure, and strength of the two main precipitation cores closely match each other.

4. Forecast results

The ultimate goal of storm-scale data assimilation is to increase warning lead times by obtaining more accurate 3D analyses of storm structure and short-term forecasts of severe-storm events. Thus, to evaluate the accuracy of the forecasts from assimilating both PAR and WSR-88D observation over a short period of time, the 40 analyses from the last assimilation cycles are used as the initial conditions for each of the ensemble members and short-term forecasts are produced. The ensemble-mean forecasts are then compared with the truth run.

a. Forecasts from 15-min analyses

The rms errors of the ensemble-mean forecasts show that the rms errors grow rapidly during the forecast period from both PAR and WSR-88D observation assimilation, as expected (Fig. 11). However, the rate of forecast error growth is larger for WSR-88D observation assimilation than for PAR observation assimilation. In addition, the forecast errors from PAR observation assimilation are significantly smaller than the forecast errors from WSR-88D observation assimilation for the entire 50-min forecast period. The reflectivity contours from the truth simulation and 5-min forecast at 6.1 km AGL and 20-min forecasts at 2.1 km from PAR and WSR-88D observation assimilation indicate that the forecasts from PAR observation assimilation maintain the strength, split-storm-cell structure, and location of the two main precipitation cores more closely to the truth than do those of the WSR-88D forecasts (Fig. 12).

FIG. 8. Reflectivity contours at 6.122 km AGL at \( t = 39 \) min for (a) truth runs and ensemble-mean analyses at the last assimilation cycle when the radar is very close to the storm from assimilating PAR observations using (b) regular scanning strategy and (c) enhanced scanning strategy.
A closer look at the 20-min forecasts also reveals that the location of the high-reflectivity core of the southern cell is more accurately captured by the PAR observation assimilation (Fig. 12e) forecasts than by the WSR-88D forecasts (Fig. 12f) when compared with the truth (Fig. 12d). Thus, the more accurate analyses from the PAR observation assimilation yield forecasts that are better than the WSR-88D forecasts.
b. Forecasts from enhanced PAR scanning analyses

The ensemble-mean forecast rms errors from enhanced-and regular-scan PAR observation assimilation are similar for all variables when the storm is very close to the radar location (Fig. 13). In contrast, when the radar is far away from the storm, the rms errors from the enhanced scan are smaller than those from the regular scan for almost the entire 50-min forecast period (Fig. 14). Thus, even though the sample resolution of the storm is low when the storm is far away from the radar, the oversampling of the low levels of the atmosphere may be helpful in increasing the accuracy of storm assimilation.

5. Discussion

Results from OSSEs show that high-temporal-frequency PAR observations can generate accurate analyses when assimilated into a storm-scale numerical weather prediction model over a short 15-min period. The more frequent PAR observation assimilation is able to suppress most of the spurious cells in regions around the storm during the brief 15-min assimilation period, yielding a more accurate depiction of the two precipitation cores and smaller rms errors for the unobserved variables of winds, temperature, and precipitation mixing ratios relative to results from the WSR-88D observation assimilation. In both PAR and WSR-88D ensemble-mean forecasts, there is a rapid increase in rms errors, but the errors for PAR observation assimilation are consistently smaller than for WSR-88D observation assimilation. These results highlight the benefits of more frequent observations to the rapid creation of storm-scale analyses and more accurate very short range forecasts of convective weather. Moreover, results also indicate the potential for improved analyses and forecasts from assimilating enhanced scanned volumes of PAR observations relative to those of the regular VCP-11 scans of PAR observations of the same storm when the radar is either very close to or far away from the radar location. However, more rigorous studies of the influence of enhanced-scanning strategies on storm observation assimilation, the effects of the observation operator $H$ as distance to the radar changes, and the effects of model resolution and radar observation locations on storm analyses and forecasts are needed.

The ultimate goal of storm-scale radar data assimilation is to extend warning lead times for convective-scale weather events by providing both complete, physically consistent three-dimensional storm analyses and ensemble-based probabilistic hazard information to NWS forecasters (Stensrud et al. 2009). This inclusion of model analyses and forecasts in the warning process shifts the

FIG. 10. As in Fig. 8, but when the radar is far away from storm at 2.105 km AGL.
FIG. 11. The rms errors of ensemble-mean forecast from the 15-min assimilation experiment during the 50-min forecast period for (a) $u$ (m s$^{-1}$), (b) $v$ (m s$^{-1}$), (c) $w$ (m s$^{-1}$), (d) $t$ (K), and (e) $q$ (g kg$^{-1}$). Values are averaged over the domain where the total precipitation (sum of $q_r$, $q_h$, and $q_m$, mixing ratios) is greater than 0.10 g kg$^{-1}$. Details are shown in the legend.
warning paradigm from warn on detection to warn on forecast. Although there are a number of challenges to overcome before warn on forecast can become a reality, the results of this study show that high-temporal-frequency radar observation assimilation may improve short-term forecasts and warnings of severe-weather events with the potential to increase warning lead time by assimilating over a shorter period of time. However, caution is warranted as the results obtained from these OSSE studies may be too optimistic since the experiments are based on a perfect-model assumption in which model error does not play a role. These studies represent only a first step in this direction. To lay a foundation for the value of the new and emerging PAR technology beyond the current WSR-88D network in storm-scale modeling, a broader range of experiments needs to be conducted with real radar observations.

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FIG. 13. As in Fig. 11, but for ensemble-mean forecast rms error from PAR observation assimilation when the storm is very close to the radar. The rms errors from regular PAR observation are shown in gray, and the enhanced PAR observation is shown in black.
FIG. 14. As in Fig. 13, but for ensemble-mean forecast rms error from PAR observation assimilation when the storm is far away from the radar.
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APPENDIX

Description of the Radar Emulator

Although, in reality, the radar reflectivity and radial velocity observations are generated from averaging radar pulses, the radar emulator in this study constructs the reflectivity and radial velocity values by averaging distributed reflectivity and wind components from the three-dimensional gridded model data within the beamwidth area as in Wood et al. (2009). The reflectivity

![Figure A1](https://journals.ametsoc.org/mwr/article-pdf/138/2/517/4251435/2009mwr2925_1.pdf)
located within the radar sampling volume centered at range \( r_0 \), elevation \( \theta_0 \), and azimuth \( \phi_0 \) is expressed as

\[
Z(r_0, \theta_0, \phi_0) = \frac{\sum_{vol} Z_{ijk} \omega_{ijk}}{\sum_{vol} \omega_{ijk}}.
\]  

(A1)

and the corresponding radial velocity is expressed as

\[
v(r_0, \theta_0, \phi_0) = \frac{\sum_{vol} V_{ijk} Z_{ijk} \omega_{ijk}}{\sum_{vol} Z_{ijk} \omega_{ijk}},
\]

(A2)

where \( Z_{ijk} \) and \( v_{ijk} \) are the model reflectivity and radial velocity, respectively, at model grid point \((i, j, k)\) and \( \omega_{ijk} \) is the beam-weighting function. The radial velocity at model grid points is calculated from

\[
V_{ijk} = u_{ijk} \sin(\phi)\cos(\theta) + v_{ijk} \cos(\phi)\cos(\theta) + (w_{ijk} + V_T)\sin(\theta),
\]  

(A3)

where \( u_{ijk} \), \( v_{ijk} \), and \( w_{ijk} \) are the model grid point wind components and \( V_T \) is the terminal fall speed calculated using a reflectivity-weighted function from the hydrometeors. Now, the mean reflectivity and Doppler velocity values in (A1) and (A2) at the center range, azimuth, and elevation of the effective resolution volume within the beamwidth are approximated by computing the weighted mean of individual Doppler velocity and reflectivity values over 13 points within the resolution volume, as shown in Fig. A1. The eight outer points within the volume carry a constant weight of 0.50, the four points in the inner ellipsoid have a weight of 0.84, and the center point has a weight of 1.0. A trilinear interpolation of the model grid values is used to obtain these 13 points in the resolution volume. A schematic illustration of the simplified volume averaging is shown in Fig. A1. Last, the mean radar reflectivity factor \( Z \) is converted to logarithmic radar reflectivity in units of reflectivity decibels (dBZ) using \( \text{dBZ} = 10 \log_{10} Z \).

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