P2.17 Impact of Spatial Over-sampling by Phase-Array Radar on Convective-Storm Analysis using Ensemble Kalman Filter and Simulated Data

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1. Introduction

The phased-array radar (PAR) of the National Weather Radar Testbed (NWRT) in Norman, Oklahoma represents a paradigm shift for weather radar observations. Through beam multiplexing (Yu et al. 2007), increased measurement accuracy can be achieved without increasing volume scan time. Alternatively, at the same measurement accuracy, more independent samples can be collected within a given time, allowing for, e.g., effective spatial over-sampling. Since the NWRT PAR radar has wider beams (on average about 2°) than the operational WSR-88D radar (about 1°), spatial resolution becomes low at far ranges. In this study, we examine the impact of spatial over-sampling on the analysis of thunderstorms, when simulated radar observations are assimilated into a storm-scale numerical weather prediction (NWP) model using the ensemble Kalman filter (EnKF) method. The truth simulation and data assimilation are carried out at 1 km and 500 m horizontal resolutions.

The EnKF method has shown great promise in a number of recent studies with simulated data within observing system simulation experiments (OSSE, e.g., Snyder and Zhang 2003; Zhang et al. 2004; Tong and Xue 2005, TX05 hereafter; Xue et al. 2006, XTD06 hereafter; Jung et al. 2008). Lei et al. (2007, L07 hereafter) applied an upgraded version of the ARPS (Advanced Regional Prediction System) EnKF data assimilation system to directly assimilate radar data in various forms, such as those on individual radials. Assimilating the data on individual radials allows for more realistic observation operators that include power weighting in range, elevation and azimuth directions. In that study, the impacts of scanning rates and over-sampling were studied using a 1 km horizontal resolution for both truth simulation and assimilation. In this paper, we further examine the impact of over-sampling using a 500 m horizontal resolution. Preliminary results are presented.

This paper is organized as follows: in section 2, the EnKF system and radar data simulation are briefly described. In section 3, OSSE design and the specification of options in the ARPS EnKF system are described. Preliminary results are presented in section 4 and further discussions are given in section 5.

2. EnKF system and simulated radar observations

In this work, the model is assumed to be perfect, namely, the truth simulation and ensemble forecasts in the EnKF use the same model with exactly the same configurations. The same observation operator is also used in EnKF analysis and in the observation simulation. The simulated observations do contain Gaussian random errors used to simulated observation errors.

The ARPS EnKF system used in this paper is based on TX05 and XTD06, and is extended by L07 to include the ability to assimilate radar observations in their native radar coordinates. The extension is necessary to study the impact of various scanning strategies, including azimuthal and vertical over-sampling. A more realistic 3D volume average approach is also added as an option in the radar observation operator.

Even though the NWRT PAR is capable of a gate spacing of 250 m, we simulate observations in this study with a gate spacing that is no smaller than the grid interval of the truth simulation. Therefore, the gate spacing is assumed to be 1 km for the 1 km OSSEs and 500 m for the 500-m OSSEs.

The range weighting function, *W(r)*, within the radar sampling volume has the following form:

$$W\left(r_{\mathrm{i,j,k}}\right)=\begin{cases} 1, & \left|r_{\mathrm{i,j,k}}-r_0\right|\le a\cdot r_6 \\ W_{\mathrm{t}}\left(\left|r_{\mathrm{i,j,k}}-r_6\right|-a\cdot r_6\right), & \left|r_{\mathrm{i,j,k}}-r_0\right|> a\cdot r_6 \end{cases}, \quad (1)$$

where α is 1.5 for experiments of 1 km horizontal mesh size and 0.5 for experiments of 500 m horizontal mesh size., W_{t} has the same functional form as given by Eq. (11.118) of Doviak and Zrnic (1993)

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$$\left|W_{\mathrm{t}}\left(dr\right)\right|^2 = \exp\left[-\left(dr\right)^2 \big/ 2\sigma_r^2\right], \tag{2}$$

and from Eq. (5.76) of Doviak and Zrnic (1993),

$$\sigma_r^2 = (0.30 r_6)^2, \tag{3}$$

and r_6 is taken as 235 m as in Wood and Brown (1997), a parameter based on the WSR-88D radars.

For the azimuth and elevation weighting, Eq. (A.3) of Wood and Brown (1997) is used:

$$f^4\left(\theta_{\mathrm{i,j,k}}, \phi_{\mathrm{i,j,k}}\right) = \exp\left\{-4\ln 4\left[\left(\frac{\theta_{\mathrm{i,j,k}}-\theta}{\theta_w}\right)^2 + \left(\frac{\phi_{\mathrm{i,j,k}}-\phi}{\phi_w}\right)^2\right]\right\}, \tag{4}$$

θ_w and ϕ_w are beam width in azimuth and elevation respectively, and their values will be specified for individual experiments. A function like Eq. (4) is used in XTD07 for beam pattern weighting in the vertical only while assuming the radar data are already in a Cartesian coordinates in the horizontal.

3. OSSE design and EnKF configuration

a. OSSE design

In the truth simulation and analysis system, the horizontal resolutions are either 1 km or 500 m, and the vertical grid spacing is applied in the vertical directions. For the 1 km experiments, the model domain is 64 × 64 × 20 km with 43 vertical levels in the vertical. The 500 m experiments used a shallower 64 × 64 × 16 km^3 domain which has also higher vertical resolutions when vertical level number is not changed, and produces similar results as the 20 km domain is applied. Different from the earlier 1 km experiments, the 1.5-order TKE (turbulent kinetic energy)-based subgrid-scale (SGS) turbulence option (used in TX05) in ARPS is used instead of the Smagrinski (used in XTD06) option.

For the 500 m experiments, both 64 × 64 × 20 km with the same 43 vertical levels are also tested. In the former, as in the 1 km experiments, the Smagrinsky subgrid-scale (SGS) turbulence closure scheme is used. Present experiments do not show any significant differences between the two different configurations of 500 m horizontal resolution experiments, and, among them, only experiments of 16 km vertical domain are reported here.

As in TX05 and XTD06, the truth simulation uses the May 20, 1977 Del City Oklahoma sounding (see, also Xue et al. 2001). The Lin ice microphysics scheme (Lin et al.,1983) is used. The model storm is triggered by a thermal bubble placed at the low level of a horizontally homogeneous environment, and the model is integrated for two hours. The general evolution of the simulated storms on both 1 km and 500 m grids is similar to those reported in Xue et al. (2001), with the 500 m simulation containing ,more finer scale characteristics.

The impact of over-sampling is dependent on the radar sample volume resolution at the location of the storms. When the radar is far away, the radar sampling resolution is lower and the data assimilation should benefit more from over-sampling. In this study, we present results where the radar is located at (- 100, 0) km, with the coordinate origin defined at the lower left corner of the model domain. The main storm cell, or the right moving cell after storm splitting, is located close to the 64 × 64 km domain center.

In addition, two experiments with radar positions at (0, 0) km are conducted, for the 1 km and 500 m grid, respectively. These experiments assume, as in TX05, that the radar observations are taken at the scalar points of the model grid. These experiments serve as the benchmarks and represent the optimal scenario where no horizontal interpolation or radar volume averaging is involved. This is also the assumption made in earlier EnKF radar assimilation studies of Snyder and Zhang (2003) and Zhang et al. (2004), where excellent analysis results were obtained.

In our experiments, different over-sampling rates, defined as the ratio between beam width and the sampling increment in azimuth or elevation, are examined. In particular, two radar beam widths of 2^{o} or 1^{o} are considered, with angular (in azimuth and/or in elevation) sampling increments of 2^{o}, 1^{o} or 0.5^{o}. When the sampling increment is smaller than the beam width, we call it over-sampling in the corresponding direction. In other words, angular over-sampling occurs if the beam width is larger than the data increments. Specific configurations of these parameters are listed in Table 1 for the experiments.

b. ARPS EnKF configuration

In this work, the ensemble square root filter (EnSRF) scheme is used, as in XTD06. Both radial velocity and reflectivity are assimilated starting from the first analysis cycle.

As in TX05, XTD06 and L07, the initial ensemble forecast starts at 20 min of model time, and the first analysis occurs at 25 min. The initial ensembles are specified by adding smoothed random perturbations to the initial guess defined by the truth simulation sounding. Again following XTD06, forty ensemble members are used in the control experiments. Effects of a larger member size will also be discussed. For the 500 m experiments, the use of 80 ensemble members represents a significant computational challenge before the support for distributed-memory parallelization is available.

In experiments reported here, all radial velocity and reflectivity observations where reflectivity is larger than or equal to zero are used in the analysis.

Based on the results of a series of experiments, the covariance inflation coefficient is chosen to be 1.1 for experiments of 1 km resolution and 1.2 for the 500 m experiments. Covariance localization is applied in the same way as in TX05, XTD06 and L07, applying a Schur product to the calculated covariance. For the 1 km experiments, a localization cut-off radius of 4 km in all directions is found to work generally the best for experiments assimilating radar data on the radials. For the 1 km benchmark experiments where radar data are at the scalar grid points, a cut-off radius of 6 km in the horizontal and a radius of 4 km in the vertical are found to work better for the radial velocity data. For reflectivity data, a 4 km cut-off radius is used in all directions. For the 500 m experiments, the cut-off radius is 3 km in the horizontal and 2 km in the vertical for both radial data and the benchmark experiments.

Table 1. List of experiments.

Categories Parameters	W2I2	W2I1	W2I0.5	N88D
Beam width	2°	2°	2°	1°
Angular increment in azimuth/elevation	2°	1°	0.5°	1°
Lowest elevation	1°	1°	1°	0.5°
Volume scan time interval	5 min	5 min	5 min	5 min

4. Results

For both 1 km and 500 m experiments, there are 4 experiments using radar data on the radials (Table 1). For all simulated radar observations, random errors drawn from Gaussian distributions of zero mean and standard deviations of 1 m s^{-1} and 2 dBZ for the radial velocity and reflectivity data, respectively, are added to the observations.

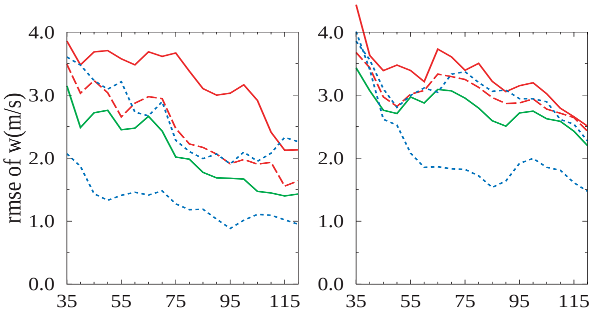

Fig. 1. The rms errors of ensemble mean analyses of vertical velocity w, averaged over points at which the true reflectivity is greater than 10 dBZ. The lower solid lines are for experiment N88D, dashed lines for W2I1, upper dotted lines for W2I0.5, upper solid lines for W2I2 and lower dotted line are for the benchmark experiments. (a) is for the 1km experiments and (b) is for the 500 m experiments. and The lower blue dashed lines are for benchmark experiments where the radar is located at (0,0) km.

The rms errors of the analyzed vertical velocity through the analysis cycles are shown in Fig. 1 for the experiments described in Table 1 and their corresponding benchmark experiments.

As shown in Fig. 1, for both 1 km and 500 m experiments, W2I2 with a two-degree beam width and two-degree increments shows the worst performance. Among the experiments using data on the radials, N88D, which has a one degree beam width and one degree increment, shows the best performance. For 1 km horizontal mesh size experiments, W2I1 and W2I0.5, which over-sample by a factor of 2 and 4, respectively, exhibit clearly improved results compared to W2I2, which does not perform over-sampling. For the 500 m experiments, the improvement due to over-sampling also exist but to a less extent compared to the 1 km counterparts. On one hand, the results reported here conform those of L07, and demonstrates the potential of spatially over-sampling for improving observation resolution and storm-analysis accuracy. On the other hand, the smaller impact of spatial over-sampling for the 500 m resolution case is unexpected. At 500 m resolution, the analysis errors are generally larger. An examination of the 500 m truth simulation also reveals that the 500 m simulations are noiser, containing more poorly-resolved 2 grid interval structures than the 1 km truth simulation.

5. Discussion

Applying the EnKF data assimilation method and a more realistic representation of radar sampling volume averaging in the radar observation operators in both the EnKF system and its companion emulator, this work makes use of high-resolution experiments of up to 500 m horizontal resolution to study the impact of spatial over-sampling possible with the NWRT PAR.

Experiments with both 1 km and 500 m horizontal resolutions demonstrate the advantages of over-sampling. Using the same 40 ensemble members, the improvement from over-sampling is reduced instead of being increased when the data and assimilation resolution is 500 m in the horizontal, compared to the 1 km case. Because of the increased degree of freedom and possible shorter time scales involved in the system, a large ensemble size and/or a shorter volume scan interval may be needed to achieve a similar level of analysis accuracy as the 1 km case. One 500 m benchmark experiment (not shown here) with 80 members has been completed which shows improved analysis results. Additional experiments will be performed to hopefully demonstrate at least a similar level of positive impact from spatial over-sampling.

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