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COMBINING PHASE ERROR CORRECTION AND 3DVAR IN STORM-SCALE DATA ASSIMILATION

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1. Introduction

Phase or position errors are common in numerical weather forecasts, especially for storm-scale phenomenon. It is especially difficult to use a storm-scale forecast directly as the background for data assimilation because any incorrect positioning of thunderstorms within such a forecast could produce complex error covariance structures which do not fit typical spatial models of error covariance. Furthermore, any predicted thunderstorms with little or no overlap with their counterpart in the data could produce very large magnitudes of error. There are many phase error correction methods for different weather scenarios. We will briefly review two methods that have been applied to numerical weather prediction.

The idea of correcting phase error for storm-scale models was described by Brewster (1991). He found that the knowledge of phase errors determined from one variable in the dynamic system could be used to update the system, correct errors in all fields and improve the forward forecast effectively.

To correct phase error in synoptic-scale storms over the ocean, an approach of shifting the short-term forecast was developed by Hoffman et al. (1995). First they calculated the short-term forecast equivalents of the unconventional observations. Then they moved the resulting simulated observations to best fit the actual observations. A further development of this approach was described in Hoffman et al. (1996). They determined displacement and amplification by minimizing an objective function to best fit the "forecast" and data. Then the corrected field can be used in a conventional data analysis.

To correct a numerical forecast field in storm, an objective method of determining the phase error was developed by Brewster (2003a, b). The goal of the method is to find an optimal field of shift vectors that minimizes a squared-error difference from high-resolution observations, and it was applied to mesoscale and storm-scale observations including WSR-88D Doppler radar winds and reflectivity. It was shown that scheme can successfully correct errors in thunderstorm locations, and a positive influence on the subsequent forecast was found. The advantage of the phase error corrections over the control run lasted for about 3 h despite storm dissipation and regeneration, and interactions among multiple storms.

In this paper, we describe a method that combines phase error correction and three-dimensional variational (3DVAR) analyses in a data assimilation system. Basically, we divide the background error into displacement (phase) error and amplitude error. The phase error correction algorithm developed by Brewster (2003a) is first used to correct the displacement error, then the resultant field is used as a background for the 3DVAR analysis to correct any amplitude error (Gao et al. 2002, 2004; Hu, et al. 2005a, b). Finally, the 3DVAR analysis is used as initial conditions for the Advanced Regional Prediction System (ARPS, Xue et al. 2000, 2001). The phase-error and 3DVAR analyses are repeated every 10-minutes in an intermittent data assimilation cycle. The impact of the phase error correction algorithm on the data assimilation cycle and subsequent storm-scale forecast will be evaluated using a case study of a severe convective storm.

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2. Methodology

Our combination data assimilation system consists of three principle components: 1) ARPS-Shift Phase/Position Error Correction Program, 2) a 3DVAR analysis package including a separate cloud-and-hydrometeor analysis which also applies diabatic adjustments to the temperature fields. 3) An assimilating and forecast model, ARPS. Each component is briefly discussed below.

2.1 ARPS-Shift Phase/Position Error Program

Brewster (2003a) described a method that finds and determines the shift vectors in thunderstorm forecast. The phase-correction method seeks a field of local translation vectors, δx, to apply to the forecast field in order to best match the observed data. The method divides the analysis domain into overlapping three-dimensional test volumes and then determines the phase or position correction needed to best match the observations. An objective function based on squared-error difference is formed:

$$J[\delta x] = \frac{s(|\delta x| l^{-1})}{N_\alpha} \sum_{j=1}^{n_v} \alpha_j \frac{\left\{H[\overline{F}(x_i + \delta x)] - o_{i,j}(x_i)\right\}^2}{\sigma_{i,j}^2}, \quad (1)$$

where $o_{i,j}$ is an observation, x_i is the observation location, $\sigma_{i,j}^2$ is the expected observation variance, $\overline{F}$ is the forecast field, H represents a transformation from the forecast variables to the observed quantity. Each of the n_v variables is weighted by α, while n_o is the total number of observations of each type in the considered region. The multiplier $s(|\delta x| l^{-1})$ serves as a penalty function. The function is from Thiebaux et al. (1990), the inverse of the second-order autoregressive (SOAR) function:

$$s(|\delta x| l^{-1}) = \frac{\exp(|\delta x| l^{-1})}{(1 + |\delta x| l^{-1})}, \quad (2)$$

Where l is a length-scale parameter.
N_α is a normalization factor,

$$N_\alpha = \sum_{j=1}^{n_v} \sum_{i=1}^{n_o} \alpha_j . \quad (3)$$

The position correction can be done in a single step or it can be done gradually in a time window within the ARPS model. In this work the first method is used.

It is possible that widely differing solutions in neighboring overlapping test volumes would result in discontinuities in the resulting field of correcting phase or position error. Therefore, it is better to do some dynamic adjustment after the variable shifting, in order to maintain the consistency of the corrected field.

2.2 3DVAR Analysis System

The ARPS 3DVAR uses an incremental form of cost function that includes the background, observation and equation constraint terms (Gao et al. 2002, 2004). The analysis variables include the three wind components potential temperature, pressure and water vapor mixing ratio. Hydrometeors are not analyzed variationally, but analyzed by a complex cloud analysis package as described by Zhang et al. (1998) with later updates by Brewster (2002) and Hu et al. (2005a).

In the current system, the spatial covariances of background error are modeled by a recursive filter. The observation errors are assumed to be uncorrelated, hence the observation error covariance is a diagonal matrix. The observation error variances are specified according to the estimated errors. Multiple analysis passes are used to analyze different data types with different filter scales in order to account for variations in observation spacing among different data sources.

2.3 ARPS Model

ARPS is a mesoscale nonhydrostatic compressible numerical model with a great deal of successful examples of high-resolution numerical simulations (Xue et al. 2000, 2001). It uses a generalized terrain-following coordinate system with vertical stretching and a horizontal Arakawa C grid. There are several options for microphysics and other parameterizations. Here we use the Tao (1993) ice microphysics and no cumulus parameterization. In this configuration ARPS is practicable for storm-scale numerical weather prediction in a regional forecast system.

2.4 Design of Assimilation and Forecast Experiment

To demonstrate the effectiveness of the described method for a real data case, we apply it to an Oklahoma tornadic thunderstorm that occurred on the evening of May 29, 2004 (local time). The analysis is performed with 3-km grid resolution in a 580X580 km^2 domain which covers the entire state of Oklahoma and a portion of southern part of Kansas.

The analysis process includes six assimilation cycles applied within a one-hour period starting at 00:00 UTC May 30 and ending at 01:00 UTC May 30, 2004. The procedure is illustrated in Fig 1. At the beginning, we apply 3DVAR for the initial analysis, using the NCEP Eta model output as a background. We analyze the observations from an entire volume-scan of radar data from the KTLX WSR-88D operational Doppler radar collected at the beginning of the hour. Then the ARPS model is used to make a 10-minute forecast. This intermittent assimilation cycle is then repeated another 5 times until 01:00 UTC May 30. In the control experiment the phase correction program is not used. In the combined phase-correction experiment, the phase error correction algorithm is used in each cycle before the 3DVAR analysis. After one-hour assimilation, at 01:00 UTC May 30, we begin a run of the ARPS model for about 1.5-h using the initial conditions from the two data assimilation experiments to examine the impact of phase error correction on the forecast.

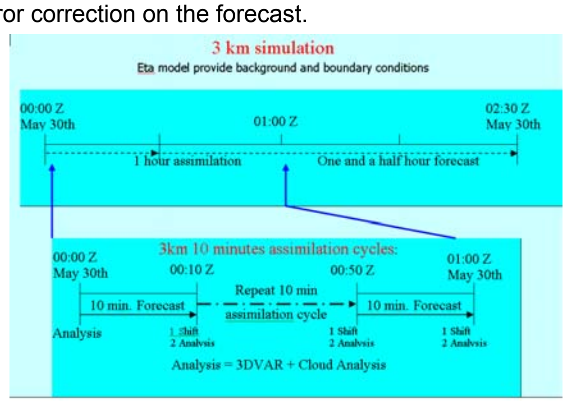

Fig. 1: Procedure of the assimilation and forecast experiment on the 3 km grids for the May 30, 2004 OKC thunderstorm case.

3. Results

Fig 2a shows the reflectivity observation at elevation angle 1.14^0, 01:00 UTC from KTLX radar on May 30, 2004. A large supercell storm was located in Kingfisher County extending into the northern portions of Canadian and Oklahoma County (highlighted with bold lines).

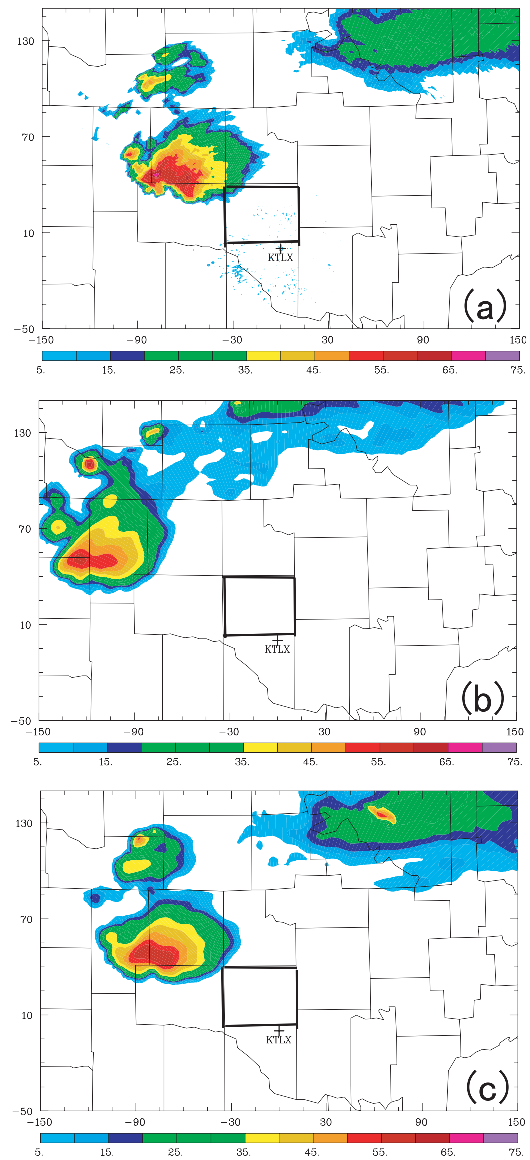

Fig. 2: Radar reflectivity images at elevation angle 1.14^o, 01:00 UTC May 30, 2004. (a) observed by KTLX radar; b) derived from the last data assimilation cycle without applying ARPS-Shift program; (c) derived from the last data assimilation cycle with applying ARPS-Shift program.

In the control data assimilation experiment, the analysis after 6 data assimilation cycles without using the ARPS-Shift program produces a storm that is incorrectly positioned west of the actual storm (Fig 2b). In the second experiment, which included phase correction, the center of the storm in the forecast field is much closer to the observed reflectivity (Fig 2c).

In the 1.5-hour forecast, we compare the radar reflectivity field derived from the forecasts valid at 02:30 UTC with and without using the ARPS-Shift program with observed reflectivity at the same time (Fig 3). It can be seen that the predicted main cell without using phase error correction program (Fig 3b) propagated much faster than the one when the phase error correction program is used, and the latter is much closer to the observation. However, we also note there appear to be multiple cores within the predicted storm when the ARPS-Shift program is used (Fig 3c) in contrast to the observed storm that consists of a single, very large, precipitation core.

4. Summary

In this work, we have combined a phase error correction algorithm with a 3DVAR data assimilation system. The phase error correction algorithm is applied between the assimilating model forecast and the 3DVAR analysis step. The result from phase error correction is used as the background for 3DVAR. The impact of the phase error correction algorithm is examined by using real observations from a tornadic storm case that occurred on May 29, 2004 in the Oklahoma City area.

The effect of phase error correction is obvious. The forecast position of storm after a 1.5 h forecast is much closer to the observation than that without phase error correction. However, there are details of the structure of the storm which are not as good as that without phase error correction. The repositioning of the storm location may damage the balance of storm dynamics. In the ongoing study, we are adding a weak constraint term in the cost function in the 3DVAR system to couple the adjusted analysis variables, which we hypothesize will improve the forecasted storm structure.

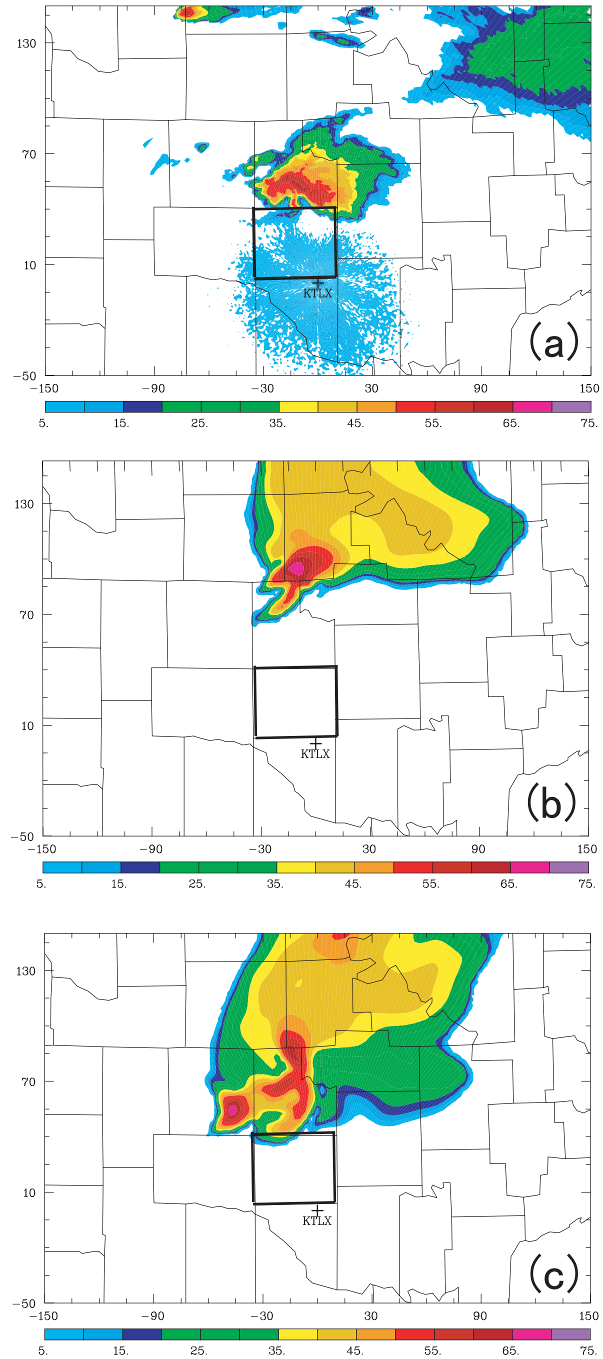

Fig.3: Radar reflectivity field at elevation angle 1.14°, 02:30UTC May 30, 2004. (a) observed by KTLX; (b) derived from 1.5-h forecast using initial condition without ARPS-Shift program; (c) derived from 1.5-h forecast field with ARPS-Shift program.

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