ASSIMILATION OF MULTIPLE-DOPPLER RADAR DATA WITH THE WRF 3-D VAR AND A CLOUD ANALYSIS

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1. INTRODUCTION

A reliable application of a numerical weather prediction to short-range quantitative precipitation forecasting (QPF) is needed to forecast disastrous severe storms. The success of the dynamic, thermodynamic, and microphysical retrievals at the convective scale using Doppler radar observations are important but still great challenges.

The use of three-dimensional variational data assimilation (3-D Var) is a suitable approach for the retrievals in a large domain. Sugimoto et al. (2005) demonstrated the performance of the WRF 3-D Var through observing system simulation experiments (OSSEs) and concluded that radar data assimilation with the WRF 3-D Var works reasonably well in recovering key features at scales larger than the convective scale. Improvement of large-scale forcing leads to positive impact on short-range QPF.

The purpose of this study is to evaluate the performance of radar data assimilation with the WRF 3-D Var through an application of real radar data. A main concern is whether the performance evaluated is similar to the one obtained from an OSSE study, because an application to a real world suffers from issues related with data quality (i.e. clutters, aliases, and data density) and assumptions in the WRF 3-D Var (i.e. background error, and drop size distribution).

2. METHOD OF DATA ASSIMILATION

The 3-D Var function in the WRF-Var system is used in this study. This function originates and evolves from the MM5 3-D Var (Barker et al. (2004)). Some other progresses can be referred to as Skamarock et al. (2005)). Here, descriptions of differences and additions from the original 3-D Var are given.

Control Variables and Microphysics

In the WRF-Var system, several options for control variables (hereafter, cv options) are prepared to compute efficiently the inverse of the background error matrix with preconditioning. This study chooses the cv option 5 with modifications for assimilation of radar reflectivity, so that streamfunction, unbalanced velocity potential, unbalanced temperature, and the total water mixing ratio are adopted as control variables. The total water mixing ratio (q_t) is defined as the sum of water vapor (q_v), cloud water (q_c), and rainwater (q_r) mixing ratios, which means that radar reflectivity contributed by warm rain is only able to be assimilated as described later.

Since the total water mixing ratio q_t is used as a moisture control variable, we need to introduce a scheme to partition the increments of q_t into the ones of q_v, q_c, and q_r. In this study, four microphysical processes (condensation, autoconversion, accretion, and evaporation) are considered. Although the same isobaric process for condensation is used as the original WRF 3-D Var, the empirical equations and technical ideas in Sun and Crook (1997) are newly introduced for other processes.

Observation Operators

Observation operators for radar data assimilation are the same as the ones in the original 3-D Var. Here, an observation operator for radar reflectivity is just noted. The following equation is used:

$$Z = 43.1 + 17.5\log(\rho q_r),$$

where Z is radar reflectivity factor [dBZ], ρ the air density [kg m^{-3}], and q_r the rainwater mixing ratio [g kg^{-1}]. The derivation of the above equation is based on Marshall-Palmer type drop size distribution, and no contribution by ice phases is assumed. Therefore, radar reflectivity observed below the altitude of 5 km is limited to be assimilated in this study.

A Cloud Analysis

The modification with partitioning is largely

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influenced by the background because of the incremental formulation. For example, some difficulty can arise if the background has no convection whereas there is rainfall indicated by radar, or vice versa. Sugimoto et al. (2005) suggested that a cloud analysis is necessary to some permissible extent for modifying the background to mitigate huge departure from observation. This study also uses the same cloud analysis as Sugimoto et al. (2005), so that humidity, temperature, and mixing ratios are modified only using radar reflectivity before the 3-D Var is applied. The details will be presented at the workshop.

3. SET-UP AND CONFIGURATIONS

A Dryline Case for Application

The performance of the WRF 3-D Var radar data assimilation will be investigated through an application to a severe storm case associated with a dryline. This storm occurred over the central Great Plains on June 4 to 5, 2005. Fig. 1 shows fields of horizontal winds and humidity using NCEP final analysis (FNL). The fields represent synoptic-scale flows, but a clear gradient of humidity and the convergence of winds are indicated.

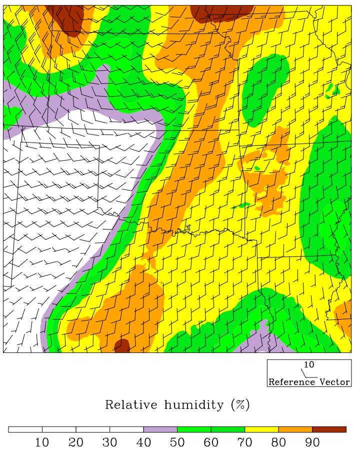

Fig.1: Synoptic-scale fields at a model level of 5.

Pre-Processing of Radar Data

Radar observations from the WSR-88D network are assimilated in this study (Fig. 2). For each PPI of each radar site, a pre-processing with dealiasing of radial velocities is performed. For dealiasing, Eilts and Smith (1990), which is based on checking 2-D continuity, is used with the introduction of a modified VAD method by Tabary et al. (2001).

After removing carefully radar reflectivity from clear air echoes, a spatial transformation is performed using Cressman filter (Cressman (1959)) to prepare datasets in (*x*,*y*,*e*) format. Here, (*x*,*y*) represents the relative distance from a radar site, and *e* is an elevation angle. In this transformation, data are smoothed with the horizontal resolution of 4 km, and observation error is computed by scaling the standard deviation within effective radius of Cressman filter. Note that radar observations are assimilated if data point locates within 230 km from a radar antenna.

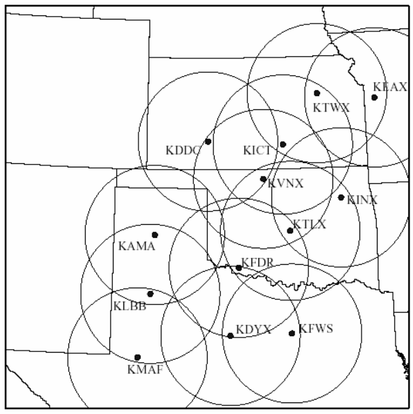

Fig. 2: WSR-88D radar sites for assimilation.

Configuration of the WRF Model

The ARW version 2.1.2 of the WRF model is used. A single domain has a horizontal grid spacing of 4 km, and 36 full sigma levels are contained in the vertical with the model top of 50 hPa.

No cumulus scheme is used, and WSM6 is used as an explicit microphysical scheme. Some of other primary physics options include YSU PBL scheme, Noah LSM, MM5 similarity theory for surface layer scheme, RRTM longwave radiation, Dudhia shortwave radiation, and 2nd order Smagrinski diffusion scheme.

The model is initialized using FNL data. FNL data are provided at 6-hour intervals with a horizontal resolution of about 100 km. A time step of 20 seconds is used for model integration.

Configuration of the WRF 3-D Var

The domain-averaged background error statistics (regression coefficients, eigenvalues/eigenvectors, and length scales) required for control variable transformation are prepared a priori. The NMC method is used with 24-hr forecasts and 12-hr forecasts. Note that statistics except for regression coefficients are scaled (for example, a scaling factor for length scale of streamfunction is 0.4).

Fig. 3 illustrates the time-line in case studies. The starting time of a control run without assimilation is 1800Z, June 4, 2005. Data assimilation is performed at

0000Z, June 5. Then, the forecast by the control run valid at 0000Z is used as the first-guess. Assimilation is followed by a 6-hr forecast run with 3-D Var analysis.

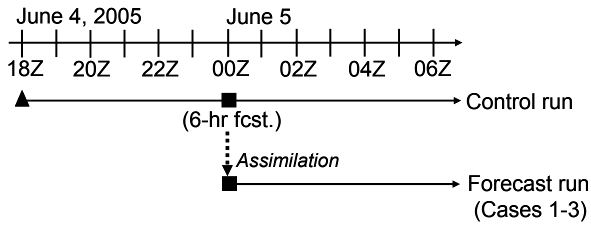

Fig. 3: Time-line in case studies.

Case studies performed are summarized below:

Case 1: Both of radial velocities and radar reflectivity are assimilated.

Case 2: Radial velocities are only assimilated.

Case 3: Radar reflectivity data are only assimilated.

4. RESULTS

Modifications of Model Variables

Fig. 4 shows the increments of model variables (horizontal winds, potential temperature θ, and rainwater mixing ratio q_r) at a model level of 5 (in the lower atmosphere). Assimilation of radial velocities enhances the convergence of horizontal winds along the dryline (circle). Meanwhile, assimilation of radar reflectivity effects largely to the increments of θ and q_r. Positive increments of q_r and evaporation effect contributes to negative increments of θ. Positive increments of θ due to condensation are also found at a higher level (not shown).

Impact of Assimilation on Short-Range QPF

Forecasts of 1-hr accumulated precipitation for a control run and case studies are shown in Fig. 5. Forecasts up to 6-hr ahead (0600Z, June 5) after assimilation are plotted. First of all, the control run suffers from a typical spin-up problem, so that convections along the dryline are not forecasted well till 0300Z (circle). After 0300Z, the location and the evolution of convections are not still forecasted accurately especially in that the movement of convections is quite slow (dotted circle).

Considering the results of cases 1 and 2, problems mentioned above are mitigated by assimilation of radial velocities. Assimilation of both data (case 1) leads to the best performance. Positive impact found in cases 1 and 2 lasts during 6 hours at least. Positive impact of assimilation in case 3, however, disappears quickly after 1-hr ahead. Such basic features of the WRF 3-D Var radar data assimilation are consistent with ones obtained by an OSSE study.

Some limitations are also indicated in the capability of forecasting back-building convections (bold circle). Downdrafts at the convective scale from pre-existing convections are generally important for enhancing such a type of convections. Although retrievals at the convective scale is beyond the capability of an approach based on 3-D Var, assimilation of radar reflectivity contributed by ice phases is necessary at least for recovering more accurate effect of pre-existing convections.

5. SUMMARY

The performance of the WRF 3-D Var is examined in assimilation of real Doppler radar data. Results indicate that the performance evaluated is consistent with the one which was found in an OSSE study. Assimilation of radial velocities is primarily important for triggering and controlling convections. Additional use of radar reflectivity for assimilation improves the skill of QPF, so that assimilation of both of radar data is the most beneficial. Positive impact is found up to 6-hr ahead after assimilation. The case is exceptional that

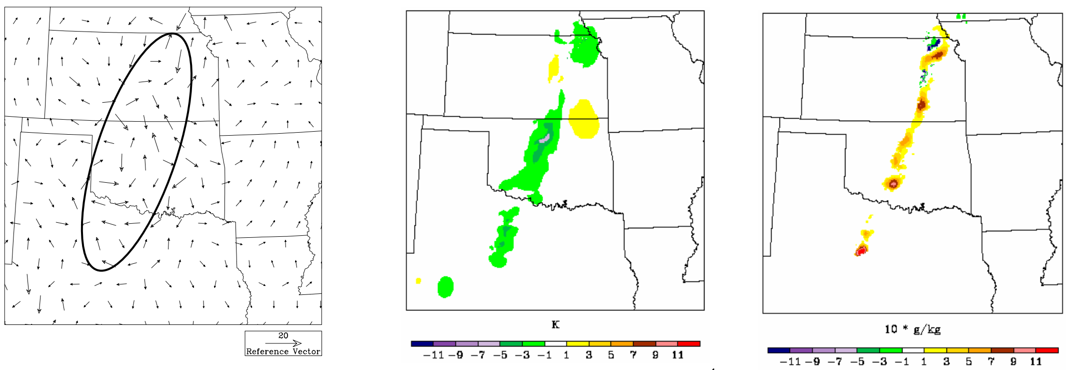

Fig. 4: Increments of model variables (left: horizontal winds [m s^{-1}], middle: potential temperature, right: rainwater mixing ratio).

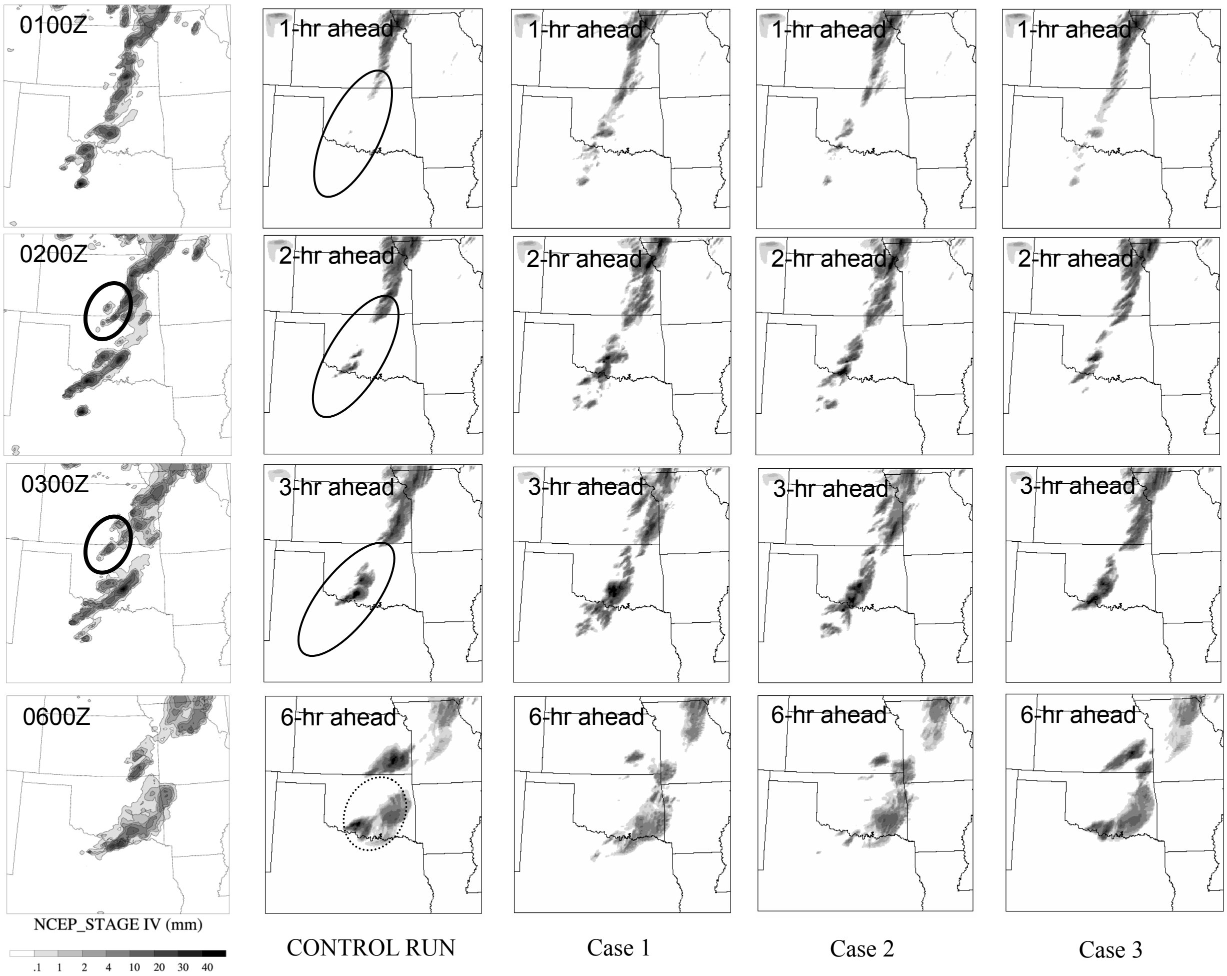

Fig. 5: 1-hr accumulated precipitation in analysis (NCEP Stage IV) and forecasts.

only radar reflectivity is assimilated, because impact is likely limited up to 1- or 2-hr ahead.

Some of limitations are indicated in this study. One of important issues is the inclusion of ice phases in microphysics of the WRF-Var. The development of tangent-linear and adjoint models for WSM6 is ongoing according to the roadmap of R&D of the WRF 4-D Var. Another big issue is related with the background error. Although the framework of assimilation works well with crude domain-averaged error statistics, the use of a flow-dependent error is expected to raise the skill. Researches on the hybrid of Var system and ensemble transform Kalman filter are very remarkable.

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