DOPPLER RADAR DATA ASSIMILATION WITH WRF-VAR: CURRENT STATUS AND FUTURE PLAN

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1. INTRODUCTION

During the past several years, NCAR developed the capabilities to assimilate Doppler radial velocity (Xiao et al. 2005) and reflectivity (Xiao et al. 2006) data with the WRF/MM5 three dimensional variational(3D-Var) data assimilation system (Barker et al. 2004, Skamarock et al. 2005). Recently, with the addition of WRF 4D-Var, the system was renamed to WRF-Var. Doppler radar data assimilation is an important component in this system.

The major development of the Doppler radar data assimilation in the WRF 3D-Var is the nclusion of the analyses (increments) for vertical velocity and cloud water and rainwater mixing ratios. In this paper, we present the methodology for generating the vertical velocity increments, as well as increments of cloud water and rainwater mixing ratios. We also describe the observation operators for Doppler radial velocity and reflectivity in the WRF-Var system. The results of the 3D-Var radar data assimilation in several case studies and operational applications in Korea Meteorological Administreation (KMA) are presented. These results demonstrate positive impacts of the Doppler radar data assimilation on the short-range quantitative precipitation forecasting (QPF).

In addition to the review on the current status of research and applications of the WRF 3D-Var Doppler radar data assimilation, we outline a future plan for further development of the Doppler radar data assimilation schemes in the WRF-Var system (including 3D-Var and 4D-Var) in the last section.

2. CURRENT STATUS OF DOPPLER RADAR DATA ASSIMILATION IN WRF-VAR

2.1 WRF 3D-Var

The configuration of the WRF/MM5 3D-Var system is based on the multivariate incremental formulation. The preconditioned control variables in this study are stream function, velocity potential, unbalanced pressure and total water mixing ratio. The background error statistics can be carried out via NMC-method (Parish and Derber 1992) or ensemble method (Fisher et al., 1999). Horizontally isotropic and homogeneous recursive filters are applied to the horizontal components of background error. The vertical component of background errors is projected onto climatologically averaged (in time, longitude, and optionally latitude) eigenvectors of the estimated vertical error. A detailed description of the 3D-Var system can be found in Barker et al. (2004).

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2.2 Vertical velocity increments

Based on Richardson (1922), a balance equation that combines the continuity equation, adiabatic thermodynamic equation, and hydrostatic relation is derived and expressed as:

$$\gamma\, p\frac{\partial w}{\partial z}=-\gamma\, p\nabla\cdot\overrightarrow{v_h}-\overrightarrow{v_h}\cdot\nabla p+g\int_z^\infty\nabla\cdot(\rho\overrightarrow{v_h})dz \qquad (1)$$

where w is vertical velocity, $\overrightarrow{v_h}$ is the vector of horizontal velocity (components u and v), γ the ratio of specific heat capacities of air at constant pressure/volume, p pressure, ρ density, T temperature, c_p specific heat capacity of air at constant pressure, z height, and g the acceleration due to gravity. For simplicity, hereafter Eq. (1) will be referred to as the Richardson's equation. For the future applications, latent heat term which uses convective parameterization can be included. Linearizing Eq. (1) by writing each variable in terms of a basic state (overbar) plus a small increment (prime) gives:

$$\gamma\overline{p}\frac{\partial w'}{\partial z}=-\gamma p'\frac{\partial\overline{w}}{\partial z}-\gamma\overline{p}\nabla\cdot\overrightarrow{v_h'}-\gamma p'\,\nabla\cdot\overrightarrow{\overline{v}_h}-\overrightarrow{\overline{v}_h}\cdot\nabla p' \qquad (2)$$
$$-\overrightarrow{v_h'}\cdot\nabla\overline{p}+g\int_z^\infty\nabla\cdot(\overline{\rho}\overrightarrow{v_h'})dz+g\int_z^\infty\nabla\cdot(\rho'\overrightarrow{\overline{v}_h})dz$$

The linear and adjoint of Richardson's equation are incorporated into the 3D-Var system, which serve as a bridge between the 3D-Var analyses and the vertical velocity component of the Doppler radial velocity observations. Detailed implementation and results can be found in Xiao et al. (2005).

2.3 Partitioning of moisture and water hydrometeor increments

Because total water mixing ratio q_t is used as a control variable, partitioning of the moisture and water hydrometeor increments is necessary in the 3D-Var system. A sophisticated microphysical process would be necessary to do the partitioning. However, development of the adjoint scheme for such process is not trivial. In this study, a simple warm rain process is introduced into the WRF/MM5 3D-Var system. The warm rain process includes condensation of water vapor into cloud (P_{CON}), accretion of cloud by rain (P_{RA}), automatic conversion of cloud to rain (P_{RC}), and evaporation of rain to water vapor (P_{RE}).

The autoconversion term, P_{RC}, is represented by

$$PRC = \begin{cases} k_1(q_c - q_{crit}), & q_c \geq q_{crit} \\ 0, & q_c < q_{crit} \end{cases}, \tag{3}$$

where q_c is the cloud water mixing ratio. According to Kessler (1965), $k_1 = 10^{-3}s^{-1}$, $q_{crit} = 0.5g \cdot kg^{-1}$. The accretion of cloud water by rain is parameterized by

$$P_{RA} = \frac{1}{4}\pi\rho a q_c E N_0 \frac{\Gamma(3+b)}{\lambda^{3+b}}, \tag{4}$$

where Γ is the gamma-function, E is the collection efficiency. N_0=8X10^6 m^{-4}, a=841.99667 and b=0.8. The evaporation of rain can be determined from the equation:

$$PRE = \frac{2\pi N_0(S-1)}{A+B}\left[\frac{f_1}{\lambda^2} + f_2\left(\frac{a\rho}{\mu}\right)^{1/2} S_c^{\,1/3} \frac{\Gamma(\frac{5+b}{2})}{\lambda^{\frac{5+b}{2}}}\right] \tag{5}$$

where f_1=0.78, f_2=0.32. P_{CON}, the condensation is determined by

$$P_{CON} = \frac{q_v - q_{vs}}{1 + \frac{L_v^{\,2} q_{vs}}{R_v C_{pm} T^2}}, \tag{6}$$

where q_{vs} is saturated water vapor mixing ratio, L_v, R_v and C_{pm} are latent heat of condensation, gas constant for water vapor and specific heat at constant pressure for moist air, respectively.

Details of the warm rain process are referred to the Appendix of Dudhia (1989). The tangent linear and its adjoint of the scheme are developed and incorporated into the 3D-Var system. Although the control variable is q_t, the q_v, q_c and q_r increments are produced through the partitioning procedure during the 3D-Var analysis. The warm rain parameterization builds a relation among rainwater, cloud water, moisture and temperature. When rainwater information (from reflectivity) enters into the minimization iteration procedure, the forward warm rain process and its backward adjoint distribute this information to the increments of other variables (under the constraint of the warm rain scheme. Once the 3D-Var system produces q_c and q_r increments, the assimilation of reflectivity is straightforward (refer to Xiao et al. 2006).

2.4 Observation operator for Doppler radial velocity and reflectivity

The observation operator for Doppler radial velocity is:

$$V_r = u\frac{x - x_i}{r_i} + v\frac{y - y_i}{r_i} + (w - v_T)\frac{z - z_i}{r_i}, \tag{7}$$

where (u, v, w) are the wind components, (x, y, z) are the radar location, (x_i, y_i, z_i) are the location of the radar observation, r_i is the distance between the radar and the observation, and v_T is terminal velocity. Following the algorithm of Sun and Crook (1998),

$$v_T = 5.40a \cdot q_r^{\,0.125}. \tag{8}$$

The quantity a is a correction factor defined by

$$a = (p_0 / \overline{p})^{0.4}, \tag{9}$$

where $\overline{p}$ is the base-state pressure and p_0 is the pressure at the ground.

The observation operator for Doppler radar reflectivity is (Sun and Crook 1997):

$$Z = 43.1 + 17.5\log(\rho q_r), \tag{10}$$

where Z is reflectivity in the unit of dBZ and q_r is the rainwater mixing ratio.

3. CASE STUDIES

3.1 An IHOP_2002 squall line case

This study focuses on the northeast-to-southwest-oriented squall line in the U. S. Great Plains on June 12-13 during the IHOP_2002 experiment (Xiao and Sun 2006). The squall line was initiated at around 2100 UTC 12 June 2002. It was well developed at around 0000 UTC 13 June. At least 12 WSR-88D Doppler radars in the IHOP_2002 experiment documented the squall lines. It gradually moved southeastward and finally dissipated at around 1000 UTC 13 June. Figure 1 shows the observed 3-h rainfall at 0300, 0600, 0900 and 1200 UTC 13 June based on NCEP/OH Stage IV data.

Doppler radar data assimilation with the WRF 3D-Var system is carried out for this case. 12-h WRF forecast with WSM6 microphysics and YSU boundary layer parameterization schemes is conducted from the Doppler radar data enhanced initial conditions at 0000 UTC 13 June. The domain covers a 1600X1600 km^2 area with grad-spacing of 4km (outer domain of Fig. 1). The data assimilation starts from 2100 UTC 12 June, with the first-guess interpolated from NCEP eta analysis. We conduct 3-h cycling of observations until 0000 UTC 13 June. With different combinations of the observation data, several experiments are carried out to evaluate the QPF skills of the WRF 3D-Var Doppler radar data assimilation scheme. The threat scores (TS) of precipitation forecast verified against 3-h accumulated precipitation from the NCEP/OH Stage IV precipitation analysis are calculated (Fig. 2).

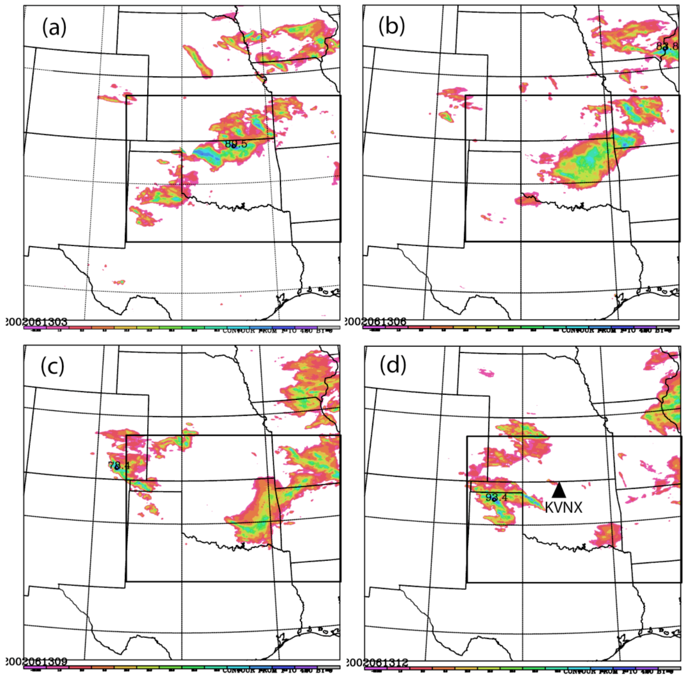

Fig. 1: 3-h accumulated precipitation derived from the National Stage-IV Precipitation Analysis (from NCEP) for (a) 0000-0300 UTC, (b) 0300-0600 UTC, (c) 0600-0900 UTC and (d) 0900-1200 UTC 13 June 2002. The inner box is used for the threat score calculation. The radar station of KVNX (solid triangle) is shown in (d).

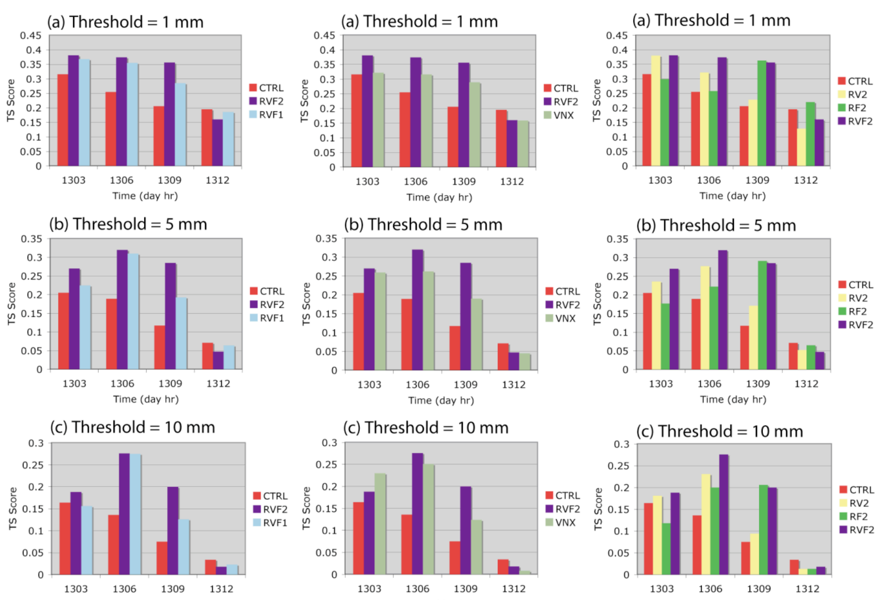

Fig. 2: Comparison of threat scores for the 3-hr accumulated precipitation among different experiments with the threshold of (a) 1 mm, (b) 5 mm and (c) 10 mm. The QPF verification is performed against the NCEP Stage-IV precipitation. (CTRL: only GTS data; RVF1: Doppler radar data from 12 radar sites at 0000 UTC 13 are included; RVF2: same as RVF1 but with radar data at both 2100 UTC 12 and 0000 UTC 13 included; VNX: same as RVF2 but with only KVNX radar data; RV2: same as RVF2 but with only radial velocity data; RF2: same as RVF2 but with only reflectivity data)

It is demonstrated that the WRF 3D-Var system can extract useful information from Doppler radar data assimilation, and improve the QPF skill for this squall line case. Without the Doppler radar data, the experiment CTRL obtains the lowest TS score. With the Doppler radar data assimilated, we found that: a) cycling of the radar data using the WRF 3D-Var cycling mode improves the QPF skill compared to the experiment with one-time radar data assimilation; b) multiple radar data assimilation has added benefits for the subsequent QPF compared to a single Doppler radar data assimilation; and c) assimilation of both radial velocity and reflectivity has more positive impact on the QPF skill than assimilation of either radial velocity or reflectivity only. We also found that the improvement of the QPF skills with multiple radar data assimilation experiments is more clearly observed in heavy rainfall than in light rainfall. The verification results are valid for 9 hours for this case. The squall line was dissipated after 0900 UTC 13 June.

3.2 A tropical cyclone case

This is the case study of a tropical cyclone in East Asia. Typhoon Rusa was the most disastrous storm in Korea in 2002. It made landfall on the Korea south coast at 0630 UTC 31 August 2002 and dumped deadly torrential rainfall in a short time. Inland flooding was responsible for the death of more than 100 people in that nation. Prior to Rusa's (2002) landfall on Korea's south coast, Jindo radar started capturing the radial velocity and reflectivity data from 0000 UTC 30 August. We conducted 3D-Var data assimilation from 0000 UTC 30 through 0000 UTC 31 August with 3 hourly update cycles. The initial time for numerical simulation is 0000 UTC 31 August 2002. Numerical experiments were performed with a grid-spacing of 10 km. Four experiments were carried out: CTRL for assimilation of only conventional GTS observations; RAV for assimilation of GTS plus Jindo radar radial velocity data; REF for assimilation of GTS plus reflectivity data; and BOTH for assimilation of GTS as well as both radial velocity and reflectivity data.

It is indicated that Doppler radar data assimilation improves the typhoon initialization and enhances the inland QPF skills. Figure 3 presents the 3-hr rainfall verification of the equitable threat score (ETS, Rogers et al. 1996) for 12 hours; results clearly indicate that assimilation of Doppler radar data had a positive impact on a short-range rainfall forecast. Rainfall verification was performed using Korean high-resolution Automatic Weather Station (AWS) hourly rainfall observations. In general, the average ETS of the experiment RAV, REF, or BOTH was higher than that of the experiment without radar data assimilation (CTRL). The positive impact of radar reflectivity assimilation (REF) appeared mainly in the first 3-hr forecast. The positive impact of radial velocity assimilation (RAV), however, existed in 6-hr forecast. The results in the 9-hr rainfall verification were mixed. The decrease of ETS scores in REF after 3-hr and then increase again after 9-hr indicated that the rainfall forecast underwent an adjusting process in the REF experiment. Even though REF matched the rainfall very well in the beginning, there were imbalances in the analyses due to difference of the warm rain process in 3D-Var and the microphysics in the model. At the 12-hr forecast, the ETS scores were higher in RAV, REF, and BOTH than in CTRL. For heavy rainfall (threshold of 10 mm), the reflectivity assimilation experiment (REF) obtained the highest ETS score among the four experiments at the 12-hr forecast. Doppler radar data assimilation experiments produced noticeable positive impacts that lasted for 12 hours.

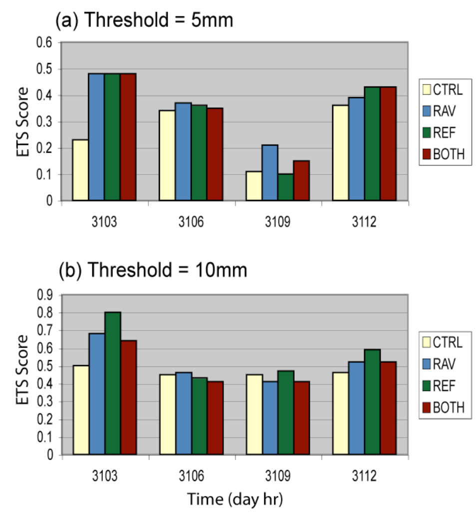

Fig. 3: Equitable threat scores of 3-hr rainfall simulations for experiments CTRL, RAV, REF, and BOTH with (a) threshold = 5mm and (b) threshold = 10mm.

The experiment REF in Figure 4 presented a notably high ETS score at 0300 UTC 31 August. To display the rainfall structure more clearly at this time, Figure 4 shows the composite reflectivity for the observation (Fig. 4a) as well as the forecasts by CTRL (Fig. 4b) and REF (Fig. 4c) at 0300 UTC 31 August (3-hr forecast). The rainfall distribution in Figure 4c is much closer to the observation (Fig. 4a) than the distribution of the experiment without radar data assimilation (Fig. 4b).

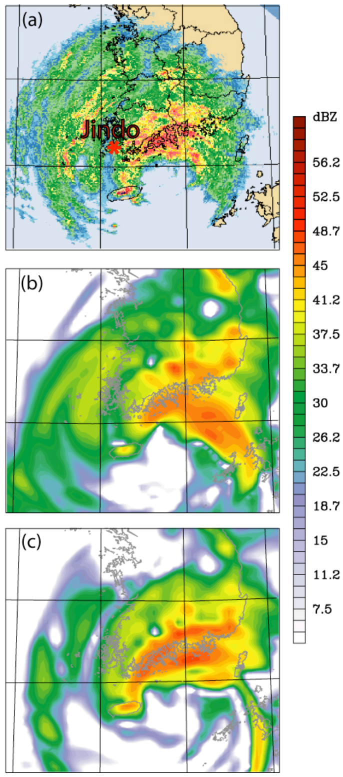

Fig. 4: Radar reflectivity at 0300 UTC 31 August 2002 for, (a) observation, (b) Experiment CTRL, and (c) Experiment REF. (The color bar on the right side of the figure shows the scales of the reflectivity. Jindo radar station is shown in asterisk in Fig. 4a.

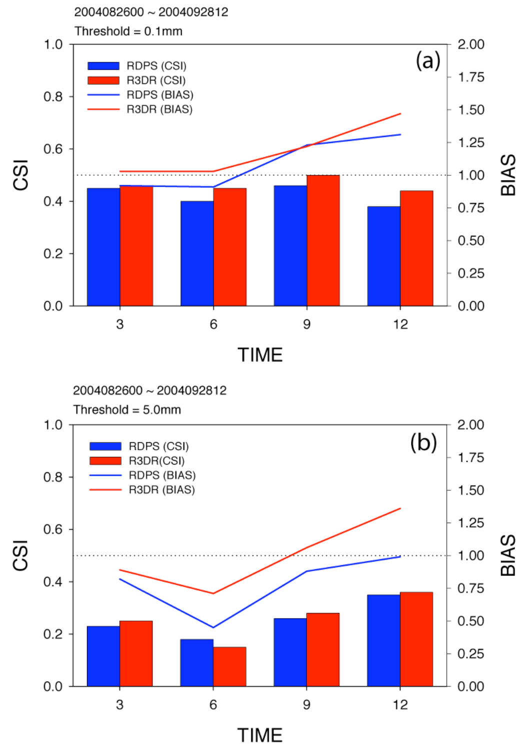

Fig. 5: Threat score (bars) and bias (solid lines) of the KMA preoperational forecasts with 3 hourly cycling of radar data. Blue = no radar data assimilation, Red = both radial velocity and reflectivity are assimilated. (a) Threshold = 0.1 mm and (b) Threshold = 5 mm

4. REAL-TIME VERIFICATIONS

The 3D-Var Doppler radar data assimilation capability was tested in real time at the Korea Meteorological Administration (KMA) for the period of 26th August – 28th September 2004 before it was implemented in KMA operational applications. The KMA operational model is MM5 with horizontal resolution of 10 km. The Doppler radar data from four radar stations are included in the 3D-Var assimilation cycles (every three hours) during the real time verifications.

Verified against the KMA AWS precipitation data, threat scores and bias scores of the 3-h accumulated precipitation for thresholds of 0.1 mm and 5 mm in the 12-h prediction are calculated and shown in Figure 5. The verifications are performed for the 10 km, 3-hourly cycling 3D-Var with Doppler radar data from 26th August through 28th September 2004. For the light precipitation (threshold of 0.1 mm), the TS scores are all increased with Doppler radar data assimilation, but bias is also increased at 12-h QPF (the bias scores are further deviated from 1). For the heavier precipitation (threshold of 5mm), in general, Doppler radar data assimilation also improves the QPF skills, except that the TS score is decreased at 6-h and the bias is further deviated from 1 at 12-h predictions. Overall, Figure 5 indicates a statistically significant positive impact of the Doppler radar data assimilation on the short-range QPF (0-12 hours). Started from 2005, the Doppler radar data assimilation is in operation in Korea Meteorological Administration.

5. DISCUSSIONS AND FUTURE PLAN

The Doppler radar data assimilation with the 3D-Var version of WRF-Var system has been developed. Numerical experiments were conducted for several selected cases. Several research institutes and universities adopted the scheme in their studies (Lee et al. 2006; Lin et al. 2006; Sugimoto et al. 2005; Gu 2006). It was also implemented in operational applications in Korea. It is indicated that:

• Assimilation of Doppler radial velocity and/or reflectivity data improves the QPF skills for squall line, mesoscale cyclone and tropical cyclone cases.

• Assimilation of multiple Doppler radar observations and cycling of more temporal radar data can further improve the QPF skills.

• We conducted 3D-Var cycling of the Doppler radar data every three hours up to 3 days. It is shown that the QPF skills are improved with the 3D-Var cycling mode. Further experiments with larger cycling window and higher update frequency are underway.

• Real-time applications with the KMA operational model indicate a statistically significant positive impact of Doppler radar data assimilation on the short-range QPF (0-12 hours).

There are several components that will be included in the WRF-Var Doppler radar data assimilation scheme in the near future. These components are important to further enhance the capability of radar data assimilation in research and real-time applications. They are summarized as follows:

• We will include a more sophisticated microphysics scheme in the 3D-Var hydrometeor partitioning. The current warm rain scheme will be updated to include ice phase. Accordingly, the reflectivity observation operator will also be updated to include ice-phase hydrometeors.

• The diabetic term in the Richardson's equation will be included to allow diabetic initialization. The vertical velocity increments from the diabetic initialization are expected to improve the initiation of convective systems.

• WRF 4D-Var will be built in the WRF-Var framework. The Doppler radar data assimilation in WRF 4D-Var will be developed in the near future.

• More real-time applications of the WRF 3D-Var radar data assimilation will be proposed and implemented in the United States and some east Asia countries.

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