3.01 ASSIMILATION OF DOPPLER RADAR OBSERVATIONS USING WRF/MM5 3D-VAR SYSTEM AND ITS IMPACT ON SHORT-RANGE QPF

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1. INTRODUCTION

Although there have been marked improvements in recent years, quantitative precipitation forecasting (QPF) is still a challenging problem for mesoscale and microscale weather prediction. One of the fundamental underlying reasons for this challenge is that precipitation is often concentrated in convective cells, or mesoscale bands or clusters which are difficult to be presented in the model’s initial conditions from the large-scale analysis. An immediate step in addressing this problem is to develop a mesoscale and microscale data assimilation system and utilize observations which match the spatial and temporal scales of thunderstorms and other small scale weather features. During the past several years, NCAR developed the capabilities to assimilate Doppler radial velocity (Xiao et al. 2005) and reflectivity (Xiao et al. 2004) data using the WRF/MM5 three dimensional variational (3D-Var) data assimilation system (Barker et al. 2004).

The major development of the Doppler radar data assimilation in the WRF/MM5 3D-Var system is inclusion of the analyses (increments) for vertical velocity and cloud water and rainwater mixing ratios. Although the 4D-Var approach is usually used for retrieving all these fields (Sun and Crook, 1997; 1998), 3D-Var has advantages due to its computational efficiency. In the continuous cycling mode, 3D-Var can also integrate the model nonlinearity into the analysis. We will present the methodology for the WRF/MM5 3D-Var System to generate vertical velocity increments, as well as increments of cloud water and rainwater mixing ratios. We will also describe the observation operators for Doppler radial velocity and reflectivity in the WRF/MM5 3D-Var system. The results of the 3D-Var radar data assimilation system in case studies of an IHOP squall line case of 13 June 2002 in the United States, a heavy rainfall case in East Asia, and operational applications in Korea Meteorological Administration (KMA) will be shown. We obtain positive impacts of the Doppler radar data assimilation on the short-range quantitative precipitation forecasting (QPF).

2. METHODOLOGY

2.1 WRF/MM5 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 $q_t$. 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).

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:

$$\frac{\gamma p \partial w}{\partial z} = -\gamma p V \cdot \nabla v_h - p \cdot \nabla p + g \int V \cdot \left( \rho \nabla v_h \right) dz \tag{1}$$

where $w$ is vertical velocity, $v_h$ is the vector of horizontal velocity (components $u$ and $v$), $\gamma$ the ratio of specific heat capacities of air at constant pressure/volume, $p$ pressure, $\rho$ 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:

\[
\gamma \frac{\partial q'}{\partial z} = - \gamma p' \frac{\partial q}{\partial z} - \gamma p' \nabla \cdot \vec{v} - \gamma p' \nabla \cdot \vec{v} - \nabla p' \quad (2)
\]

The basic state (overbar) variables satisfy Eq. (1). They also satisfy the continuity equation, adiabatic equation and hydrostatic equation. 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.

### 2.3 Partition of moisture and water hydrometeor increments

Because total water mixing ratio \( q_w \) 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 a 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:

\[
P_{RC} = \begin{cases} k_i(q_r - q_{ori}), & q_r \geq q_{ori} \\ 0, & q_r < q_{ori} \end{cases}
\]

where \( q_r \) is the cloud water mixing ratio. According to Kessler (1958),

\[
k_i = 10^{-3} \text{s}^{-1}, \quad q_{ori} = 0.5 \text{g} \cdot \text{kg}^{-1}.
\]

The accretion of cloud water by rain is parameterized by

\[
P_{RA} = \frac{1}{4} \Gamma \frac{(3+b)}{\lambda^b},
\]

where \( \Gamma \) is the gamma-function, \( E \) is the collection efficiency. \( N_0=8\times10^6 \text{m}^{-4} \) and \( b=0.8 \). The evaporation of rain can be determined from the equation:

\[
P_{RE} = \frac{2\pi N_o (S-1)}{A+B} \left[ \frac{f_1 + f_2 (\gamma p_0/\mu)^{1/2} S^{1/3}}{\lambda^{1/3}} \right]^{1/2} \]

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

\[
P_{CON} = \frac{q_r - q_{esi}}{1 + \frac{L_v q_{esi}}{R C_{pm} T}}
\]

where \( q_{esi} \) 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 \( q_r \), \( q_r \) 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 \( q_r \) and \( q_r \) increments, the assimilation of reflectivity is straightforward.

### 2.4 Observation operator for Doppler radial velocity and reflectivity

The observation operator for Doppler radial velocity is:

\[
V_r = u - \frac{\dot{x}}{r_j} + v - \frac{\dot{y}}{r_j} + (w - \dot{z}) - z_r,
\]

where \( (u, v, w) \) are the wind components, \( (x, y, z) \) are the radar location, \( (\dot{x}, \dot{y}, \dot{z}) \) are the location of the radar observation, \( r_j \) is the distance between the radar and the observation, and \( v_r \) is terminal velocity. Following the algorithm of Sun and Crook (1998),

\[
v_r = 5.40 a \cdot q_r 0.125.
\]

The quantity \( a \) is a correction factor defined by

\[
a = (p_0/\overline{p})^{0.4},
\]

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):

\[
Z = 43.1 + 17.5 \log(p q_r),
\]

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

### 3. CASE STUDIES

#### 3.1 IHOP squall line case

A squall line case was observed during the IHOP experiment on June 12-13, 2002. This squall line was documented by more than eleven WSR-88D radars in Oklahoma and Kansas and several other observing platforms. At 2200 UTC 12 June 2002, a convective line extended from...
western Oklahoma to the Texas panhandle. The squall line was well developed from southeast Kansas to the Texas panhandle at around 0000 UTC 13 June. 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 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 experiments are started 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. Here we show the QPF skills of three experiments:

- **GTS**: Only conventional GTS observations are assimilated in this experiment;
- **RVRF_ALL**: In addition to the conventional GTS observations, the Doppler radar data from all 11 radar stations in the area are assimilated;
- **RVRF_VNX**: Same as RVRF_ALL, but the Doppler radar data from only 1 radar station KVNX (shown in Fig. 1d) are assimilated.

To evaluate the QPF skills of the designed experiments, threat score (TS) of precipitation forecast in each experiment, verified against 3-h accumulated precipitation from the NCEP/OH Stage IV precipitation analysis, is calculated. Figure 2 shows TS scores of the three experiments with the threshold of 1 mm (Fig. 2a) and 10 mm (Fig. 2b). It is clearly indicated that RVRF_ALL gives consistently higher scores for both light and heavy rainfall. If the radar data from only one radar station KVNX are assimilated (RVRF_VNX), the scores are lower than those of RVRF_ALL, but higher than those of GTS.

This set of experiments suggests 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 GTS obtains the lowest TS score. With more Doppler radar data from one radar station to eleven radar stations, the TS scores are increased. The verification results are valid for 9 hours for this case. The squall line was dissipated after 0900 UTC 13 June.

3.2 A heavy rain case in East Asia

On 10 June 2002, a heavy rainfall event with a mesoscale cyclone occurred in South Korea. The KMA Automatic Weather Station (AWS) network observed that the rain-band started around 06 UTC 10 June 2002. Its maximum 1-hr rainfall occurred at 15 UTC 10 June 2002 (34 mm). The observed maximum 3-hr rainfall reached 54.8 mm ending at 18 UTC 10 June 2002 (Figure omitted). The heavy rainfall cell was located at the southwestern tip of Korea at 15 UTC, but it moved inland to the northeast at 18 UTC 10 June 2002. This rain-band moved southeastward along with the cold front of the mesoscale cyclone and crossed South Korea at around 00 UTC 11 June 2002. During the rain-band movement, the KMA Jindo radar captured the rainfall structures of the system over most of the period while the rain-band was in South Korea.

The 3D-Var system is set up in a 3-hr cycling mode. In addition to the conventional GTS data and AWS (Automatic Weather Station) surface observations, the Doppler velocities from Korean Jindo radar station are processed (quality control and preprocessing) and included in the 3D-Var analysis. The model configuration is the same as the KMA operational design with grid-spacing of 10 km. There are 33 layers in the vertical. The MM5 model is used for this case study. We conducted six experiments: 3D-Var with only conventional data (3DV_C1000, 3DV_C0912, 3DV_C0700), and with conventional data plus Doppler radar radial velocity data (RDR_C1000, RDR_C0912, RDR_C0700). The conventions _C1000, _C0912, and _C0700 denote the 3D-Var cold start times at 0000 UTC 10, 1200 UTC 9 and 0000 UTC 7 June 2002, respectively. All the numerical forecasts (following the assimilation) start from 1200 UTC 10 June 2002. More details of the experiment design and overview of the case can be found in Xiao et al. (2005).

Using KMA high-resolution AWS hourly rainfall observations, we calculated threat scores for the QPF of the six experiments. Figure 3 shows the threat scores for 3-h accumulated rainfall with thresholds of 5 mm and 10 mm for 3D-Var experiments with and without Doppler radial velocity assimilation. The threat scores for experiments with radar data assimilation are higher than those without radar data assimilation (RDR_C1000 vs. 3DV_C1000; RDR_C0912 vs. 3DV_C0912; and RDR_C0700 vs. 3DV_C0700, respectively). The positive impact of Doppler velocity assimilation exists mainly in the first six hours of forecast. It is not clear if the positive impact can last longer than six hours because the main rainfall event moves to the sea and the AWS network captures far less rainfall after 2100 UTC 10 June 2002. However, the TS scores in the first 6-hr forecasts clearly suggest that the Doppler radial velocity data assimilation is beneficial to short-range precipitation forecasts. The positive impact of Doppler velocity data assimilation on short-range rainfall forecast can be seen in almost every pair of experiments with and without radar data assimilation.
Results from these experiments also show the impact of continuous assimilation through update cycles for the rainfall forecast. During the 3D-Var update cycling procedure, the forecast from the previous cycle serves as the background for the next cycle when the AWS data and Jindo radar radial velocity data are assimilated. A better dynamic balance among the analysis variables can be achieved with continuous assimilation through update cycles. It is shown that a longer assimilation window can result in a higher TS score (Fig. 3).

4. REAL-TIME VERIFICATIONS

The 3D-Var Doppler radar data assimilation capability was tested in real time at the Korean 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 24-h prediction are calculated and shown in Figure 4. 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 are also increased at 12, 15 and 18-h QPF (the bias scores are further deviated from 1). For the heavier precipitation (threshold of 5 mm), 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 4 indicates a statistically-significant positive impact of the Doppler radar data assimilation on the short-range QPF (0-24 hours).
5. SUMMARY AND CONCLUSIONS

The unified 3D-Var system for WRF and MM5 with the capability of assimilating Doppler radial velocity and reflectivity data has been developed. Numerical experiments are conducted for several selected cases. We also implement real-time 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 can further improve the QPF skills compared with the experiment with assimilation of single Doppler radar data.
- 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 is 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 (0-24 hours).

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Reference


