

ASSIMILATION OF DOPPLER RADAR OBSERVATIONS WITH A REGIONAL 3D-VAR SYSTEM: A HEAVY RAINFALL CASE STUDY

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I. INTRODUCTION

With the continual increases in computer power, Doppler radar observation has highlighted prospects for its application in the operational implementation of numerical weather prediction (NWP). Toward this end, NCAR, partnered with Korean Meteorological Administration (KMA), developed the capability to assimilate Doppler radar observations (radial velocities) with the MM5 3D-Var system (Barker et al. 2003). In the Doppler radar data pre-processing, the technique of generating radar super-observations (which represents the radar observations at reduced resolution) is developed. Data quality control is performed and undesired radar echoes, such as ground clutter and anomalously propagated clutter (AP clutter), sea clutter, range folding, velocity folding, and noise are removed or corrected. A method to specify the error variance of the Doppler radar data is tested. In order to assimilate Doppler radial velocity, the MM5 3D-Var system is modified to include vertical velocity (w) increments, and cloud water (q_c) and rainwater (q_r) in the background. The observation operator for Doppler radial velocity is developed and tested individually and within the 3D-Var system. A series of experiments assimilating KMA Jindo radar data for the heavy rainfall case on 10 June 2002 are carried out. Results from the case studies show positive impact of the Doppler radial velocity assimilation upon the quantitative precipitation forecasting of the case over the Korean Peninsula.

II. KOREAN JINDO RADAR DATA AND PREPROCESSING

Jindo is in the southwestern tip of Korean Peninsula. The capability of the Jindo radar is comparable to the WSR-88D network in the United States. The radar has a dual-pulse

repetition frequency (PRF) at a 4 to 3 ratio (600/400 s⁻¹) with Nyquist velocity of 31.4 ms⁻¹ and the maximum unambiguous range of 240 km.

Data quality control is conducted by interactively editing the radar data using NCAR SOLO software (Oye et al. 1995). Each scan is carefully examined in order to identify undesired radar echoes. The undesired radar echoes are either recovered (e.g., velocity folding) or removed (all other undesired returns).

The Doppler radar super-observations are generated using NCAR's software SPRINT (Sorted Position Radar INTERpolation) and CEDRIC (Custom Editing and Display of Reduced Information in Cartesian space) developed by Mohr and Vaughan (1979) and Mohr (1981). The major steps in the processing are interpolation of data to Cartesian grid, removal of noisy data, filling data voids and data filtering. We use the standard deviation calculated in SPRINT during the interpolation to represent the super-observation errors.

III. VERTICAL VELOCITY INCREMENTS

Doppler velocity observations contain important information about atmospheric vertical velocity distribution. In order to ingest this information, MM5 3D-Var system has to be modified to include vertical velocity analysis. The balance equation from Richardson (1922) and White (2000) is chosen and implemented in MM5 3D-Var. For simplicity, it is called Richardson equation, and expressed as:

$$\gamma p \frac{\partial w}{\partial z} = \gamma p \left[\frac{Q}{T c_p} - \nabla \cdot \bar{v}_h \right] - \bar{v}_h \cdot \nabla p + g \int_z^{\infty} \nabla \cdot (\rho \bar{v}_h) dz$$

where w is vertical velocity, \bar{v}_h horizontal velocity (components u and v), γ 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, g acceleration due to gravity, and Q is diabatic

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heating. Assuming no diabatic heating ($Q=0$), the linearized Richardson equation is

$$\gamma \bar{p} \frac{\partial w'}{\partial z} = -\gamma p' \frac{\partial \bar{w}}{\partial z} - \gamma \bar{p} \nabla \cdot \bar{v}'_h - \gamma p' \nabla \cdot \bar{v}'_h - \bar{v}'_h \cdot \nabla p' - \bar{v}'_h \cdot \nabla \bar{p} + g \int_z^\infty \nabla \cdot (\rho \bar{v}'_h) dz + g \int_z^\infty \nabla \cdot (\rho' \bar{v}'_h) dz$$

The linear equation is discretized, and its adjoint is developed according to the linear program. Before the code is linked to the MM5 3D-Var system, extensive tests for the linear program and its adjoint are completed. The so-called adjoint check (Navon et al. 1992) is passed. After the programs pass the adjoint check, we include them in the MM5 3D-Var system. As a result, the system now produces vertical velocity increments and analysis. The modified version of 3D-Var also passes a series of tests embedded in the system.

IV. INCLUSION OF CLOUD WATER AND RAINWATER IN THE 3D-VAR BACKGROUND

In the MM5 3D-Var system, the background could be MM5 input analysis, or MM5 output forecasts. During the initial development, the MM5 3D-Var background is mainly from MM5 input analysis. There is no cloud water or rainwater in the system. When 3D-Var is set up for cycling run, inclusion of cloud water and rainwater mixing ratios q_c and q_r becomes important. When the previous cycle produces cloud water and rainwater, inclusion of background q_c and q_r in MM5 3D-Var system enables the passing of these variables to the next cycle. This can reduce the cloud water and rainwater spin-up time when the model integrates from the analysis in the cycling run. In addition, inclusion of q_c and q_r is a requirement to implement Doppler radar data assimilation in the MM5 3D-Var system.

V. OBSERVATION OPERATOR FOR DOPPLER RADIAL VELOCITY

The observation operator for Doppler radial velocity is

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

where (u, v, w) are the wind components, (x, y, z) is the radar location, (x_i, y_i, z_i) are the radar super-observation locations, r_i is the distance between radar and the observations, and v_T is terminal velocity. There are different ways to calculate terminal velocity. In the modified MM5 3D-Var

system, the algorithm of Sun and Crook (1998) is used:

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

with

$$a = (p_0 / \bar{p})^{0.4}.$$

Radial velocity is not a direct variable in 3D-Var. A comprehensive testing is performed after the operators (linear and adjoint) are included in the system. The whole 3D-Var system after including w increments and radial velocity assimilation pass the adjoint check. We have demonstrated that the assimilation of Doppler velocities in the modified MM5 3D-Var now works properly in our assimilation experiments.

VI. EXPERIMENTAL DESIGN

The MM5 3D-Var system is set up in a 3-hr cycling mode. The script files and the execution environment are designed according to the KMA operational run. In addition to the WMO GTS (World Meteorological Organization, Global Transmitting System) data and AWS (Automatic Weather Station) surface observations, the Korean Jindo radar data are processed (quality control and preprocessing) and included in the 3D-Var analysis. The model configuration is the KMA domain 2 with grid-spacing of 10 km. There are 33 layers in the vertical. The horizontal grid points are 160X178. The main model physics include Kain-Fritsch cumulus parameterization, Reisner-1 microphysics, simple radiation scheme and MRF PBL parameterization. The model boundary conditions are nested down from KMA 30-km domain forecast.

VII. RESULTS

On 10 June 2002, a heavy rainfall event 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 54.8mm 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 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. There are some data voids in Jindo radar Doppler velocity. However, the radar data preprocessing has the capability to fill some voided data with a two-dimension, linear, least-square fit methodology. Assimilation of the pre-processed radar data and assessment of their impact are our main goal for this case study.

We diagnose the wind and vertical velocity increments with radial velocity assimilation. The purpose of this diagnosis is to understand the characteristics and influence of radial velocity in the regional 3D-Var analysis. Figs. 1a and 1b show a comparison of 850-hPa wind increments between 3D-Var with and without radial velocity assimilation at 12 UTC 10 June 2002 (Experiment R3DV_C1000 vs. RDR1_C1000). With the radial velocity assimilation, the wind increment maximum is located further south and the northwesterly wind is stronger in the vicinity of the cold front at 850 hPa. The analyzed horizontal winds are more realistic in the radial velocity assimilation experiment (RDR1_C1000) compared to the non-radar data assimilation experiment (R3DV_C1000). Because of the increase of the northwesterly wind after assimilating Jindo Doppler velocities, the lower level convergence in the vicinity of the cold front at 12 UTC 10 June 2002, is increased (figure omitted). As the 3D-Var is now modified to include vertical velocity analysis, the lower level convergence results in a stronger upward motion from the lower to mid-level troposphere in the warm sector of the front (Fig. 1c).

Fig. 2 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 with radar data assimilation are higher than those from experiments without radar data assimilation (RDR3_C1000 vs. R3DV_C1000; RDR3_C0912 vs. R3DV_C0912; and RDR3_C0700 vs. R3DV_C0700, respectively).

The positive impact of Doppler velocity assimilation is mainly in the first 6 hours of the forecast. It is not very clear if the positive impact can last longer because the main rainfall event moved over the sea and AWS network captured far less rainfall observations at 21 UTC 10 June 2002 and afterwards. However, TS scores in the first 6 hours of the forecast clearly suggests that the Doppler radial velocity data assimilation is very effective in extracting useful information from the radar data. The benefit of Doppler velocity data assimilation with respect to the rainfall forecast can be seen in almost every pair of experiments.

From our study, we also found that 3D-Var cycling is important for the rainfall forecast. Fig. 2 indicates that the TS scores increase as 3D-Var cycles increase. The highest TS score with threshold of 5 mm at 15 UTC reaches 0.39 for RDR3_C0700, and 0.38 for RDR3_C0912. The highest TS score with threshold of 10 mm at 15 UTC reaches 0.26 for RDR3_C0700, and 0.25 for RDR3_C0912. During the 3-hr update cycling, the forecast from the previous cycle serves as the background for the next cycle, and the AWS data and Jindo radar radial velocity data are assimilated. We found that this strategy is a good approach for implementing 3D-Var in the forecasting system for at least 3.5 days period cycling.

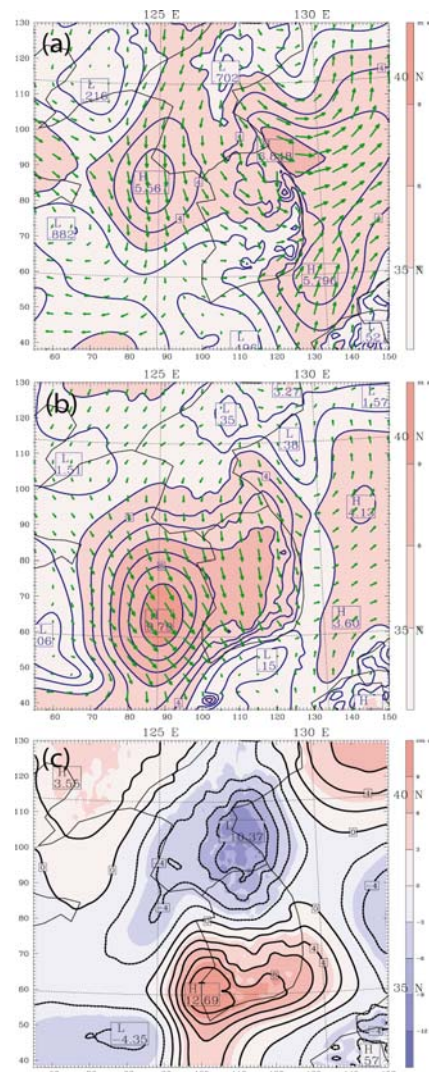


Fig. 1: 850 hPa wind increments (isolines with 1 m/s interval and shading are wind speed increments, and arrows are wind increment vectors) for 3D-Var (a) R3DV_C1000 without radar data, (b) RDR1_C1000 with radar data, (c) vertical velocity increments from radar data assimilation (RDR1_C1000)

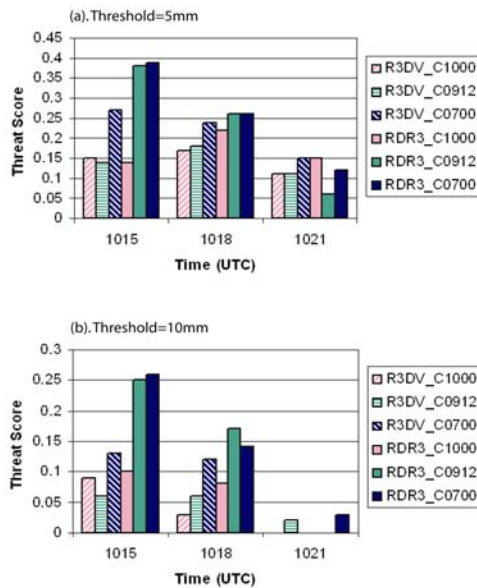


Fig. 2: Comparison of threat scores between experiments with and without Doppler velocity assimilation. (a) Threshold=5mm; (b) Threshold=10mm

VIII. Summary and conclusions

The MM5 3D-Var system has been further developed for assimilation of Doppler velocities. The preprocessing of the Doppler radar data includes data quality control, generation of super-observations in Cartesian grid points and error statistics of the Doppler radar data. The 3D-Var system has been modified to include vertical velocity (w) increments and background cloud water (q_c) and rainwater (q_r). The observation operator for Doppler radial velocity has been developed and tested individually and within the 3D-Var system. Numerical experiments performed over the Korean Peninsula demonstrated that:

1). The modified 3D-Var produced sound and appropriate wind and vertical velocity analyses in the region where the Doppler velocity data are assimilated. The root-mean-square errors (RMSEs) of the forecasted winds are reduced compared to the experiments without radar data assimilation experiments.

2). The rainfall forecast in the first 6 hours from 3D-Var analysis with Doppler velocity data is better than the forecast without radar data, verified against AWS observed rainfall with all the thresholds. The 3D-Var radar data assimilation experiments obtained much more clear rain-band structure for heavy rainfall.

3). Generally speaking, 3D-Var with more 3-hr cycles results in improved rainfall forecasts. Assimilating Jindo Doppler velocities while applying more 3-hr cycles is good strategy to increase the skills of heavy rainfall forecasts.

Future work for the 3D-Var radar data assimilation will include improvement and tuning of the error statistics for Doppler radar data. We will also include Doppler reflectivity assimilation capability in the regional 3D-Var system. We expect this work will yield far-reaching benefits in the field of 3D-Var radar data assimilation.

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