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Assimilation of Doppler radar observations and its impacts on forecasting of the landfalling typhoon Rusa (2002)

Qingnong Xiao[1], Y.-H. Kuo[1], J. Sun[1], W.-C. Lee[1], D. M. Barker[1], and E. Lim[2]

[1]National Center for Atmospheric Research, Boulder, Colorado, USA
[2]Korean Meteorological Administration, Seoul, Korea

Abstract. Doppler radar data (radial velocity and reflectivity) assimilation capability has been developed with the MM5 3D-Var system. To assimilate radial velocity and reflectivity data, the 3D-Var system includes analyses of vertical velocity increments, as well as the increments of cloud water and rainwater mixing ratios. The model total water mixing ratio is used as a control variable in the MM5 3D-Var system. A warm rain process, its linear and adjoint are incorporated into the system to partition the moisture and water hydrometeor increments. Richardson's equation is used to balance the increments of vertical velocity and other dynamic and thermodynamic variables. The observation operators for Doppler radial velocity and reflectivity are developed and incorporated into the 3D-Var system. A case study is conducted for the landfalling Typhoon Rusa (2002) in South Korea. Experiments show positive impacts of assimilating Doppler radar data on the tracks and rainfall simulations of Typhoon Rusa (2002).

1 Introduction

Hurricane and typhoon forecasts have improved steadily over the last decade primarily due to the increased use of remote-sensing data over oceans to improve the tropical cyclone initialization. For tropical cyclone near landfall, Doppler radar observations from onshore radar sites are very useful in defining the storm position and structures. How to incorporate the data optimally in the initialization of tropical cyclones for numerical prediction is an interesting and challenging topic.

In this research, Doppler radial velocity and reflectivity data are ingested in the tropical cyclone initialization procedure. The recently developed regional 3D-Var system for the Penn State/NCAR mesoscale model version 5 (MM5) is used to perform the initialization. Numerical forecasts are conducted with the MM5 model. Application of the MM5 3D-Var system with Doppler radar data assimilation to Typhoon Rusa (2002) indicates that the assimilation of Doppler radial velocity and reflectivity observations is capable of correcting the typhoon position, enhancing the typhoon initial structure and improving the skills of the typhoon forecasts.

Correspondence to: Qingnong Xiao
(hsiao@ucar.edu)

2 Methodology

2.1 MM5 3D-Var

The configuration of the MM5 3D-Var system is based on an incremental formulation producing a multivariate incremental analysis in the MM5 model space. The incremental cost function minimization is performed in a preconditioned control variable space. The preconditioned control variables in this study are stream function, velocity potential, unbalanced pressure and total water mixing ratio q_t. Balance between mass and wind increments is achieved via a geostrophically and cyclostrophically balanced pressure derived from the wind increments. Statistics of differences between 24 h and 12 h forecasts are used to estimate background error covariances (NMC-method). Representation of the horizontal component of background error is via horizontally isotropic and homogeneous recursive filters. The vertical component is applied through projection onto climatologically averaged (in time, longitude, and optionally latitude) eigenvectors of vertical error estimated via the NMC method. Horizontal/vertical errors are nonseparable, in that horizontal scales vary with vertical eigenvectors. A detailed description of the 3D-Var system can be found in Barker et al. (2004).

2.2 Vertical velocity increments

In order to have a capability to assimilate Doppler radial velocity observations, vertical velocity increments are included in the MM5 3D-Var system. Based on Richardson (1922), a balance equation that combines the continuity equation, adiabatic thermodynamic equation, and hydrostatic relation is derived and expressed as:

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

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 Richardson's equation. Linearizing Eq. (1) by writing each the variable in terms of a basic state (overbar) plus a small increment (prime) gives:

$$\begin{aligned}\gamma\bar{p}\tfrac{\partial w'}{\partial z} &= -\gamma p'\tfrac{\partial\bar{w}}{\partial z} - \gamma\bar{p}\nabla\cdot\overrightarrow{v_h'} - \gamma p'\nabla\cdot\overrightarrow{\bar{v}_h} - \overrightarrow{\bar{v}_h}\cdot\nabla p' \\ &- \overrightarrow{v_h'}\cdot\nabla\bar{p} + g\textstyle\int_z^\infty\nabla\cdot(\bar{\rho}\overrightarrow{v_h'})dz + g\int_z^\infty\nabla\cdot(\rho'\overrightarrow{\bar{v}_h})dz\end{aligned} \quad (2)$$

The linear Eq. (2) is discretized, and its adjoint is developed according to the code of the linearized equation. The linear and adjoint of Richardson's equation are incorporated in the MM5 3D-Var system, which can build a bridge between MM5 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_t is used as a control variable, partitioning of the moisture and water hydrometeor increments is necessary in the 3D-Var system. A warm rain process is introduced into the 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}), evaporation of rain to water vapor (P_{RE}).

In all the relevant processes, the Marshall-Palmer distribution is assumed. The autoconversion term, P_{RC}, is represented by

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

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

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

where Γgs the gamma-function, E is the collection efficiency. The evaporation of rain can be determined from the equation:

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

P_{CON}, the condensation is determined by

$$P_{CON} = \frac{q_v - q_{vs}}{1 + \frac{L_v^2 q_{vs}}{R_v C_{pm} T^2}}. \quad (6)$$

More details of the warm rain process are referred to the Appendix of Dudhia (1989). The tangent linear code is developed according to the nonlinear program, and its adjoint is developed based on the tangent linear routine. After the correctness of the developed tangent linear and adjoint codes are verified, we incorporate them into the MM5 3D-Var system. Although the control variable is q_t, the q_v, q_c and q_r increments are produced through the partition procedure during the 3D-Var analysis. Once the 3D-Var system produces q_c 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:

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

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. For radar scans at nonzero elevation angles, the fall speed of precipitation particles has to be taken into account. There are different ways to calculate terminal velocity. Here, we use the algorithm of Sun and Crook (1998), with:

$$v_T = 5.40a \cdot q_r^{0.125}. \quad (8)$$

The quantity a is a correction factor defined by

$$a = (p_0/\bar{p})^{0.4}, \quad (9)$$

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

The observation operator for Doppler radar reflectivity is derived analytically by assuming the Marshal-Palmer distribution of raindrop size. The $Z - q_r$ relation between the rainwater and reflectivity (dBZ) is (Sun and Crook 1997):

$$Z = 43.1 + 17.5\log(\rho q_r), \quad (10)$$

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

3 Typhoon Rusa (2002) Case

Typhoon Rusa was the most disastrous weather system for Korea in 2002. It moved across the country and produced very heavy rainfall in a short time period. More than 110 people were killed and thousands of homes were destroyed.

Typhoon Rusa was initiated from a tropical wave in the mid-Pacific ocean. It tracked towards the west-northwest direction and reached typhoon strength on 26 August. Rusa turned north on 30 August and made landfall over South Korea on 31 August at around 6:30 UTC. Rusa was a very strong typhoon, with the minimum sea-level pressure of 950 hPa

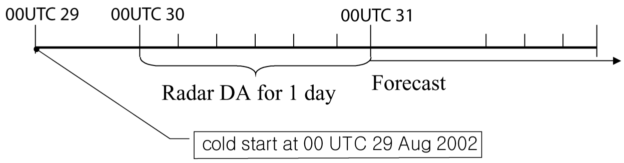

Fig. 1. Experimental design for the Doppler radar data assimilation and numerical simulations.

sustained from 00 UTC 29 until 12 UTC 30 August. Before landfall on 31 August, the typhoon kept the strength in central sea-level pressure between 950 and 960 hPa. But it weakened rapidly after landfall and became an extratropical cyclone over the Sea of Japan on the first day of September.

Because of an interest in typhoon initialization with the onshore Doppler radar data, 00 UTC 31 August 2002 is selected as initial time for simulation. We anticipate that assimilation of the Jindo radar data will result in a better simulation of the typhoon.

4 Experimental Design

Totally, 4 experiments are carried out in this study. The 3D-Var cold-start time for the experiments is 00 UTC 29 August. It is then cycled every three hours afterwards. All conventional observations are assimilated. The Jindo radar data from 00 UTC 30 through 00 UTC 31 August are included in the 3D-Var analyses, cycled at 3-h interval. Quality control is performed on the Korean Jindo radar data. It is then preprocessed into gridded PPI coordinates before ingesting into 3D-Var assimilation. All the experiments used the same domain with the grid-spacing of 10 km. Numerical forecasts start at 00 UTC 31 August 2002. Figure 1 shows the experimental design. The 4 experiments are listed below:

CTL: Only conventional data are assimilated during the two-day cycling, followed by 24-hr MM5 model forecast;

RAV: Conventional data plus Jindo Doppler radial velocities are assimilated during the two-day cycling, followed by 24-hr MM5 model forecast;

REF: Conventional data plus Jindo Doppler reflectivity data are assimilated during the two-day cycling, followed by 24-hr MM5 model forecast;

ALL: Conventional data, both radial velocity and reflectivity data are all assimilated during the two-day cycling, followed by 24-hr MM5 model forecast.

5 Results

5.1 Typhoon track

As this is a typhoon case, we naturally expect that the assimilation of Doppler radar data can correct the typhoon initial position and therefore has improved forecast skill for the typhoon track. Figure 2 presents the forecasted typhoon tracks at every 6 h. The observed best track (OBS) from Tokyo Typhoon Center is also plotted for comparison. It is important to note that the initial typhoon vortex is relocated closer to the observed position in the three Doppler radar data assimilation experiments. The position error of CTL at 00 UTC 31 August is the largest. Assimilation of Doppler radial velocity (RAV) obtains a better initial typhoon position than assimilation of reflectivity data (REF). Because reflectivity data contain mostly hydrometeor information, assimilation of Doppler reflectivity data has less impact on the typhoon pressure and wind increments than assimilation of Doppler radial velocity data. Assimilation of both radial velocity and reflectivity data (ALL) obtains the best track forecast in the 24-h period. Generally speaking, assimilation of radial velocity data has more positive impact on either typhoon initialization or its track prediction.

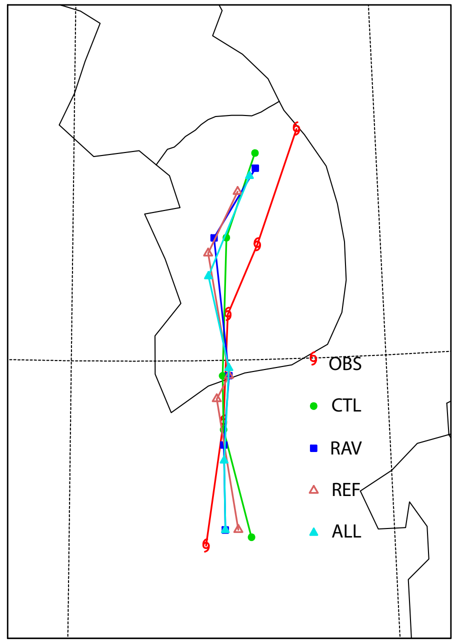

Fig. 2. The tracks of Typhoon Rusa (2002) from 00 UTC 31 August to 00 UTC 1 September 2002 for OBS (typhoon symbol), CTL (dot), RAV (square), REF (triangle) and ALL (filled triangle).

5.2 Rainfall

We also performed rainfall verification (Fig. 3) and the results clearly indicate that assimilation of Doppler radar data has a positive impact on the short-term rainfall forecast. The rainfall verification is performed using the Korean high-resolution AWS (Automatic Weather Station) hourly rainfall observations. With the radar data assimilations (experiments RAV, REF and ALL), the threat scores are higher than that from experiment without radar data assimilation (CTL). The positive impact of Doppler reflectivity assimilation (REF) is mainly in the first 3 h forecast. After 3 h, the results are

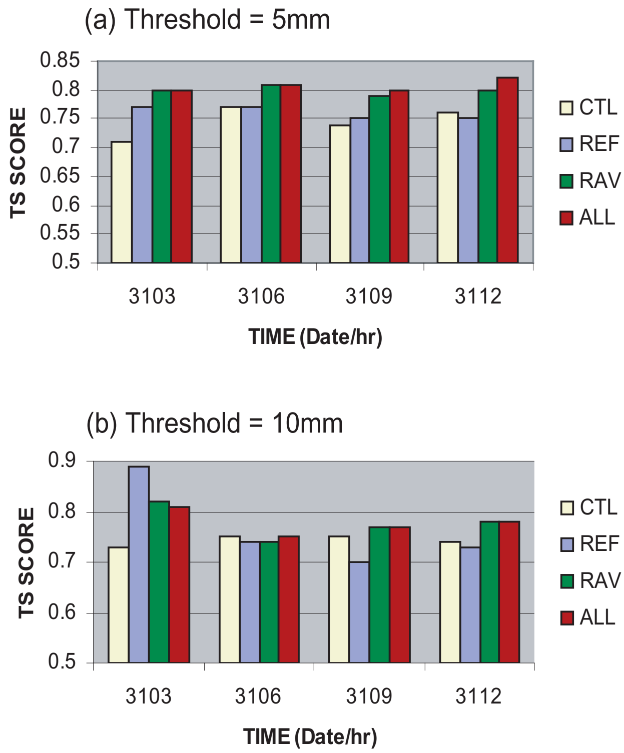

Fig. 3. Threat scores of 3-h rainfall simulations for (a) threshold=5 mm, and (b) threshold=10 mm.

mixed. However, assimilations of radial velocity (RAV) or both (ALL) result in positive impacts which last for 12 h. Assimilation of both radial velocity and reflectivity obtains the highest threat scores at almost all the verification times for either threshold of 5 mm or 10 mm. This suggests that the assimilation of Doppler radial velocity data is effective in extracting useful information from the radar data. Assimilation of reflectivity data adds additional positive impact on the rainfall forecasts.

It is noticed that the experiment REF in Fig. 3 obtains a very high 3-h rainfall TS score at 03 UTC 31 August. To display the rainfall structure more clearly at this time, Fig. 4 shows the observed reflectivity (Fig. 4a) as well as the simulated reflectivity for CTL (Fig. 4b) and REF (Fig. 4c) at 03 UTC 31 August (3-h forecast). Compared with observation, assimilation of Doppler reflectivity (Fig. 4c) improves the 3-h rainfall forecast. The rainfall distribution in Fig. 4c is much closer to the observation (Fig. 4a) than the distribution of the experiment without radar data assimilation (Fig. 4b).

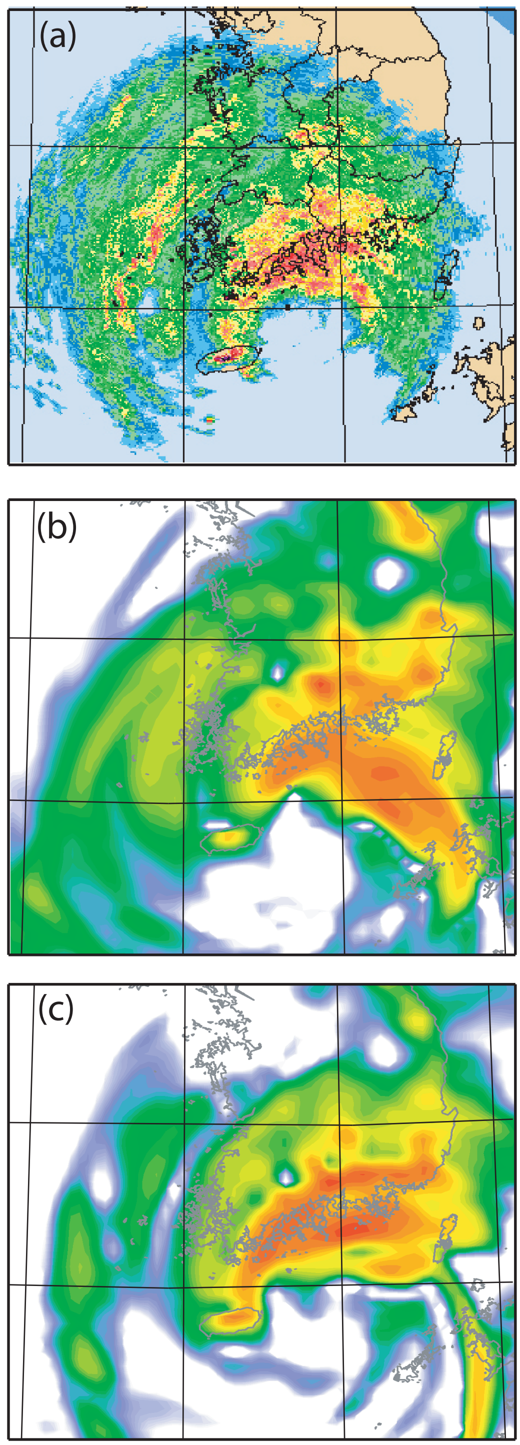

Fig. 4. Radar reflectivity at 03 UTC 31 August 2002 for (a) observation, (b) Experiment CTL, and (c) Experiment REF.

6 Summary and conclusions

The MM5 3D-Var system with the capability of assimilating Doppler radial velocity and reflectivity data has been developed. The system works well with 3-h cycling of the observed radar data. Doppler radar observations (radial velocity, reflectivity, or both) can be incorporated into the 3D-Var analyses. Based on experiments of the landfalling typhoon Rusa (2002) case, it is indicated that:

– Assimilation of Doppler radial velocity or reflectivity data improves the short-term rainfall prediction for the Typhoon Rusa (2002) case. Assimilation of both radial velocity and reflectivity data can extend the positive impact on rainfall forecast up to 12 h.

– Typhoon position is adjusted toward the observed position during the 3D-Var cycling of the Doppler radar data (either radial velocity or reflectivity or both). Radial winds (dynamical field) adjusted the typhoon position more than reflectivity (mainly hydrometeor field). The forecast skill of typhoon track is also improved with Doppler radar data assimilation.

– Radial wind appears to have more positive impact than reflectivity in this case. Assimilation of radial velocity only results in higher skill in typhoon initialization and short-term rainfall prediction than assimilation of reflectivity only.

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