Tropical Cyclone Initialization with Doppler Radar Data Using a Regional 3D-Var System and Its Application to Typhoon Rusa (2002) Case

Qingnong Xiao[1]*, Jianfeng Gu[1,2], Dale M. Barker[1] and Ying-Hwa Kuo[1]

1. National Center for Atmospheric Research, Boulder, Colorado
2. Chinese Academy of Meteorological Sciences, Beijing, China

1. Introduction

Hurricane and typhoon forecasts have improved steadily over the last decade primarily due to the increasing use of the 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 velocities are ingested in the tropical cyclone initialization procedure. The recently developed regional 3D-Var system for the Weather Research and Forecasting (WRF) model is used to perform the initialization. Numerical forecasts are conducted with the WRF model. Application of the WRF 3D-Var system with Doppler radar data assimilation to Typhoon Rusa (2002) indicates that the assimilation of Doppler radial velocities is capable of correcting the typhoon position, enhancing the typhoon initial structure and improving the skills of the typhoon forecasts.

2. Methodology

2.1 WRF 3D-Var

The configuration of the WRF 3D-Var system is based on an incremental formulation producing a multivariate incremental analysis in the WRF model space. The incremental cost function minimization is performed in a preconditioned control variable space**.** The preconditioned control variables we used in this study are stream function, velocity potential, unbalanced pressure and humidity (WRF 3D-Var CV_option II). 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 via the NMC-method (Parrish and Derber 1992). 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 include a capability to assimilate Doppler radial velocity data, vertical velocity increments are included in the WRF 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 variable in terms of a basic state (overbar) plus a small increment (prime) gives:

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

The linear equation (2) is discretized, and its adjoint code is developed according to the code of the linearized equation. The correctness of the adjoint check following the method proposed by Navon et al. (1992) is verified. The linear and adjoint of Richardson's equations are incorporated in the WRF 3D-Var system, which can build a bridge between WRF analyses and the vertical velocity component of the Doppler radial velocity observations.

2.3 *Observation operator for Doppler radial velocity*

The observation operator for Doppler radial velocity is:

$$V_r = u\frac{x-x_i}{r_i} + v\frac{y-y_i}{r_i} + (w-v_T)\frac{z-z_i}{r_i}\,, \quad (3)$$

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

**Corresponding author address*: Qingnong Xiao, NCAR, MMM, P. O. Box 3000, Boulder, CO 80307-3000; Email: hsiao@ucar.edu

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:

$$v_T = 5.40a \cdot q_r^{\,0.125} \tag{4}$$

The quantity a is a correction factor defined by

$$a = (p_0 / \overline{p})^{0.4}\,, \tag{5}$$

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

3. Typhoon Rusa (2002) Case

Typhoon Rusa was the most disastrous weather system in Korea in 2002. It moved across the country and produced very heavy rainfall in a short time period. The heavy rainfall of 870 mm/day at Kangnung city is the highest on record in recent 100 years in Korean history. 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. On 23 August, Rusa formed as a tropical depression over the Pacific, about 600 km southwest of Wake Island. It tracked towards the west-northwest and strengthened into a tropical storm the same day. Rusa reached typhoon strength on 26 August and continued to move west-northwestwards over the Pacific. It then turned to the northwest and skirted the Ryukyu Islands. 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 sustained from 00UTC 29 until 12 UTC 30 August. Before landfall on 31 August, the typhoon kept the strength of 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.

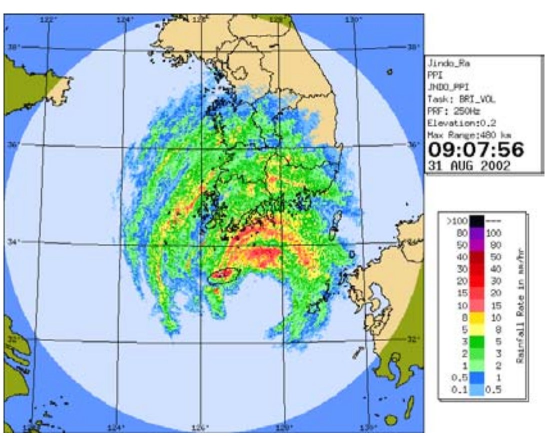

Fig. 1: Korean Jindo radar captured image (rainfall rate) of Typhoon Rusa at about 00 UTC 31 August 2002

Because of an interest in typhoon initialization with the onshore Doppler radar data, 00 UTC 31 August 2002 is selected as the analysis time for assimilation and initial time for simulation. The Doppler radar observations (Fig. 1) captured by Korean Jindo radar site are assimilated into the WRF 3D-Var analyses to generate the initial conditions at that time. Figure 1 depicts a radar-captured typhoon structure at about 00 UTC 31 August 2002. Assimilation of the Jindo Doppler radial velocities will help recover and improve the typhoon vortex structures before its landfall. We expect that the assimilation of the Jindo radar data will results in a better simulation of the typhoon track, intensity and structure.

4. Experimental Design

Totally, 5 experiments are carried out. In order to generate the vertical velocity in the WRF 3D-Var first-guess, a previous 24-h forecast is executed using NCEP AVN analyses and WRF standard initialization. Typhoon initialization using WRF 3D-Var system is conducted at 00 UTC 31 August 2002. Quality control is performed on the Korean Jindo radar data. It is then pre-processed into gridded PPI coordinates before ingesting into WRF 3D-Var assimilation. The forecasts using WRF model start at 00 UTC 31 August 2002. The 5 experiments are listed below:

CTRL: WRF model forecast starts with the 3D-Var first guess without data assimilation;

GTS: Conventional GTS data are assimilated using WRF 3D-Var without w increments, followed by model forecast;

GTS_W: Conventional GTS data are assimilated using WRF 3D-Var with w increments, followed by model forecast;

GTS_R: Conventional GTS data plus Jindo Doppler radial velocities are assimilated, followed by model forecast, the default 3D-Var maximum error check is conducted;

GTS_RA: Same as GTS_R, but without 3D-Var maximum error check for the Doppler radial velocity data.

5. Results

5.1 *WRF 3D-Var experiments without radar data*

For typhoon forecast, the main concern is the track prediction. Figure 2 shows the 24-h typhoon positions for CTRL, GTS, and GTS_W. The Tokyo Typhoon Center best track (OBS) is also plotted for comparison. The two WRF 3D-Var experiments (GTS and GTS_W) improve the track prediction compared to CTRL. When vertical velocity (w) is also reanalyzed via the WRF 3D-Var (w increments are included in the 3D-Var analysis), GTS-W produces slightly better track than the experiment GTS. The average position errors for CTRL, GTS and GTS_W over the 24-h forecast period are 94.6km, 64.0km, and 62.9km, respectively (Table 1).

It is noted that the initial typhoon positions for experiments GTS and GTS_W become worse than CTRL. Table 1 indicates that the initial position errors for both GTS and GTS_W are 46.5km, while CTRL has an initial position error of 35.4km. Since experiments GTS and GTS_W assimilate only conventional GTS data, which are not available in the typhoon region over ocean, the initial typhoon position is not refined via the 3D-Var analysis. However, the overall forecast skill of the typhoon track is improved with 3D-Var enhancing GTS observations.

5.2 *Typhoon initialization with Doppler radar data*

At 00 UTC 31 August, Korean Jindo radar observed very high resolution (about 1km) Doppler radial velocity data from the Typhoon Rusa vortex (Fig. 1). The model resolution used in this study is 10km. Therefore, we thinned the data to gridded PPI points before assimilation. The forecasted tracks of experiments GTS_R, GTS_RA via WRF 3D-Var initializations with Doppler radial velocities are shown in Figure 3. For comparison, the tracks from observation (best track) and experiment GTS are also shown.

Table 1: The deviation between simulation and observation for Typhoon Rusa (2002) position (unit: km)

	0h	3h	6h	9h	12h	15h	18h	21h	24h	average
CTRL	35.4	43.7	53.6	71.3	137.7	109.1	128.5	133.9	138.4	94.6
GTS	46.5	44.5	65.5	52.1	88.3	74.5	72.0	79.0	53.5	64.0
GTS_W	46.5	49.7	60.8	53.2	86.8	66.9	72.7	79.6	50.0	62.9
GTS_R	35.5	38.2	47.7	66.1	81.5	61.4	62.0	79.1	49.0	57.8
GTS_RA	9.8	16.5	82.1	70.5	134.7	75.7	19.9	51.9	38.4	55.5

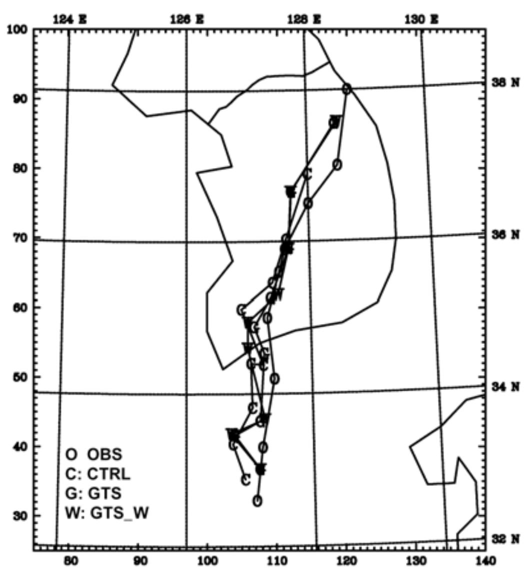

Fig. 2: Typhoon Rusa tracks (at 3 h interval, starting from 00 UTC 31 August 2002) for observation and three experiments (CTRL, GTS and GTS_W)

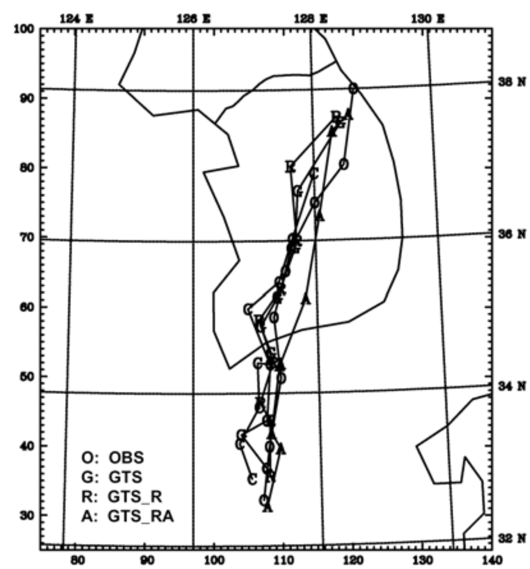

Fig. 3: Typhoon Rusa tracks (at 3 h interval, starting from 00 UTC 31 August 2002) for observation and three experiments (GTS, GTS_R and GTS_RA)

From Figure 3 and Table 1 we can see that both Doppler radar data assimilation experiments (GTS_R and GTS_RA) improve the forecasts of the typhoon track. The average position errors of GTS_R and GTS_RA are 57.8km and 55.5km, respectively, reducing the average position error of 64.0km from experiment GTS. Assimilation of Doppler radial velocities at 00 UTC 31 August 2002 gives a positive impact on the typhoon track forecasts. It is important to note that assimilation of Doppler radial velocities at 00 UTC 31 August relocates the initial typhoon position closer to the observed position. Experiment GTS_RA has the initial position error of 9.8km, which is less than the model resolution. In other words, GTS_RA initializes the typhoon in the same grid mesh as the observation.

The difference between GTS_R and GTS_RA is in the WRF 3D-Var maximum error check. In GTS_R, the radial velocity observation that has more than 5 times of the specified error compared to the first-guess equivalent, is rejected (it is the default criterion of WRF 3D-Var maximum error check). Because the typhoon vortex is shifted in the first-guess field from observation, over half of the radar observations are rejected in GTS_R during assimilation due to its maximum error check. When all radar data are assimilated in GTS_RA, we obtain much better typhoon initialization. The initial typhoon position is adjusted closely to the observed point. Assimilation of the high-density Doppler radar data is able to refine the typhoon initial position.

To analyze the typhoon vortex enhanced by Doppler radial velocity observations, Figure 4 shows the 850-hPa wind distribution. The typhoon initialization with Doppler radial velocities is much more compact. The wind around the typhoon is increased, and the radius of the maximum wind is decreased. The corrected position and improved vortex structure enhanced by Doppler radar observations improve the subsequent forecast skill of the typhoon track (Fig. 3). The experiment GTS_RA obtains the best track among all our experiments in this study.

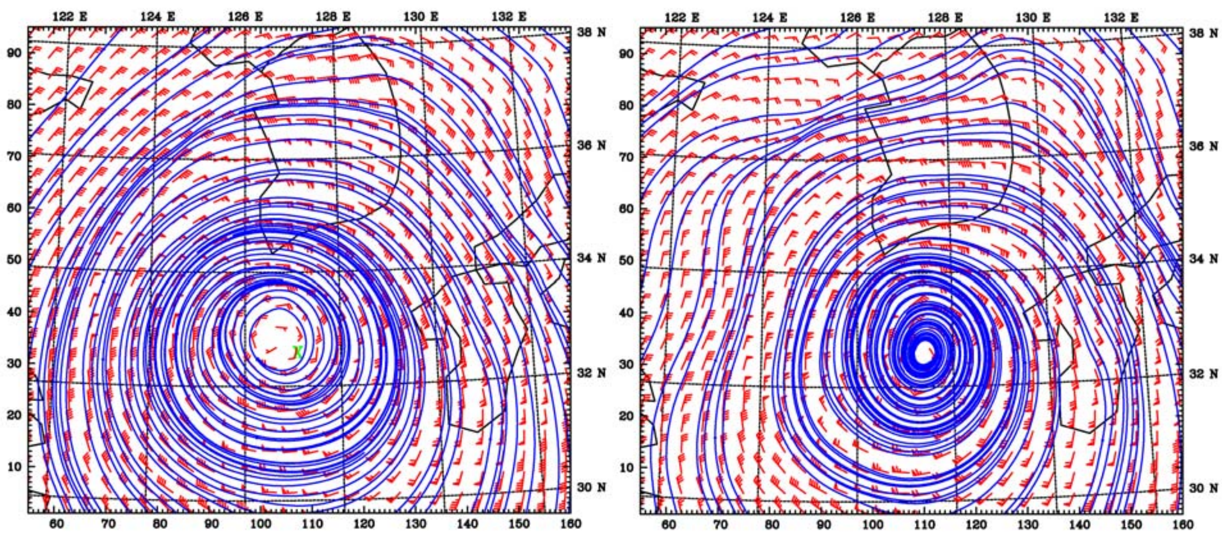

Fig. 4: 850-hPa streamlines and wind barbs at 00 UTC 31 August 2002: (a) CTRL, and (b) GTS_RA

5. Summary and conclusions

Using the recently developed WRF model and WRF 3D-Var system, we studied the impact of typhoon initial fields enhanced via conventional GTS data and Doppler radar data upon the initial vortex structure and subsequent track forecasts of Typhoon Rusa (2002). The most important results from this study are summarized as follows:

- WRF 3D-Var analyses improve typhoon forecast, compared with the experiment without data assimilation. Inclusion of the vertical velocity increments in the WRF 3D-Var analyses further improves the typhoon forecast.
- Typhoon initialization with Doppler radial velocities shows positive impact on the typhoon initial vortex structure and subsequent forecasts. As Doppler radar observations have very high resolution, assimilation of these data can adjust the typhoon vortex to the right position with improved vortex structure. Therefore, the typhoon forecasts using the initialization enhanced by radar data are also improved.

Reference

Barker, D. M., W. Huang, Y.-R. Guo, and Q. Xiao, 2004: A three-dimensional variational (3DVAR) data assimilation system for use with MM5: Implementation and initial results. *Mon. Wea. Rev.*, 132, 897-914.

Navon, I. M., X. Zou, J. Derber, and J. Sela, 1992: Variational data assimilation with an adiabatic version of the NMC spectral model. *Mon. Wea. Rev.,* **120**, 1433-1446.

Parish, D. F., and J. Derber, 1992: The National Meteorological Center's spectral statistical-interpolation analysis system. *Mon. Wea. Rev*., **120**, 1747-1763.

Richardson, L. F., 1922: *Weather Prediction by Numerical Process*. Cambridge University Press, London, 1922, 236pp.

Sun, J., and N. A. Crook, 1998: Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint. Part II: Retrieval experiments of an observed Florida convective storm. *J. Atmos. Sci*., **55**, 835-852.