Doppler Radar Data Assimilation in KMA's Operational Forecasting

BY QINGNONG XIAO, EUNHA LIM, DUK-JIN WON, JUANZHEN SUN, WEN-CHAU LEE, MI-SEON LEE, WOO-JIN LEE, JOO-YOUNG CHO, YING-HWA KUO, DALE M. BARKER, DONG-KYOU LEE, AND HEE-SANG LEE

During 2001–03, the Mesoscale and Microscale Meteorology Division (MMM) at the National Center for Atmospheric Research (NCAR) partnered with the Korean Meteorological Administration (KMA) and Seoul National University (SNU) to use Doppler radar data in the MM5 with the Weather Research and Forecasting (WRF) 3-dimensional variational (3D-Var) data-assimilation system. After case studies and one-month comparison experiments with and without radar data assimilation in 2004, the system proceeded to semioperational testing in 2005 and was implemented for full operational production in 2006. The case studies showed benefits of radar data assimilation, and further tests indicated that Doppler radar data assimilation in WRF 3D-Var performed robustly and improved rainfall forecasting.

The procedure for KMA Doppler radar data assimilation is rather sophisticated: it includes data preprocessing (quality control, error statistics, and formatting), assimilation with WRF 3D-Var, and analysis update cycling. The algorithms for direct assimilations of radial velocity and reflectivity are advanced and innovative. The transfer of the developed system from research mode at NCAR to operational mode at KMA has been very smooth and successful. With great efforts from all parties, KMA is running the advanced system operationally and benefiting Korea. The WRF 3D-Var Doppler radar data-assimilation system now resides in both NCAR and KMA and serves as a very useful tool for research.

AFFILIATIONS: XIAO, LIM, SUN, W.-C. LEE, KUO, AND BARKER—National Center for Atmospheric Research, Boulder, Colorado; LIM, WON, M.-S. LEE, W.-J. LEE, AND CHO—Numerical Prediction Center, Korea Meteorological Administration, Seoul, Korea; D.-K. LEE—School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea; H.-S. LEE—National Institute of Meteorological Research, Korea Meteorological Administration, Seoul, Korea
CORRESPONDING AUTHOR: Dr. Qingnong Xiao, NCAR/MMM, P.O. Box 3000, Boulder, CO 80307-3000
E-mail: Hsiao@ucar.edu

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INTRODUCTION TO DOPPLER RADAR DATA ASSIMILATION. Assimilation of high-resolution Doppler radar observations has long been recognized as an efficient way to improve short-range quantitative precipitation forecasting (QPF). Since the Weather Surveillance Radar 88 Doppler (WSR-88D) network in the United States was established, methods to assimilate Doppler radar data have been extensively explored. Although a lot of questions remain, research (including real-time experiments) through the past decade has yielded progress. Doppler radar data assimilation is showing significant promise now compared to its initial research stage in the early 1990s.

For Doppler radar data assimilation, 4D-Var and an ensemble Kalman filter have been actively researched in recent years but remain computationally expensive and thus impractical. However, 3D-Var is a feasible and advanced technique for Doppler radar data assimilation in operational applications. During the present decade, 3D-Var has been one of the most widely used techniques for operational data assimilation. Use of 3D-Var is a quick approach to adding Doppler radar data to operational forecasts. In addition to computational efficiency, 3-D Var offers a way to directly assimilate observations (radial velocity and reflectivity) that are not model variables through the use of the observation operators. Direct assimilation of radial velocity and reflectivity is an advantage of the variational method over the Newtonian relaxation nudging and optimal interpolation approaches, in which retrievals are required to produce model variables for assimilation.

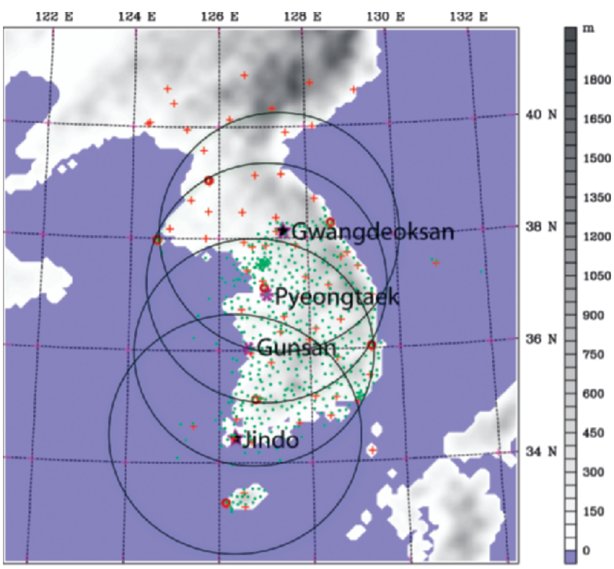

Fig. 1. The observations in the Korean Peninsula. The symbol "o" represents radiosonde station, "+" represents surface station, "•" represents automatic weather station (AWS). The two stars are two KMA S-band Doppler radar stations, and the two asterisks represent two NEXRADs of the U.S. military. The range of each Doppler radar observation is 200 km and is shown with a circle. The shading inside the Korean peninsula represents terrain height, with the scaling on the right of the figure.

There are three novel achievements in the Doppler radar data assimilation within WRF 3D-Var. First, we included the vertical velocity increments via a new balance equation, Richardson's equation, in the physical transform routine of the WRF 3D-Var system. With this development, the three-dimensional radial velocity can be assimilated into the analysis. Second, we used total water hydrometeors as a control variable and introduced partitioning of water vapor and hydrometeor increments in the 3D-Var system. Assimilation of reflectivity data can generate water hydrometeor analyses, which are balanced with other variables via microphysical process. Third, the Level II Doppler radar data (radial velocity and reflectivity) are directly assimilated into WRF 3D-Var analyses by minimizing the misfit between the observations and their model counterparts. No retrievals are needed. In our recent study for a squall-line case observed during the IHOP-2002 campaign, we applied the WRF 3D-Var system to 4-km resolution for multiple Doppler radar data assimilation, and improved QPF substantially with marginally greater computational cost than for the nonradar or single-radar data assimilation experiment.

In this article, we briefly describe the NCAR/KMA/SNU collaboration and show some testing and operational results.

KMA DOPPLER RADAR NETWORK AND DATA PROCESSING. There are several Doppler radars in and around the Korean Peninsula, including two Next Generation Weather Radars (NEXRADs) operated by the U.S. military (Fig. 1). In 2001, KMA operated only one S-band radar. This radar was installed in 1988 and was initially used only for monitoring rainfall systems, especially those from the Yellow Sea. As a result of the NCAR/KMA/SNU collaboration, KMA Doppler radar observations were applied to numerical forecasting operations.

During the collaboration, we developed radar data preprocessing for 3D-Var, which removes noise and ground/sea clutter, unfolds velocity, and performs data thinning. The Doppler radar data are thinned horizontally by interpolating them onto 0.2° × 0.2° latitude–longitude grids in each vertical elevation using NCAR software called Sorted Position Radar Interpolation (SPRINT). The maximum reflectivity is selected wherever the data coverage is overlapped by multiple radars. Sea and ground clutter are removed using a procedure that is based on the vertical gradient of reflectivity in the first few elevation angles. The radial velocity unfolding is performed using a 3-h forecast of the KMA regional model with 10-km resolution. We prepared radar data every 3 h for analysis/forecast cycling in KMA operational forecasts with the 10-km resolution model.

COMPARISON WITH/WITHOUT RADAR DATA ASSIMILATION. Along with developing algorithms for Doppler radar data assimilation in WRF 3D-Var, we conducted several case studies to evaluate their capability by assimilating radial velocity and both radial velocity and reflectivity. In early 2004, NCAR delivered the whole system to KMA. The fifth-generation PSU/NCAR mesoscale model (MM5) was KMA's operational model, configured with Kain–Fritsch cumulus parameterization, Reisner-2 microphysics, and MRF PBL parameterization. It is used for all results described in this article. After conducting several case studies to evaluate the developed system and analyze the impact of radar data assimilation, KMA performed comparison experiments for 33 days starting from 0000 UTC 26 August 2004. Parallel runs with and without Doppler radar data assimilation were carried out. Observations from three Doppler radars (Jindo, Gunsan, and Pyeongtaek, shown in Fig. 1) were assimilated in the Doppler radar data-assimilation runs during the period. These radar data-assimilation runs were designed with 3-h analysis and forecast cycling, and numerical forecasts lasted 12 h initialized at 0000 and 1200 UTC.

Figure 2 shows verification of the 3-h rainfall accumulation forecast against the KMA rain gauge and Automatic Weather Station (AWS) rainfall observations during the 33 days. For the light rainfall (threshold of 0.1 mm; Fig. 2a), radar data assimilation produces higher threat scores (TS) than the forecasts without radar data assimilation for all lead times. The BIAS scores (which measure the ratio of the frequency of forecasted events to the frequency of observed events) with Doppler radar data assimilation are reduced except at 12 h. In general, for heavier rainfall (threshold of 5 mm; Fig. 2b), Doppler radar data assimilation improves the QPF skill as expressed by TS and BIAS scores, except that the TS at 6 h is decreased and the BIAS score at 12 h is further deviated from 1. In addition to the one-month verification shown in Fig. 2, we also performed numerous retrospective case studies, including squall lines, fronts, hurricanes, and other convective storms. Overall, our experiments and verifications indicated a statistically significant positive impact of the Doppler radar data assimilation on the short-range QPF (0–12 h).

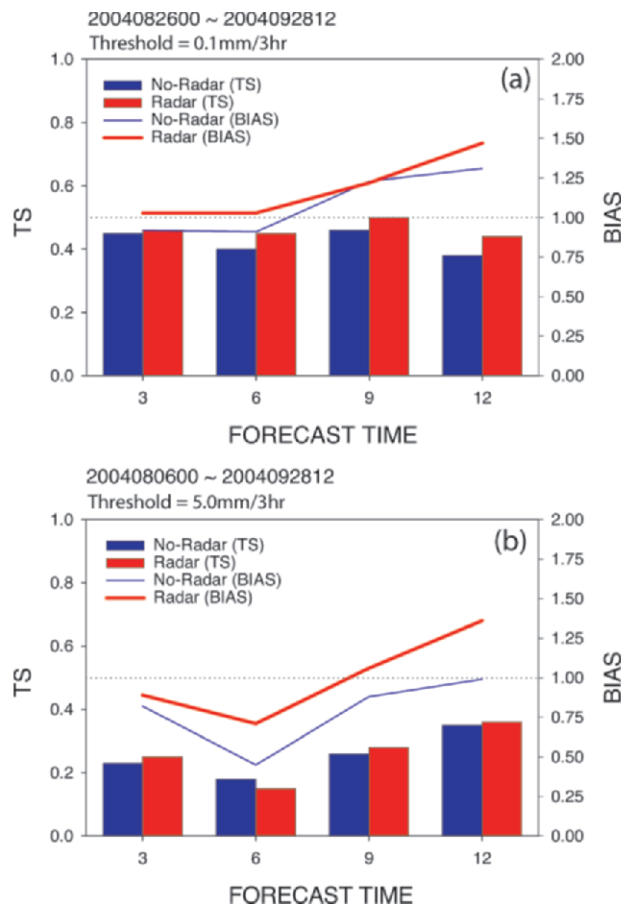

Fig. 2. The threat score (TS, bars) and BIAS score (solid lines) of the comparison runs for 3-h rainfall accumulation forecasts with (radar) and without (no radar) Doppler radar data assimilation: (a) threshold = 0.1 mm $(3h)^{-1}$; and (b) threshold = 5 mm $(3h)^{-1}$. (The blue bars and lines represent TS and BIAS scores in the no-radar data-assimilation runs, and the red bars and lines represent TS and BIAS scores in the radar data-assimilation runs).

SEMIOPERATIONAL AND OPERATIONAL RESULTS. In 2005, KMA updated its computation system. Doppler radar data were not regularly included in the assimilation at that time. In the summer of 2006, the observations from four Doppler radars in the Korean peninsula (shown in Fig. 1) were successfully included in the assimilation/forecast cycling of the KMA 10-km operational system. Here we report the verification results from the summers of 2005 and 2006 (June, July, and August).

Figure 3 shows the TS and BIAS scores for 3-h rainfall verification (with thresholds of 0.1 mm). All BIAS scores in summer 2005 have values larger than 1, indicating an overprediction of rainfall. In summer 2006, there was a tendency to underforecast rainfall within 12 h. The overall TS and BIAS scores in 2006 are better than the results of 2005, and the improvement after 12 h is more significant than during the first 12 h. Many factors could contribute to the variability between 2005 and 2006. However, the model configurations were the same in 2005 and 2006. Since the operational forecast in 2006 regularly included assimilation of Doppler radar data from four stations, the improved scores for 2006 are probably an indication of the positive impacts of radar data assimilation on the rainfall forecasts.

In addition to the improvement of rainfall forecasts, the overall pattern of the weather systems was better predicted in the summer of 2006 than during the summer of 2005. For example, the RMSEs of the 12-h geopotential height forecasts at 850 hPa were

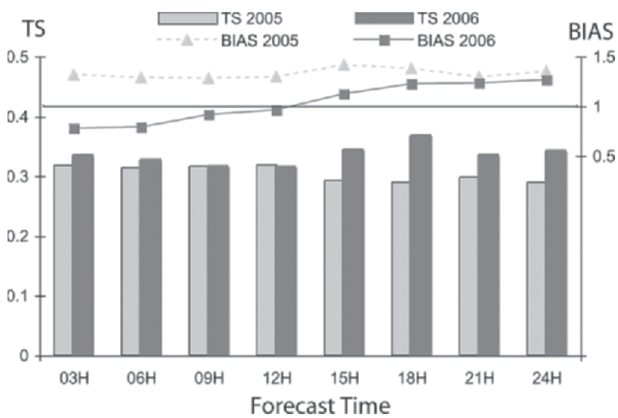

FIG. 3. The 3-h rainfall verification scores (TS and BIAS scores) with threshold of 0.1 mm for the summer (June, July, and August) of 2005 and 2006.

9.4, 10.1, and 8.8 m in June, July, and August 2006, respectively, compared to 13.2, 13.9, and 12.2 m in June, July, and August 2005. The reduced RMSEs are probably due to radar data assimilation.

LOOKING AHEAD. KMA planned to deploy more Doppler radars in the peninsula. In addition to the current four Doppler radars, Qsungsan radar was to be included operationally in KMA in the summer of 2007. We anticipate that short-range (< 1 day) forecasts of rainfall and other weather systems should be further improved with assimilation of more Doppler radar observations.

While Doppler radar data assimilation with 3D-Var is currently applied in KMA operational forecasts, we notice that a great deal of progress has been made using 4D-Var and ensemble Kalman filters for Doppler radar data assimilation. From a theoretical perspective there are several obvious advantages in favor of 4D-Var and ensemble Kalman filters. The main advantage is that forecast model is directly involved in 4D-Var and ensemble Kalman filter assimilations with flow-dependent analysis structure. We will gradually shift our resources to develop more advanced techniques so as to extract more useful information in KMA mesoscale analyses using data from the established Doppler radar network in the Korean peninsula. This new development will also benefit the research community.

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FOR FURTHER READING

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