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REAL-TIME ANALYSIS AND SHORT-TERM FORECASTING OF SNOWBANDS USING A MESOSCALE MODEL

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1. INTRODUCTION

High resolution mesoscale models, such as MM5, are potentially useful tools for predicting snowfall in the terminal area in the 1-12 hour range. However, despite improvements in model physics, there still exist significant discrepancies between the observations and model predictions of the timing, duration and amount of snowfall produced by snowbands. To improve the accuracy of the MM5 forecasts, high resolution datasets need to be analyzed and assimilated into the model initial conditions.

The objective of this work is to develop a real-time short-term forecasting system for airport applications during the winter storms. As the modeling framework, we have adopted the real-time four-dimensional data assimilation and short-term forecasting system (RTFDDA) developed at NCAR (Cram et al., 2001; Liu et al., 2002). Built upon a high-resolution MM5 and an observational nudging (Newtonian relaxation) scheme, the system assimilates observations from various sources continuously and provides updated 3-dimensional analyses and short-term forecasts in a cycling fashion. We wish to enhance the system for airport applications with a radar data assimilation component to incorporate multi-radar observations.

Techniques for assimilating radar observations into MM5 have been tested. In order to be more applicable to real-time operations, a less expensive method based on the grid nudging technique, is tested with RTFDDA. The radar data ingested are the real-time Level II radar observations in the Corridor Integrated Weather System (CIWS) NE domain.

Numerical experiments have been conducted using RTFDDA. Results from a case study are presented in the paper. The RTFDDA system with radar data assimilation was run in an operational demonstration during the winter of 2004. Preliminary results from the real-time test are described. The following two sections contain brief introductions to the real-time system, the CIWS observations and the radar data assimilation scheme developed for RTFDDA. Section 4 describes a winter storm case study, followed by preliminary results from the real-time opeations in Section 5.

2. THE MODELING SYSTEM

The RTFDDA system was initially developed for the Army as a quick cycling FDDA system to provide real-time local scale analyses and short term forecasts. The data assimilation engine of the RTFDDA system is based on observational nudging. Each observation is ingested into the model at the observed time and location, with proper space and time weights. The system runs in three-hour cycling mode and is cold started once a week. Currently, traditional observations (rawinsonde, metar, ship and buoy reports), as well as non-traditional observations (mesonet, aircraft reports, profilers and satellite wind) are nudged in this manner. NIDS VAD profiles can also be nudged at the radar sites.

There has been an extensive effort on testing and evaluating the RTFDDA system. Briefly, both RTFDDA analysis and short term forecasts appear to perform reasonably better than the simpler or coarse-resolution analyses and conventional cold-start model forecasts. The RTFDDA results describe additional details of local circulations forced by thermal contrasts and/or topographic influence of synoptic weather systems.

In the current operational systems, no cloud or precipitation observation is directly assimilated. Qualitative comparison of the model cloud and precipitation with satellite images and NCEP “STAGE V” surface precipitation analyses generally shows good cloud and precipitation distributions in the RTFDDA final analysis, indicating an improved interaction between the model dynamics and physical processes with the nudging of wind, temperature and humidity observations. However, verification also reveals the need for assimilating high resolution observations on the fine meshes.

3. ASSIMILATING CIWS DATA USING RTFDDA

Recently, real-time Level II radar observations in the CIWS NE domain have become available via the Collaborative Radar Acquisition Field Test (CRAFT, Droegemeier et al., 2002) network. The domain has

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more than 20 radars, and covers an area of approximately 1500km x 900 km. Three-dimensional mosaic reflectivity for the region, as well as radial velocity from the individual radars, are accessible in real-time. To produce the mosaic reflectivity, reflectivity observations from the individual radars are mapped to a common Cartesian grid, then they are combined to form a unified 3D reflectivity field (Zhang et al., 2002). The grid resolution for the mosaic reflectivity is 1 km in the horizontal and 0.5 -1 km in the vertical. The datasets are updated every 5 minutes.

Our goal is to enhance the RTFDDA system by fully utilizing the CIWS radar observations. As a first step, we have added a grid nudging scheme to assimilate the mosaic reflectivity data. The mosaic reflectivity is first converted to 3D rainwater or snow mixing ratio (q_r) field and interpolated to the model inner grids (grid 2 and 3). Then the mixing ratio field, together with the corresponding latent heat, are nudged on the two inner meshes. The data insertion are performed at an interval of 30 minutes on grid 2 and 15 minutes on grid 3 in the case studies. The scheme also includes an algorithm for adjusting the humidity field according to radar observations.

Previously we have found from simulated data experiments that both wind and thermodynamic fields are important for the evolution of snowbands. Nudging reflectivity alone for 6 hours has only marginal effect on the 3-6 hour forecasts. Given these results, one may expect very limited improvement without assimilating wind information from the radars. Nevertheless, assimilating reflectivity data in RTFDDA is a worthwhile attempt based on at least two considerations: (1) When the history of the storm is observed, continuous nudging may produce a cumulative effect. (2) RTFDDA is already assimilating some wind observations. The model wind field might be close enough to reality to support some of the assimilated q_r.

4. A CASE STUDY USING RTFDDA

A snowstorm occurred in the northeastern U.S. on December 11, 2002. The storm formed in Central Texas at the early hours of Dec. 9 and moved northeastward. The system started to show in the CIWS network around 0 Z of Dec. 11, 2002 and was covered by CIWS radars for more than 24 hours. Snowfall started in the NYC airports around 14 Z of Dec. 11. The system is associated with relatively strong large-scale forcing.

A three-grid configuration, with grid resolution of 3.3 km, 10 km and 30 km, is used in RTFDDA (Figure 2). The fine mesh centers in the New York City airports. The second grid covers an area similar to the CIWS NE domain, over which real-time radar observations are available. The mesh sizes for the inner and outer grids are 106x124, 79x157 and 84x98 points, respectiviely. There are 36 levels in the vertical. Model physics schemes, including Dudhia simple-ice microphysics, Grell CPS (on grid 1 and 2) and MRF PBL, are used.

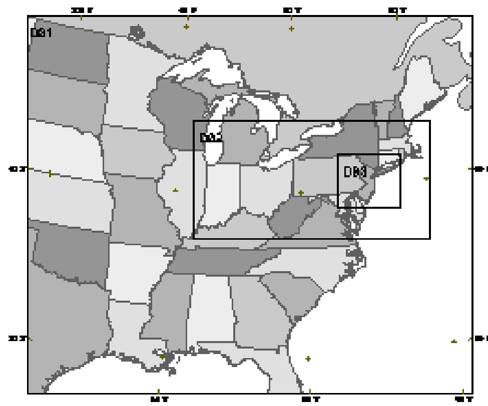

Fig. 1 The model grid used in RTFDDA for snowfall forecast in New York City area.

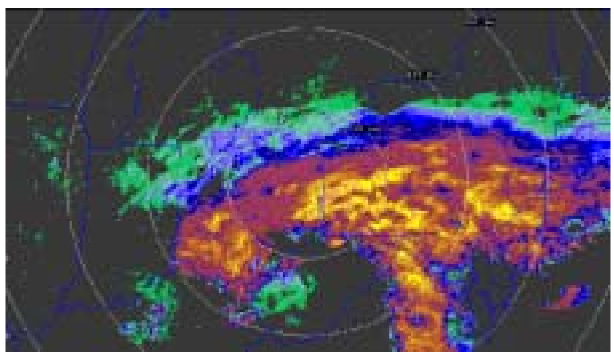

Fig. 2 Mosaic reflectivity data at 15 Z on Dec. 11, 2002.

Performance of RTFDDA without radar data

The model is cold started at 12 Z of December 9, 2002. At each 3 h cycle, a final analysis and a 12 h forecast is conducted. Due to the cycling method, the final analysis, 0-3 h forecasts, 3-6 h forecasts and 6-9 h forecasts from the many cycles each forms a continuous sequence of the storm evolutions.

The formation and general movement of the system is well simulated. When the storm moves into the CIWS domain (approximately same as model grid 2), the modelled system is slightly behind the observed storm. By 15 Z of Dec. 11, there are two major snowbands in the observations with the first one reaching NYC area (Fig. 2). The RTFDDA forecast at this time, however, shows only one principal band and no precipitation in northern New Jersey and NYC area. In the model forecast, there are some convective activities in the region a few hours earlier, but they dissipate quickly without producing any signficant snowfall.

A distinquished feature in the radar observed snowfall at the NYC airports is the two-band structure separated by a period of no snowfall (Fig. 3). When no radar data is used, the RTFDDA analysis, though significantly better than the cold start forecast (not shown), show a delayed (3-4 h) and much weaker first band. The second band is relatively well modeled. The 3-6 h forecasts from these analyses (without radar data) predict a further weakened first band (not shown).

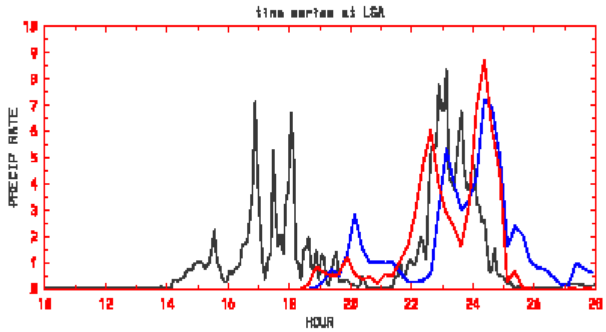

Fig. 3 Snowfall rate at New York La Guardia airport. Plotted are radar observations (black), RTFDDA analysis without CIWS data blue), and RTFDDA 3-6 h forecast with CIWS reflectivity nudging (red).

Effect of assimilating CIWS reflectivity data alone

The 3-6 h forecasts from RTFDDA with radar data assimilation show slightly earlier onset of both bands (Fig. 3). The magnitude of the first band is comparable to the 3-6 h forecast from RTFDDA without radar data (not shown). Since q_r is directly nudged, the model shows near-perfect snowfall during the assimilation stage when CIWS reflectivity is used. However this result does not last long into the forecast stage. No dramatic improvement by radar data is seen in the snowfall forecast at the La Guardia airport.

A further examination of the snow mixing ratio field reveals that when the reflectivity data alone (converted to q_r) are nudged, at the end of the assimilation the qr field is comparable to the observed. After the forecast period starts, a major portion of the added qr disappears within an hour, while a small effect remains. The 3-6 h forecast from RTFDDA assimilating CIWS reflectivity shows a slightly better agreement with the observations, especially at the northern and northeastern edges of the storm.

The RMS error and correlation coefficient between the observed and forecast snow mixing ratio fields are calculated. Fig. 5 shows that the forecast has an improved correlation with the obsevations when the CIWS reflectivity is nudged.

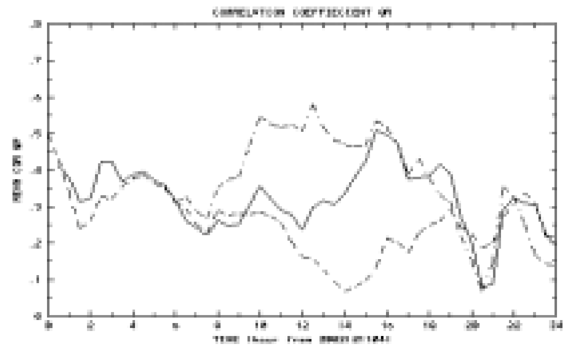

Fig. 5 Domain-average correlation between the modelled (3-6 h forecasts) and observed q_r fields. The curves are for RTFDDA without CIWS data (solid); RTFDDA without any data asaimilation (dashed); and RTFDDA with CIWS data nudging and observational nudging (dotted dashed).

Effect of assimilating latent heat

Generally, slightly more improvement is seen when a fraction of the latent heat is added to the model in addition to nudging q_r. Nudging the latent heat has a significant and lasting effect on the temperature and wind fields. The changes in temperature and wind, while noisy, are in the direction of reproducing the observed snowband (which is missing in the model forecasts). The vertical velocity produced by latent heat add-back is in general consistency but not in exact balance with the added qr. As a result, there is a period (~3 h) of spin-down/spin-up after nudging: a time of hydrometeor fallout and rebuilding. There are also times when the latent heat is added to the grid points where q_r is observed, it induces some local vertical motion instead of persistent, organized structures, thus limiting the overall positive effect of latent heat nudging. Effective filtering of the latent heat may be needed to further improve the forecast in a consistent manner.

Effect of adjusting water vapor based on reflectivity

Excessive evaporation can be a significant cause for error in the RTFDDA forecast. An experiment is therefore conducted to adjust the model water vapor in addition to nudging the reflectivity and adding the latent heat. Using an estimated cloud based height, the adjustment scheme gradually saturates the regions of upward motion above the cloud base where q_r is observed. Results from the test show that even with the adjusted water vapor, the model forecast lacks the dynamics to support the added q_r. Instead, the resultant heating from the additional water vapor excites new convective activities and causes noise in the forecasts. A more sophysticated water vapor adjustment or cloud analysis scheme needs to be tested.

5. RTFDDA DEMONSTRATION IN WINTER 2004

As a real-time demonstration, the RTFDDA system with radar data assimilation was run operationally during the period of January 31 – March 19 of 2004. To utilize the existing infrastructure, the system was run in parallel to the operational RTFDDA at the Army's Aberdeen Testing Center in Maryland (ATC). The same model grid configuration (triply nested grid with resolution of 3.3 km, 10 km and 30 km) and physics options were used in the parallel and operational runs. The fine mesh centers near the Baltimore / Washington International Airport (BWI), and the La Quaidia Airport (LGA) is covered by the 10 km grid. The observations used in each cycle of the operational run (dubbed Control run hereafter) were duplicated and used in the parallel run (dubbed Parallel run). The only difference between the parallel and control runs was the CIWS mosaic radar reflectivity data assimilated in the parallel run.

Five major storm events and several smaller storms were recorded in the CIWS domain during the period. The RTFDDA run was stable, although there were short, intermitten breaks in the radar data flow. For each 3 h cycle, 3-h data assimilation and a 9 hour forecast were performed in the parallel run. The rain/snow mixing ratio field (derived from radar reflectivity) was nudged and a fraction of the latent heat associated with the mixing ratio field was added to the model during the data assimilation period. No water vapor adjustment was done in the real-time demonstration experiment.

Statistical verification has been performed for the parallel and control runs for the entire demonstration period (20040131 – 20040319), as well as for the episodes when precipitation occurred in the model grid. Approximately 1/3 to 1/2 of the total hours of operation were characterized by some precipitation in the CIWS domain. Model analyzed and forecast fields of temperature, humidity, wind speed and wind direction are verified against surface and upper-air station observations on each domain. The precipitation fields are verified using radar observations as well as observations from tipping-bucket rain/snow gauges. The general skill of RTFDDA for winter storms and the impact of radar data assimilation are being evaluated.

Verification vs. surface station observations

Tables 1 gives the mean bias and rms errors of temperature, wind speed and wind direction from the parallel and control runs, verified against the surface station observations on the 3.3 km grid for the entire demonstration period. Only the surface observations within 10 minutes of the model output time (hourly) are used in the verification. At each model output hour, approximately 20 observations in the inner grid are used in verification. These verification observations have been used in the model analysis but not in the forecasts.

It is found that the parallel run produces surface temperature fields that agree better with observations, especially during the forecasting stage. On the other hand, it gives larger statistical errors in the wind speed and direction fields than the control run. As the reflectivity data are nudged, the model thermal fields are improved through more accurate specifications of the microphysical and radiative processes. Table 1 shows that this improvement of temperature carries through the forecast period. On the other hand, the radar data assimilation may have induced some small-scale circulations that do not agree well with the surface observations, thus degrading the wind verification. A verification of the model wind field with the radar radial velocity data will be done later.

The diurnal cycle of the verification statistics (Figure 5) indicates that the improvement in temperature verification and the error increase in wind verification do not depend on the hour of the day. In fact, the verification for individual storm cases shows that the impact of radar data is more dependent on the stage of the storm. A larger improvement in temperature verification is seen during stronger precipitation period.

T (K)	Parallel Run		Control Run	
	Bias	**Rms**	**Bias**	**Rms**
final	-0.19	1.36	-0.41	1.36
0-3 h fcst	-0.25	1.58	-0.60	1.74
3-6 h fcst	-0.41	2.01	-0.91	2.25
6-9 h fcst	-0.52	2.15	-1.07	2.44

Ws (m/s)	Parallel Run		Control Run	
	Bias	**Rms**	**Bias**	**Rms**
final	0.12	2.00	0.11	1.74
0-3 h fcst	0.31	2.26	0.17	1.93
3-6 h fcst	0.21	2.51	0.21	2.32
6-9 h fcst	0.23	2.53	0.21	2.34

Wd (degree)	Parallel Run		Control Run	
	Bias	**Rms**	**Bias**	**Rms**
final	4.47	33.50	3.69	32.43
0-3 h fcst	4.61	38.32	3.62	37.37
3-6 h fcst	5.56	42.77	4.96	42.75
6-9 h fcst	5.48	43.90	4.05	43.79

Table 1. Verification statistics for surface temperature (T), wind speed (Ws) and direction (WD) during 20040131 – 20040319.

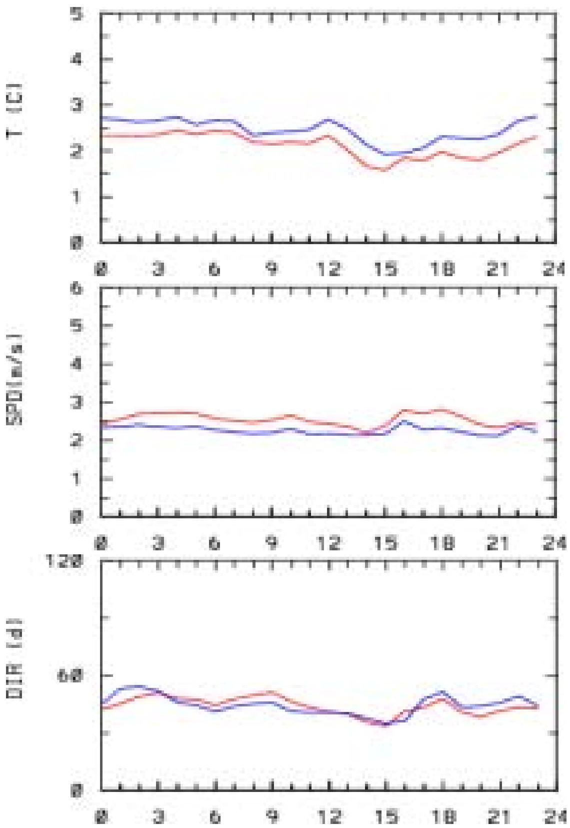

Figure 5 RMS errors in the 6-9 h forecast of T, Ws and Wd. Each value is a 7 week-long average for the hour of the day. Red: Parallel run with radar data nudging. Blue: the control atc operational run.

Verification of the precipitation field

The 3D snow mixing ratio (qr), as well as the ground precipitation from model grid 2 and 3 are verified using the CIWS radar observations. Please note that the original CIWS data have a higher spatial and temporal resolution than the qr data that are actually assimilated into the model. Figure 6 shows the mean RMS error and correlation coefficient between the modelled and radar observed qr fields, as a function of the forecast hour. The verification is only done for the cases when a moderate level of qr is observed and in the area where radar observaions are available.

Due to unexpected computer problems, the original MM5 output of forecasts from the control ATC operational run were not archived. Only the final analyses and verification pairs were saved. Therefore, on Figure 6, the qr verification from the control run is only valid for the analysis period. The short-term forecasts from these operational analyses typically have a similar or slightly less skill for precipitation forecast, so the qr verification of the final analysis of the control run may be viewed as the baseline skill in precipitation forecasting by the operational RTFDDA.

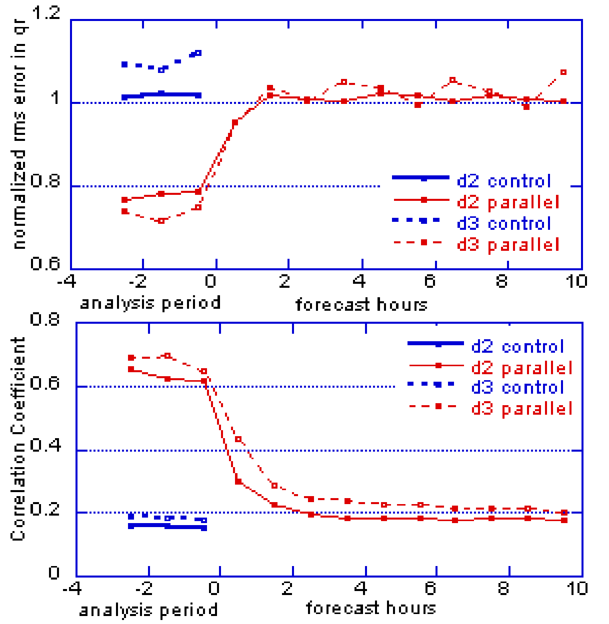

Figure 6 The RMS error and the correlation coefficient between the modelled and radar observed qr fields for the control run (blue) and parallel run (red), verified on model grid 2 (solid) and 3 (dashed).

Figure 6 shows that the prediction skills of the parallel run for the precipitation field decrease rapidly with forecast time. In the final analyses (data assimilation period), the modeled qr field follows the radar observations relatively well, as indicated by the relatively high levels of correlation coefficient. The correlation coefficient also shows improved qr forecasts within 3 h after the data assimilation. However, little impact of radar data is seen in the 3D qr field 3 hours after the data assimilation,

The qr verification demonstrates the usefulness of the radar data nudging scheme in blending the qr observations into the model analyses, and in improving the skills for 0-3 h forecasts. Little improvement by radar data is seen in qr forecasts beyond 3 hours.

Snowfall forecast at the airports: An example

A snowstorm event occurred in the northeastern U.S. on March 16, 2004. The snowfall rates at BWI and LGA airports from the parallel run (RTFDDA with radar data assimilation) are plotted in Figure 7. Also plotted are the snowfall from the final analysis of the control run. The radar data of precipitation rate at the two airports are derived from the lowest level reflectivity, and have a frequency of 5 minutes.

At both airports, the onset of precipitation in the control analyses lags behind the observation by 1-2 hours. The analysis field in the parallel run follows the observed trend very well, and shows improvement over the control analysis. There is still some positive impact from the radar data in the 0-3 h forecasts. The 3-6 h forecasts show no evident improvement of skills.

The temporal variations in model output are rather smooth. This is probably due to the smoothing effect of the model, as well as to the hourly output frequency. The performance of the system at the airports for this case is typical of its forecast skills for airport snowfall during the multi-week demonstration.

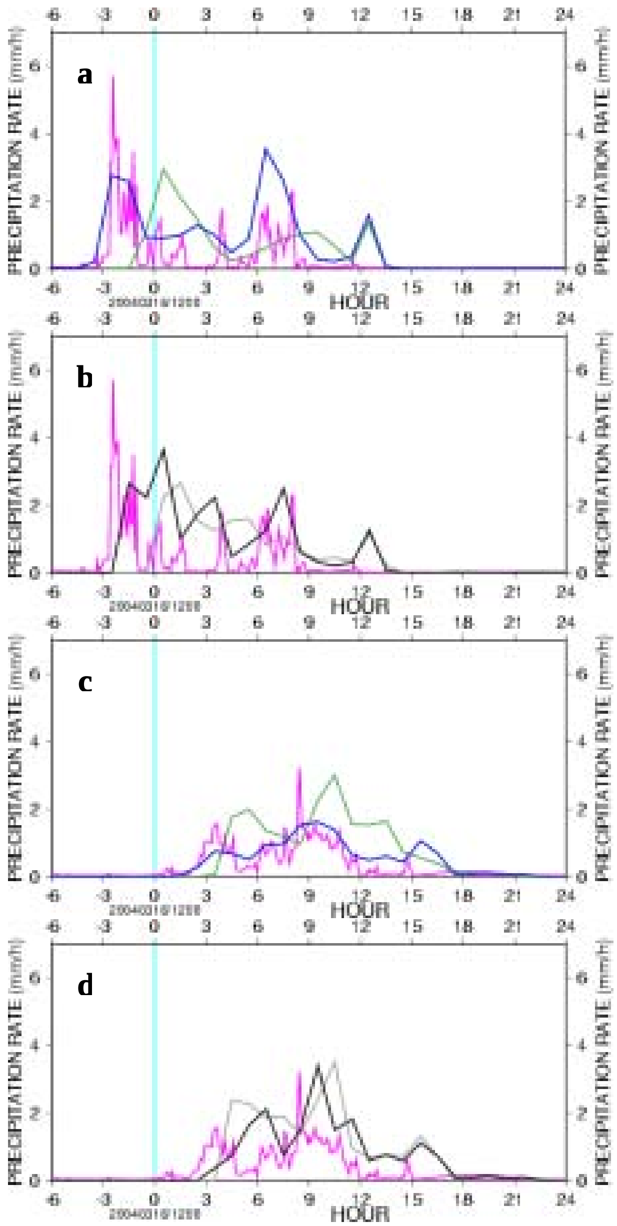

Fig. 7 Precipitation rates at BWI (a, b) and LGA (c, d) during the March 16, 2004 snowstorm event. Pink: radar observation. Green: RTFDDA analysis without radar data. Blue: RTFDDA analysis with radar data. Black: 1-3 h forecast from RTFDDA with radar data. Grey: 4-6 h forecast from RTFDDA with radar data.

6. SUMMARY

The RTFDDA system that NCAR developed for Army Test Ranges was tested for short-term forecast of snowfall. A radar data assimilation scheme based on nudging was added to RTFDDA for assimilating level II data from multiple radars. Data ingest modules were developed to make use of the CIWS mosaic reflectivity datasets. The system was designed to run efficiently in real-time.

Case studies of winter storm events show that the RTFDDA system was skillful in predicting the storm's occurrance, though not very accurate at predicting the individual bands. Some improvement was achieved by nudging the CIWS reflectivity data. Effect of assimilating Level II radar reflectivity is evaluated in a 7-week real-time run, which demonstrates the usefulness of the radar data nudging scheme in blending the qr observations into the model analyses, and in improving the skills for 0-3 h precipitation forecasts. However, nudging reflectivity produces little improvement in qr forecasts beyond 3 hours.

Additional case studies will be conducted to improve the radar data assimilation scheme. The future work will focus on correctly specifying the water vapor and wind fields. Methods for adjusting moisture field and assimilating radial velocity data will be explored. Even though the present RTFDDA system assimilates wind observations from surface and upper air stations, profilers, etc., the data are insufficient for accurately specifying the wind fields at scales that are important for individual snowbands. To predict the snowbands, correctly modelling the vertical motion field is crucial.

ACKNOWLEGEMENT

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