5.8 ASSIMILATION OF RADAR DATA FOR SHORT TERM FORECASTING OF SNOWBAND USING A MESOSCALE MODEL: SIMULATED DATA EXPERIMENTS

Mei Xu[1], N. Andrew Crook and Roy Rasmussen

National Center for Atmospheric Research[2], Boulder, Colorado

1. INTRODUCTION

High resolution mesoscale models, such as the PSU/NCAR mesoscale model (MM5), are currently being tested for real-time, short term forecasting of snowfall in the terminal area. Previous studies have shown that MM5 has limited skill in forecasting the occurrence of snowstorms in the 1-12 hour time scale. Key issues are the timing, duration, and amount of snowfall predicted by MM5. For example, correctly predicting a 30-minute break between two snowbands can be crucial for airport deicing decision making.

One way to improve the MM5 forecast of snowfall is to assimilate high resolution observations into the model initial conditions. Doppler radars are at present the only observing system capable of sampling the detailed patterns of the snowbands. With increasing computer speed and network capability, it is reasonable to expect that, in a few years, high resolution radar observations covering the spatial and temporal passage of entire winter storms will become available to the forecasting community in a real time fashion.

Techniques that can effectively assimilate radar data into MM5 are explored in this work. Using simulated data and real data, we have previously tested the feasibility of using the four-dimensional variational data assimilation (4DVAR) technique to assimilate Level II radar data into MM5 using a 5 km model grid (Xu et al. 2001). To be more applicable to real-time operations, the less expensive method, Newtonian Relaxation or nudging, is emphasized here. The nudging method, which has been shown effective in assimilating synoptic scale observations (Stauffer and Seaman, 1990), is relatively untested for high resolution data and model grids. As a first step, Observation System Simulation Experiments (OSSE) are conducted for a snowstorm event, using simulated data that emulate analyses that could be derived from Doppler radar data. The performance of the MM5 nudging (MM5-FDDA) system is evaluated, especially in terms of its ability to recover the unobserved fields, and the impact on 1-12 hour forecasts. Preliminary results of the OSSEs using the nudging method are presented in this paper.

1. Corresponding author address: Mei Xu, NCAR/RAP, P.O. Box 3000, Boulder, Colorado 80307-3000. E-mail: meixu@ucar.edu

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2. THE TECHNIQUES

The 4DVAR approach of data assimilation is to find the model variable fields by fitting a dynamical model to the data over an assimilation window. The best fit to the data is found by minimizing a cost function which represents the difference between the model solution and the data. The 4DVAR method is a powerful tool to retrieve the unobserved fields simultaneously within the model constraints. However, the 4DVAR method is numerically complicated, and computationally expensive.

In contrast, the Newtonian relaxation or nudging method is numerically simple. The approach is to relax the model state toward the observed state by adding, to one or more of the prognostics equations, artificial tendency terms based on the difference between the two states. The model solution can be nudged toward either gridded analyses or individual observations.

Given the three-dimensional nature of radar data, analysis nudging is considered here. Before nudging can be performed, 3-dimensional analyses of wind, moisture and thermal fields need to be obtained from radar data as well as other available observations. Doppler radars directly observe the reflectivity and radial velocity. Many methods have been developed for recovering the thermodynamical and microphysical fields from radar observations. For example, using empirical formula, the reflectivity can be converted to the rain/snow water mixing ratio (q_r) field. By reversing the microphysical scheme, the water vapor (q_v), cloud water/ice (q_c), and latent heating fields can then be estimated. While a radar data analysis is not included in the OSSEs, using simulated data, we are able to test the impact of nudging different combinations of the fields that may be obtained from radar analysis.

3. EXPERIMENTAL DESIGN

This case study is based on a snowstorm event that occurred on December 10, 1997 in the New York City area. The storm system developed on the Great Plains in association with a front and extratropical cyclone. It then moved northeastward and produced heavy precipitation in the midwestern states on December 10, 1997. The storm entered the New York City area around 16Z on December 10 and moved out and dissipated by 6Z on December 11. Well-defined snowband structures were the dominant features of this storm.

The numerical simulations are conducted using a two-way interactive nested-grid nonhydrostatic MM5 (Grell et al. 1994). The grid sizes are 105x97, 97x97 and 97x97 respectively for the 3 nests (Fig. 1), and the grid increments are 45 km, 15 km and 5 km. There are 20 vertical levels. A high resolution PBL scheme and the Dudhia explicit moisture scheme with simple ice are used.

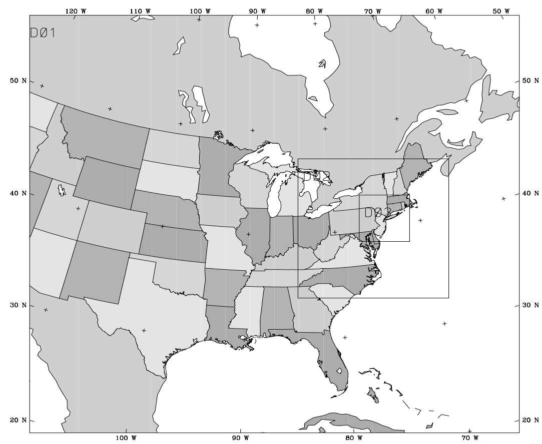

Figure 1 Domain configuration used in MM5 simulations.

The simulated radar data used in the OSSEs are obtained from an MM5 control simulation of the event. The control simulation starts from 97121000 and continues for 30 h to 97121106. It reproduced well-defined snowbands that move across the inner grid during 97121015-97121106. The simulated fields at 97121012-97121106 (simulation time of 12 h-30 h) are used as observations for data assimilation and forecast verification in the nudging experiments.

The nudging simulations start from 12Z of Dec. 10, 12 hours later than the control simulation. An NCEP analysis at 97121012 is used as the first guess of the initial conditions to be corrected in the assimilation experiments. An 18 h simulation without nudging is first conducted from these first guess initial conditions. Without data assimilation, the 'first guess' simulation departs considerably from the control simulation, especially in the fine scale structure of the snowbands.

Analysis nudging is performed on the two inner grids to improve the simulation. We have found that a relative large area of data coverage is necessary because of the snowbands movement (to the northeast at a speed of 10-15 m/s) and the need to cover them for 6-18 hours. The analysis fields are assumed available at an interval of one hour on grid 2 and 30 minutes on grid 3.

4. RESULTS OF THE NUDGING EXPERIMENTS

A set of five assimilation experiments are first conducted by nudging various fields that could be obtained from a radar analysis. In all five runs, nudging is conducted on grid 2 and 3 for 6 hours, from 12Z (t=0) to 18Z (t=6 h), followed by a free forecast for 12 h (to t=18 h). Comparison of the results from these experiments reveals the relative importance of assimilating the various fields.

Domain-averaged root-mean-square (RMS) errors in the nudging simulations are calculated from the deviation of the simulated field from the 'observed' field. Table 1 lists the RMS errors in the nudging simulations at the end of nudging (t=6 h) and after an additional 6 h forecast (t=12 h). The values in Table 1 are scaled by the RMS errors in the no-nudging simulation and therefore represent the percentage of error un-corrected by data assimlilation. The statistics are calculated for the inner points on grid 2 to avoid lateral boundary effect. Similar values are seen for the points on grid 3.

Examining the retrieveal first, Table 1 shows that when only q_r is assimilated, the nudging has little effect on the wind, temperature and moisture fields. After 6 h nudging, more than 95% of the errors in u, T and q_v remain uncorrected. Although q_r is successfully nudged toward the observation, its error increases rapidly in the forecast period due to the incorrect wind and mass fields. The rate of error growth is close to that of a simulation in which q_r is inserted directly at 18Z (not shown). Further examination shows that nudging q_r does produce some correct local structures in the temperature field, but the effect is minimal. Increasing the length of the nudging period slightly improves the retrieval of $q_{v.}$ However, the error level is still around 90% after 12 h nudging of q_r.

Table 1: Error Statistics for the nudging experiments.

EXPERIMENT	End of Assimilation				6 h Forecast Time			
	e(u)	e(T)	e(q_v)	e(q_r)	e(u)	e(T)	e(q_v)	e(q_r)
First Guess Simulation: No nudging	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
EXP1: Nudging q_r	1.00	0.97	0.95	0.21	0.99	1.00	1.01	0.91
EXP2: Nudging u, v, q_r	0.07	0.79	0.76	0.14	0.59	0.66	0.62	0.53
EXP3: Nudging u, v, q_r and T	0.04	0.04	0.64	0.07	0.34	0.34	0.50	0.31
EXP4: Nudging u, v, q_r and q_v	0.05	0.49	0.06	0.08	0.32	0.35	0.29	0.23
EXP5: Nudging T, q_r and q_v	1.04	0.11	0.07	0.08	0.82	0.68	0.82	0.80

When both wind components and q_r are nudged, the model fields of u, v, and q_r are fitted to the data effectively during the nudging period. The RMS errors in T and q_v are also reduced, but a major part of T and q_v are not retrieved (Table 1). During the forecast period, the errors in u, v, and q_r increase rapidly in the first 3 h, and then gradually flatten. The 6-12 h forecast errors of u and q_r remain at 40-70%. Compared to the run without nudging, considerable improvement is seen in all the forecast fields. As discussed later, the fine scale structures of the snowbands are clearly improved.

Significantly more error reduction is achieved when either T or q_v is used in the nudging (EXP3, 4). After 6 hours of nudging u, v, q_v and q_r, the RMS error in T is reduced to 49% of its no-nudging value (Table 1). All the forecast fields are improved. The error growth rate of q_r in EXP3 and EXP4 remains relatively low for most of the 12 h forecast period (Fig. 2a).

In the case that wind information is withheld, nudging T, q_v and q_r for 6 h does not retrieve the wind (EXP5, Table 1). Errors grow fast in the forecast stage. The 6 h forecast fields show larger errors than those in EXP2.

In EXP3 (nudging u, v, T and q_r), an additional error reduction (from 0.64 to 0.49) in the retrieved q_v can be achieved by increasing the assimilation window length from 6 h to 9 h. This improved retrieval leads to improved forecasts of all fields including q_r (Fig. 2b). Additional improvement of the retrieval and forecast can also be achieved by extending the assimilation length for EXP4 when nudging u, v, q_v and q_r (not shown).

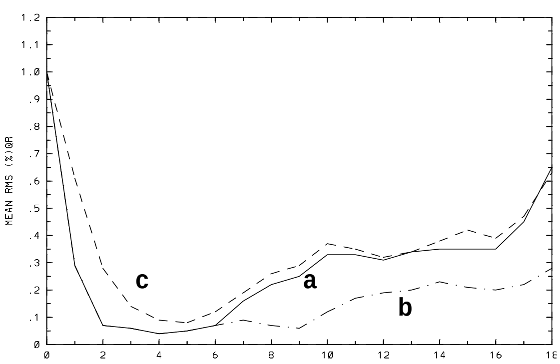

Figure 2 The RMS error in q_r vs. simulation time. (a) 6 h nudging of u, v, T and q_r; (b) 9 h nudging of u, v, T and q_r; and (c) 6 h nudging of u, v, T and q_r using G_α=6x10^{-4}s^{-1}.

The nudging coefficient G_α determines the relative magnitude of the nudging term. Under simplified conditions, the model state approaches the observed state exponentially with an e-folding time of $(1/G_\alpha)$. Therefore relatively large G_α should be used to nudge high frequency data. On the other hand, G_α should be small such that the nudging term is small compared to the physical forcing terms in the prognostic equations. A value of 2x10^{-3} s^{-1} is used in the experiments discussed above. Fig. 2c gives the result of nudging u, v, T and q_r using a smaller coefficient of 6x10^{-4} s^{-1}. A slightly smaller error is achieved with G_α=2x10^{-3} s^{-1} for this specific case.

The impact of data assimilation is also seen in the predicted snowfall rates at specific locations. Fig. 3 indicates that nudging, especially when q_v is available in addition to u, v and q_r, improves the snowfall rate forecast at La Guardia airport. The snowfall at the airport starts at approximately the end of nudging period (t=6h). The lower snowfall rate around t=10 h in the control simulation is the result of a gap between two snowbands. This feature was present in the real observations from KOKX radar and the snowgage at La Guardia airport. Without nudging, the gap is not forecast (Fig. 3b). With 6 h nudging of u, v, q_v and q_r, the gap is well predicted (Fig. 3d).

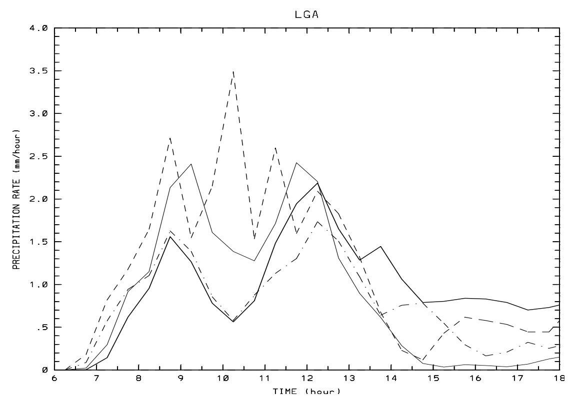

Figure 3 The snowfall rates at La Guardia airport from (a) control simulation (heavy solid); (b) first guess simulation without nudging (dashed); (c) 6 h nudging of u, v and q_r (thin solid); and (d) 6 h nudging of u, v, q_v and q_r (dotted dashed).

The overall intensity and location of the observed (control simulation) and forecast snowbands at 6 h forecast time (t=12 h) are shown in Fig. 4. In the observation, there is one major snowband and the center of the snowband is situated at New York City. In contrast, the no-nudging forecast shows several heavy snowfall centers and the northern edge of the snowfall has moved further north than in the control. When 6 h nudging is performed, the forecast snowband is clearly closer to the control one in both intensity and location, demonstrating a positive impact of the data assimilation (Fig. 4c,d). On the other hand, significant error is present in the forecast when only u, v and q_r are nudged.

5. SUMMARY AND FUTURE WORK

Observing System Simulation Experiments have been conducted to test the feasibility of using MM5-FDDA (nudging) system to assimilate radar-type analyses for snowbands. The analysis data are assumed available on a 5 km grid (480kmx480km) every 30 minutes and a 15 km grid (1400kmx1400km) every hour for 6 hours. Preliminary results show that it is possible to enhance 1-12 h MM5 forecasts of snowbands by nudging radar analysis for 6 hours. With analysis of two wind components and rain/snow water mixing ratio, nudging has some limited

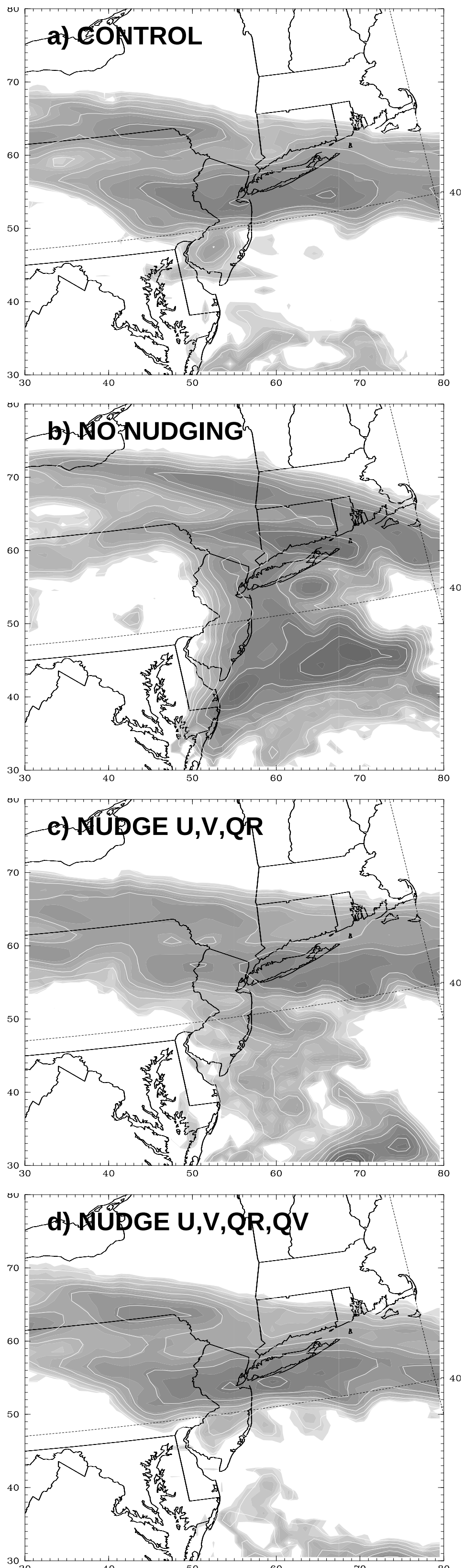

Figure 4 Column-average reflectivity at 6 h forecast time. (a) control simulation; (b) forecast from first guess without nudging; (c) forecast after 6 h nudging of u, v and q_r; and (d) forecast after 6 h nudging of u, v, q_v and q_r.

capability to recover the unobserved fields (e.g. temperature and water vapor) and improve the subsequent forecast. When either the temperature or water vapor field can be obtained from the analysis before nudging, both retrieval and forecast are improved considerably.

It should be pointed out that there are a few important limitations in our present experimental design which need to be overcome before any conclusion about real-time snowband forecasting can be made.

(1) Only one case study has been conducted. The results may be case dependent.

(2) The snowband structures in the simulated data may not be fully representative of real snowbands. It has also been recognized that when the same model is used for both observing system simulations and for subsequent assimilation and forecasts, the OSSE tends to be overly optimistic.

(3) The impact of observational error and data void has not been considered. In reality, significant errors exist in the observed and analyzed fields. Furthermore, it is assumed that both u and v wind components are observed in addition to the radar reflectivity.

Before real-data experiments can be conducted, OSSEs are still an effective way to explore the techniques to assimilate radar data for forecasting snowbands. Additional and more realistic OSSEs using nudging will be carried out in the following months. Special effort will be devoted to thermodynamic and microphysical retrieval schemes in order to estimate q_c, q_v and T. Sensitivities of the retrieval and forecast to data coverage and observational errors will be tested. We will also compare the results with other techniques, such as 4DVAR, 3DVAR and ensemble Kalman filter. The advantage and disadvantages of the techniques and their most suitable forecast range and resolution will be investigated.

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