Application of MM5/3DVAR at High Latitude: Resolution Sensitivity

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1. Introduction

In numerical weather prediction (NWP), data assimilation systems are used to provide a best estimate of the atmospheric state—the analysis—at a given time from a range of observation systems, supplemented with information from previous forecasts or analyses, error statistics, and laws of physics. The variational approach has the ability of assimilating observations through constraint of balance equations (3DVAR, e.g., Courtier et al. 1998; Lorenc et al. 2000) or even the numerical forecast model itself (4DVAR, e.g., Kalnay 2003). The data assimilation component plays a particularly important role over regions where conventional observations are sparse, such as the Arctic or Antarctic.

Recently, as reported by Barker et al. (2004), a 3DVAR system has been developed by the National Center for Atmospheric Research (NCAR) for use with the Fifth Generation Penn State University (PSU)/NCAR mesoscale model (MM5). We apply the MM5 3DVAR assimilation system over high latitude areas of the Arctic to attempt to improve mesoscale weather prediction and small scale climate analysis in this region.

Among many factors that could affect the efficiency of MM5/3DVAR in data analysis and weather forecasting, the resolution sensitivity is emphasized in this study. Horizontal grid resolution has been found by other investigators (e.g., Mass et al. 2002) to have significant impacts on mesoscale numerical weather prediction. For example, Mass et al. (2002) concluded that the decrease of grid spacing from 36 to 12 km clearly improved the forecast in precipitation, 10-m wind, 2-m temperature, and sea level pressure. However, a similar decrease in grid spacing to 4 km showed only small improvements and a limited impact on traditional objective verification scores, though increased mesoscale detail was evident in the forecasts. In applying the MM5 model simultaneously with the NCAR 3DVAR system over the high latitude areas for mesoscale weather studies, it is obviously important to understand the extent and the nature of the impacts of horizontal resolution on the 3DVAR analysis and the MM5 forecast.

Numerical experiments have been conducted to investigate the resolution sensitivity of the application of MM5/3DVAR system over high latitude areas and the Arctic region. Cases in all four seasons are examined. A pan-Arctic domain is used for winter and summer cases and an Alaska regional domain is used for spring and fall cases. Numerical experiments are carried out at two different horizontal resolutions: 60 and 30 km for the pan-Arctic domain (PARC, Figure 1a), and 45 and 15 km for the Alaska domain (AK, Figure 1b).

2. MM5/3DVAR System

The standard MM5 model accommodates four-dimensional data assimilation (FDDA) via Newtonian nudging (analysis nudging or observation nudging; Stauffer and Seaman 1990). All the simulations in this study use the Grell (1994) cumulus parameterization and the Reisner *et al.* (1998) explicit microphysics scheme without graupel. The Oregon State University (OSU) land surface model (LSM, Chen and Dudhia 2001), Hong and Pan (1996) planetary boundary layer (PBL) scheme, and Dudhia (1989) 2-stream radiative transfer formulation are also used. Initial atmospheric conditions are obtained from the NCAR/NCEP reanalysis, and are enhanced by surface and upper-air observations through

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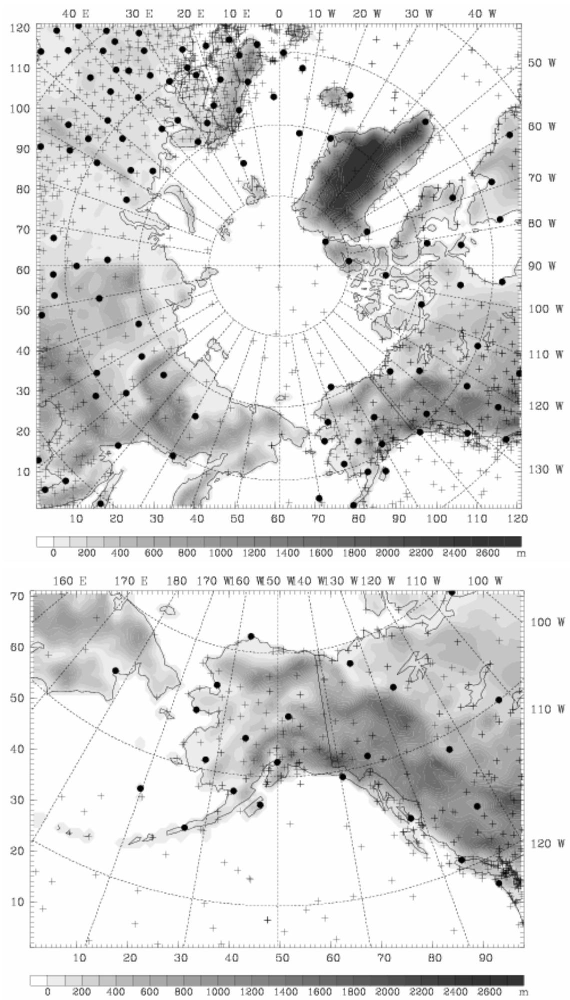

a)

b)

Figure 1 Pan-Arctic domain (a) and Alaska regional domain (b), with terrain height in shades. Solid circles stand for sounding stations and plus signs stand for surface stations.

objective analysis using the standard suite of MM5 preprocessing programs.

In this study, the background error correlation length scale has been tuned for mesoscale use in our cases so that the 3DVAR analysis produces reasonable analysis increments. Only the conventional surface and upper-air observations are assimilated in this study. However, the data is assimilated at different horizontal resolutions.

In order to investigate the impacts of horizontal resolution on the 3DVAR and MM5 forecasts more diversely, two different grid spacings for each domain are used. Each case comprises a 3-day period in the middle of each season, are selected; details are provided in Table 1.

Table 1 Cases and Domain Setup

Case name	**Domain**			**Duration**	
	name	**Grid spacing**	**Grid size**	**start**	**end**
Asr1	AK	45 km	71x98	00 UTC 16 Apr. 2002	00 UTC 19 Apr. 2002
Asr1h	AK	15 km	211x292	00 UTC 16 Apr. 2002	00 UTC 19 Apr. 2002
Asr2	PARC	60 km	121x121	00 UTC 14 Jul. 2002	00 UTC 17 Jul. 2002
Asr2h	PARC	30 km	241x241	00 UTC 14 Jul. 2002	00 UTC 17 Jul. 2002
Asr3	AK	45 km	71x98	00 UTC 14 Oct. 2002	00 UTC 17 Oct. 2002
Asr3h	AK	15 km	211x292	00 UTC 14 Oct. 2002	00 UTC 17 Oct. 2002
Asr4	PARC	60 km	121x121	00 UTC 14 Jan. 2003	00 UTC 17 Jan. 2003
Asr4h	PARC	30 km	241x241	00 UTC 14 Jan. 2003	00 UTC 17 Jan. 2003

Forty-one terrain-following sigma levels are used in the vertical for all cases.

3. Numerical Experiments

Details of the experiment design are provided in Table 2. Five experiments are performed for each case. Experiment 'Anal' utilizes NCEP/NCAR reanalysis fields enhanced by surface and upper-air observations. Experiment 'Ctrl' represents a free MM5 forecast without FDDA, while Experiment 'Fdda' utilizes analysis nudging applied at every 6-hour interval. Experiment '3DVARi' uses the 3DVAR analysis only at the initial time and otherwise is the same as 'Ctrl'. Experiment '3DVARc' applies the 3DVAR analysis in a cycling mode (Barker et al. 2004) at 6-hour intervals. In this cycling mode, every 6-hour model forecast is used as the background for 3DVAR assimilation and the model forecast continues from the resulting 3DVAR analysis.

Table 2 Design of Numerical Experiments

Experiment	**Assimilation**		**Model integration**
	approach	**time**	
Anal	--	--	--
Ctrl	--	--	72 hrs
Fdda	Nudging	Every 6hr	72 hrs
3DVARi	3DVAR cold	initial	72 hrs
3DVARc	3DVAR cycling	Every 6hr	72 hrs

4. Results

a. 3DVAR analysis

To evaluate the impact of resolution on 3DVAR analysis, statistics of the 3DVAR analyzed increment fields from Experiment '3DVARc', which applies 3DVAR at 6-hour intervals (see Table 2), have been diagnosed. The 3DVAR analysis increment stands for (A-B), i.e., analysis minus background. Figure 2 shows comparisons of the domain-averaged root-mean-square increment (RMSI) and mean increment (MI) statistics for the temperature (T) field between the low (Asrl) and high (Asr1h) resolution grids, calculated over domain AK.

Difference of RMSI with respect to the resolution increase is evident in Figure 2a, where an average of 17% and a maximum of 53% (at hour 18) change on RMSI are observed. In Figure 2b, an average of 15% and a maximum of 98% (at hour 60) change in MI magnitude is indicated. These differences may also include the impacts of the change in model forecast (used as background for 3DVAR) induced by the resolution change. Similar influences of resolution change on other variables, for example, winds, pressure perturbation, and water vapor mixing ratio, are also found (Figures not shown). However, larger impacts are found on temperature, pressure perturbation, and water vapor mixing ratio; and the impacts on wind fields are relatively small.

b. MM5 simulations verified against station observations

The MM5 model simulations have been verified against station observations for 2-m temperature, 10-m winds, sea level pressure, and relative humidity. The absolute root-mean-square error (RMSE) and bias scores have been calculated against station observations.

To investigate the impacts of assimilation approaches (i.e., Fdda, 3DVARi, and 3DVARc) on the MM5 forecasts, Figures 3a-b show the differences, for case Asr1h forecast temperatures, in a) absolute RMSE, and b) absolute bias, of experiments 'Fdda', '3DVARi', and '3DVARc', from experiment 'Ctrl'. Negative values indicate decreased absolute RMSE and absolute bias, relative to Experiment 'Ctrl'.

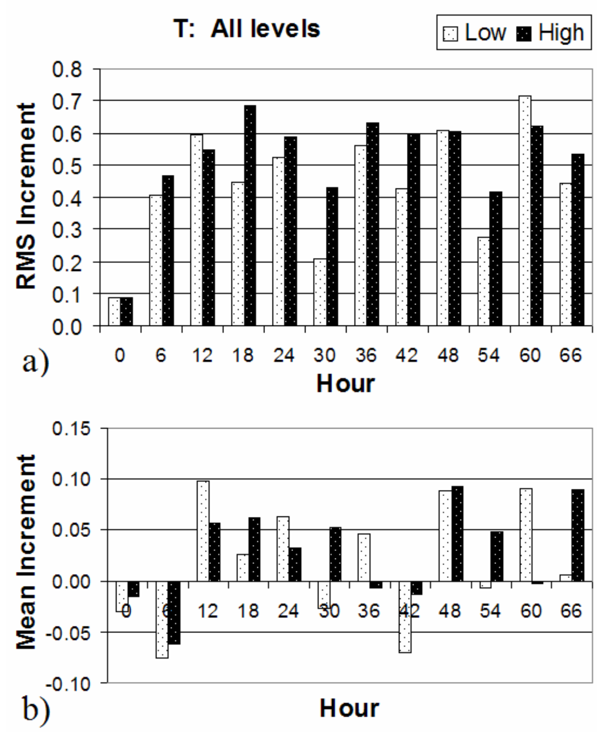

Figure 2 Statistics of 3DVAR analyzed temperature increment of case Asr1 (low resolution) and case Asr1h (high resolution): a) root-mean-square increment; b) mean increment.

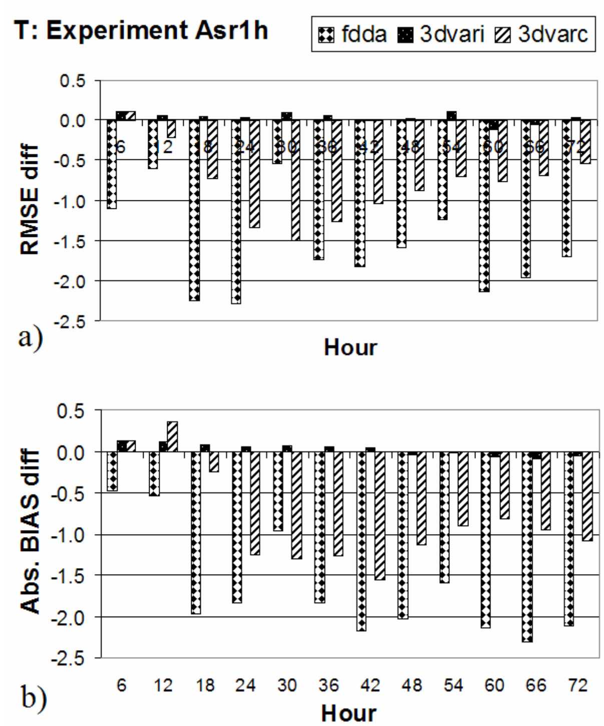

Figure 3 Difference of a) absolute RMSE, b) absolute bias, for 2-m temperature in experiments Fdda, 3DVARi, and 3DVARc from experiment Ctrl for case Asr1h.

In Figure 3a, the absolute RMSE results indicate that Experiment 'Fdda' always has smaller errors than the 'Ctrl' experiment. The '3DVARi' experiment does not improve much upon the 'Ctrl' experiment. However, the '3DVARc' experiment significantly improves the error statistics. The bias score in Figure 3b indicates smaller absolute biases for the '3DVARc' experiment relative to the 'Ctrl' experiment.

Evidence of significant improvement in the error statistics of Experiment '3DVARc' is also seen in the sea level pressure field for both cases Asr1h and Asr1 (Figures not shown). Nonetheless, Experiment 'Fdda' still shows the largest improvement on the error statistics at most forecast times.

To examine the impacts of resolution on the model simulations, Figures 4a-b show differences, with respect to a given experiment, of a) absolute RMSE, and b) absolute bias, for 2-m temperature between the high-resolution case (Asr1h) and the low-resolution case (Asr1). In Figure 4, the negative values for Experiments 'Ctrl', '3DVARi', and '3DVARc' imply that an increase of horizontal resolution decreases both the absolute RMSE and absolute bias. The larger negative values for the '3DVARi' and '3DVARc' experiments, relative to the 'Ctrl' experiment, suggests that the application of 3DVAR with high resolution can improve the model simulation. Similar results have been found for other variables and cases.

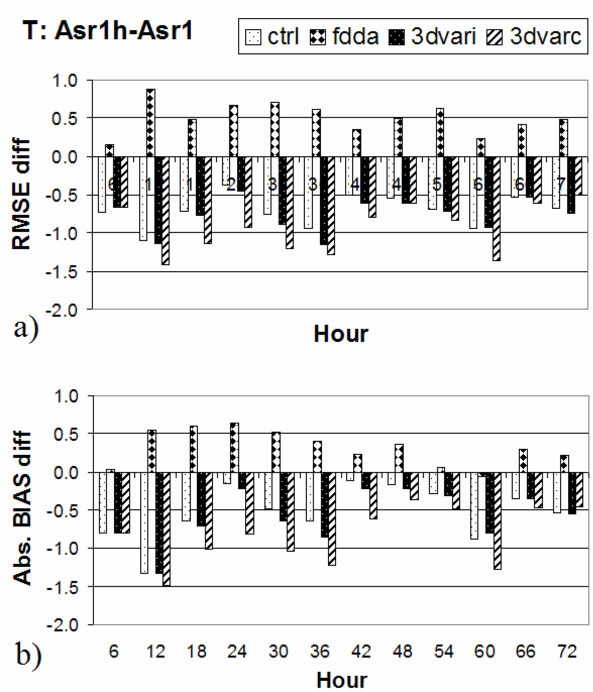

Figure 4 Difference of a) absolute RMSE, b) absolute bias, for 2-m temperature in experiments Ctrl, Fdda, 3DVARi, and 3DVARc of high-resolution case Asr1h from those of low-resolution case Asr1.

5. Conclusions

The analysis of the results from the numerical experiments stated in this paper indicates the following:

- A 3DVAR analysis that is performed at different horizontal resolutions produces different analysis increments.
- Application of 3DVAR in a cycling mode with MM5 significantly improves the model simulations, in a domain-averaged sense.
- Higher resolution application of MM5/3DVAR system produces improved simulations, again in a domain-averaged sense.

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