P3.19 SIMULATION OF AN ARCTIC EXTREME RAIN EVENT USING MM5/3DVAR AT DIFFERENT HORIZONTAL RESOLUTIONS

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1. INTRODUCTION

It has become increasingly apparent that extreme weather events, as well as extreme short- term climate variability, are at least as important to arctic residents and ecosystems as changes in the means of climate variables (Arctic Climate Impact Assessment [ACIA], 2004). It is also apparent that extreme events such as heavy rains, dry spells, strong cyclones and winds, and extreme temperatures have received little attention in the Arctic assessment and modeling communities. In this paper, we conduct simulations of an Arctic extreme rain event by a regional numerical weather prediction (NWP) modeling system, the fifth generation Penn State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model (MM5, Stauffer and Seaman, 1990), and the three-dimensional variational (3DVAR) data assimilation system developed by NCAR (Barker et al., 2004).

In numerical weather prediction and simulation studies, data assimilation systems are often 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 to data assimilation has the advantage of assimilating observations while satisfying dynamic and thermodynamic constraints, either through a set of independent balance equations (in 3DVAR, e.g., Rogers et al., 1996; Courtier et al., 1998; Lorenc et al., 2000) or the numerical forecast model itself (in 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.

The MM5/3DVAR assimilation system is applied in this simulation study to attempt to address: 1) the performance of the MM5/3DVAR system for high latitude extreme events; 2) the impacts of horizontal resolution on the simulation of extreme events, which generally involve strong interactions between large- and local- scale characteristics.

Other studies (e.g., Mass et al., 2002) have addressed the impact of horizontal grid resolution on mesoscale weather prediction and found it that resolution can sometimes have significant impacts on the structure and evolution of mesoscale systems. For example, Mass et al. (2002) showed that a 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 important to understand the extent and the nature of the impacts of horizontal resolution on both the 3DVAR analysis and the subsequent MM5 forecast. In this study, we examine the impacts of horizontal resolution on the simulation of an extreme rain event over Alaska. We utilize domains with 45 km and 15 km grid spacings, covering the area shown in Figure 1. Figure 1 also shows the available surface observations and soundings utilized in the 3DVAR assimilation process.

2. SUMMARY OF THE EXTREME RAIN EVENT

The month of July 2003 was characterized by record or near-record precipitation over much of

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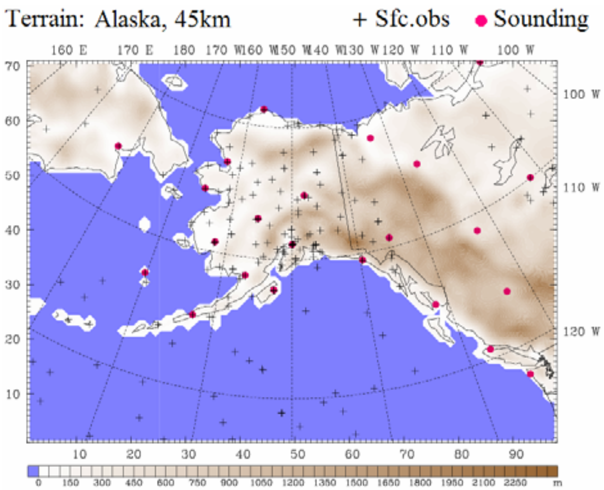

Figure 1 Model domain of 45 km resolution, with terrain in color shades, and locations of surface observations (plus signs) and soundings (solid red circles).

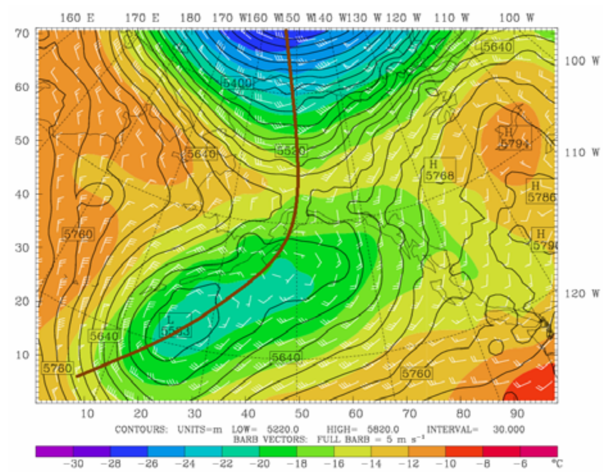

Figure 2 500 hPa geopotential heights (solid black lines), temperature (color shades), horizontal wind vectors (white wind barbs), and trough (thick solid brown line), valid at 12 Z July 26, 2003.

Interior Alaska. For example, the total rainfall for the month in the Fairbanks area was close to 6 inches, the heaviest July precipitation in nearly 100 years of record, and over 300% of normal (NWS/ACRC, 2003). Most of the precipitation in Interior Alaska during the month fell in association with two strong cold frontal passages; one passage occurred in mid-July while the second occurred during the final week of the month.

We have chosen the second period, namely July 25-28, 2003, for this study. As shown in the plot of 500 hPa geopotential heights for 12 UTC 26 July 2003 (Figure 2), the surface cold frontal passage was accompanied by a relatively (for the season) deep trough aloft, which was moving eastward into Interior Alaska. Ahead of both the upper trough and surface cold front, a rather strong southerly flow of warm and moist air from the Pacific is present, penetrating into Interior Alaska. As the frontal system moved slowly through Interior Alaska, it caused heavy rainfall during the following two days.

Figure 3 shows the observed 24-hour accumulated rainfall distribution valid at 12 UTC 28 July 2003. The rainfall shown in Figure 3 is an analysis of station observations utilizing a successive correction approach following Cressman (1959). The heaviest rainfall shown on Figure 3 exceeded a rate of 50 mm/day.

3. MODELING SYSTEM CONFIGURATION

The standard MM5 modeling system accommodates four-dimensional data assimilation (FDDA) via a Newtonian nudging approach (Stauffer and Seaman, 1990). Simulations can be "nudged" or "relaxed" towards either observations or a gridded analysis. All the simulations in this study use the Grell et al. (1994) cumulus parameterization and the Reisner et al. (1998) explicit microphysics scheme without graupel. The NOAH land surface model (e.g., 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 objective analysis using the standard suite of MM5 Little_r preprocessing programs (denoted as 'Anal' hereafter).

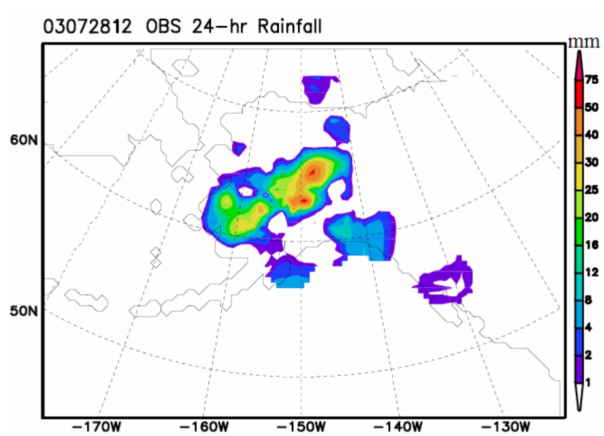

Figure 3 Station observed 24 hr rainfall (mm), interpolated onto model grids using Cressman (1959) method for 12 UTC July 28, 2003.

In this study, background error covariances needed by 3DVAR are provided from a file generated via the so-called “NMC Method” (Parrish and Derber 1992) applied to forecasts generated by a near-global MM5 domain (e.g., Dudhia and Bresch, 2002). According to NCAR Technical Note by Barker et al. (2003) on the 3DVAR use with the MM5, there is a set of tunable parameters within the 3DVAR system. For its application in this study, two parameters have been tuned and are discussed below.

The background error covariance scaling factors are adjusted from the default 1.0 to 0.5. The rationale for this adjustment is as follows: 1) the global background error covariances are calculated from the NMC method considering 12-hour forecast differences as an approximation to the model forecast error; however, in this study we are focusing on 6-hour forecast cycles between 3DVAR analyses; 2) The global background error was calculated from coarse resolution global model outputs, however, our modeling resolution is at a relatively higher horizontal resolution (15-45 km grid spacing). With this adjustment, the background error is reduced and more weight is given to the forecast model component within the 3DVAR analysis.

The correlation length-scale scaling parameters have been tuned for use in our case study. The scaling parameters have been reduced from the default value 0.25 to 0.15 based on a series of single observation tests. The original value 0.25 leads to an excessively large area of impact from each observation. The tuned value reduced the impacts of an observation on its adjacent observation locations.

These adjustments will not be necessary when model background error covariance and length-scale are calculated from the output of the same model as used for 3DVAR analysis.

In this study, only the conventional surface and upper-air observations (Figure 1) are assimilated. However, the data is assimilated at two different horizontal resolutions in order to investigate the impacts of horizontal resolution on the 3DVAR analysis and MM5 forecasts more rigorously. The simulation time period extends from 12 UTC 25 July 2003 to 12 UTC 28 July 2003. Forty-one terrain-following sigma coordinate levels are used in the vertical.

4. NUMERICAL EXPERIMENT

Details of the experiment design are provided in Table 1. Five experiments are performed at each both resolutions (15km and 45 km). Each experiment intermittently re-starts every 6-hour from different initial conditions as stated below. Experiment ‘Ctrlc’ represents a free MM5 forecast that re-starts every 6-hour from the ‘Anal’ without any data assimilation, while Experiment ‘Fddac’ utilizes analysis nudging at 6-hour intervals. Experiment ‘FddaPFc’ performs a 6-hour free forecast after each 6-hour analysis nudging cycle in ‘Fddac’. Experiments ‘3DVARc’ and ‘3DVARa’ apply the 3DVAR analysis in a cycling mode (Barker et al., 2004) at 6-hour intervals. In this cycling mode, every 6-hours the MM5 model forecast (referred to here as ‘3DVARc’) is used as the first guess background analysis for the 3DVAR assimilation process; the model forecast continues from the resulting 3DVAR analysis (referred to here as ‘3DVARa’). In contrast to the cycling mode 3DVAR, experiment ‘3DVARic’ uses the ‘Anal’ as the first guess background for the 3DVAR analysis, and the model starts from every 6-hours’ 3DVAR analysis.

Table 1 Design of Numerical Experiments

Name	Assimilation Approach	Initial Condition/ Background	Model integration	Model Output	
				what	Times
Ctrlc	--	Anal	6hr Free Forecast	6hr Free Forecast	12
Fddac	Analysis Nudging	Anal	6hr Nudging	6hr Nudging	11
FddaPFc	Analysis Nudging	Anal	6hr Nudging + 6hr Free Forecast	6hr Free Forecast	11
3DVARc	3DVAR	3DVAR Analysis*	6hr Free Forecast	6hr Free Forecast	12
3DVARa	3DVAR	6hr Free Forecast	--	3DVAR Analysis	12
3DVARic	3DVAR	Anal	6hr Free Forecast	6hr Free Forecast	12

* Background for first time periods of each case uses Anal.

5. RESULTS

Here in this section, we present an illustrative sample of our results. The model simulations are verified against station observations and are compared in terms of domain-wide average statistics, including absolute root-mean-square error (RMSE) and absolute bias. Variables verified include 2-m temperature, relative humidity (RH), 10-m winds (U and V), and sea level pressure (SLP). Additionally, the equitable threat score (ETS) and Bias statistics, both of which are based on a contingency table approach (Wilks 1995; Colle 1999), are used to verify the precipitation forecast. Both the ETS and Bias scores measure model accuracy based on the frequency of occurrence at or above a threshold. The ETS measures the skill in predicting a given threshold at a given location, while the Bias score indicates how well the model predicts the frequency of occurrence of a given threshold. The *Bias* of a perfect forecast equals one. Besides the ETS and Bias scores, absolute RMSE is used to measure the error in magnitude of precipitation. Spatial distribution and time series of precipitation at selected stations are also analyzed.

5.1 Impacts of Horizontal Resolution

Based on the domain-wide average of absolute RMSE in each experiment, the difference RMSE between high resolution run and low resolution run, for a given experiment, is calculated to illustrate the relative change of RMSE due to the change of resolution. Figure 4 shows the RMSE differences for 2-m temperature. Negative values imply a decrease of absolute RMSE for high resolution. Thus, a consistent domain-wide improvement on 2-m temperature forecast is shown from the increase of horizontal resolution. The largest impacts are seen with experiment 3DVARic in terms of time-averaged RMSE difference, followed by, in order, experiments Ctrlc, 3DVARc, and fddaPFc. Because of the relatively small sample sizes used in the verification, we evaluate the statistical significance of these results using a Student's t-test. All of these differences, including even the small impact on experiment Fddac, are significant at the 99% confidence level.

Similar to the results from temperature, significant improvement resulted from the increase of horizontal resolution are also seen in the surface RH, U, and V fields. For example, the Ctrlc experiment shows significance in RH, U, and V at confidence levels of 100%, 100%, and 90%, respectively (Figure not shown).

As an exception, the increase of horizontal resolution has inconsistent impact on SLP.

To verify the precipitation forecast, the ETS and Bias are calculated for 6-hourly accumulated precipitation at thresholds of 0.2, 1.0, 2.5, 5.0, and 8.0 mm. As an example, Figure 5 shows the results for the 2.5 mm threshold. For all experiments, the ETS statistic indicates that the

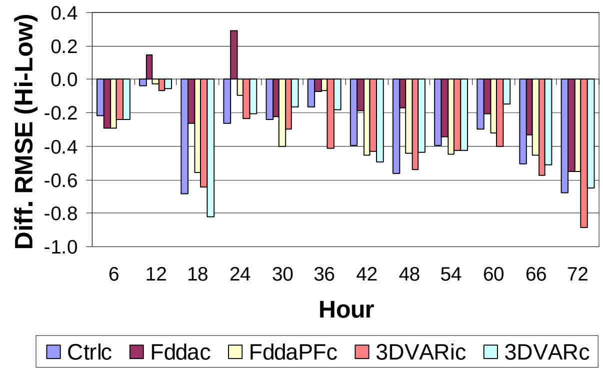

Figure 4 Difference of absolute RMSE for 2-m temperature in experiments Ctrlc, Fddac, FddaPFc, 3DVARic and 3DVARc of high-resolution from those of low-resolution.

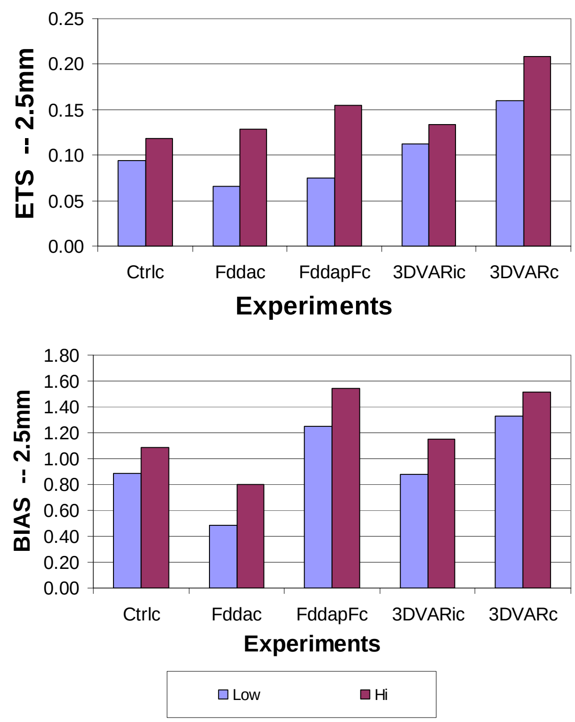

Figure 5 Averaged Equitable Threat Score (ETS) and Bias for precipitation threshold 2.5 mm from both high and low resolution experiments.

high resolution runs have greater skill than the low resolution runs in predicting the occurrences of precipitation greater than 2.5 mm. This improvement is significant at the 99% confidence level. Results for the precipitation Bias indicate that an increase of horizontal resolution leads to increased prediction of precipitation of 2.5 mm or greater in all experiments; however, this results, for experiments FddaPFc and 3DVARc, in an over-prediction of precipitation amounts of 2.5 mm or greater.

So far we have examined the impacts of horizontal resolution on model variables and precipitation on a domain-averaged basis. However, even better objective skill scores in a domain-averaged sense may not indicate a better forecast if the spatial distribution of the fields is not commensurately improved. To consider this issue, we present Figure 6, which shows the simulated 6-hour accumulated precipitation valid at 12 UTC 28 July, 2003 from the high and low resolution runs of 3DVARc. The high resolution run shows more precipitation and smaller scale structures than the low resolution run.

Figure 7 shows a time series of observed and modeled 6-hour rainfall at Fairbanks AK, including all the experiments. It is apparent that all the high resolution experiments (dashed lines) produced more precipitation than the corresponding low resolution runs and are generally closer to the observed rainfall pattern. Specifically, we note that the high resolution FddaPFc experiment (free forecast after a nudging pre-forecast) caught the double peaks of the rainfall, although the first peak was 6-hour earlier than observed

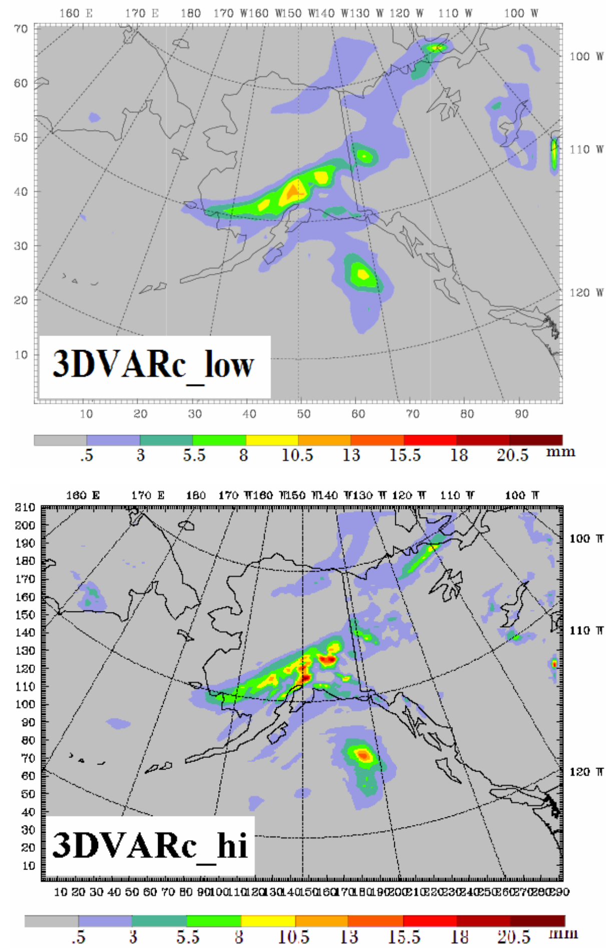

Figure 6 Model forecasted 6-hour accumulated precipitation (mm) valid at 12 UTC 28 July 2003 for low and high resolution experiment 3DVARc.

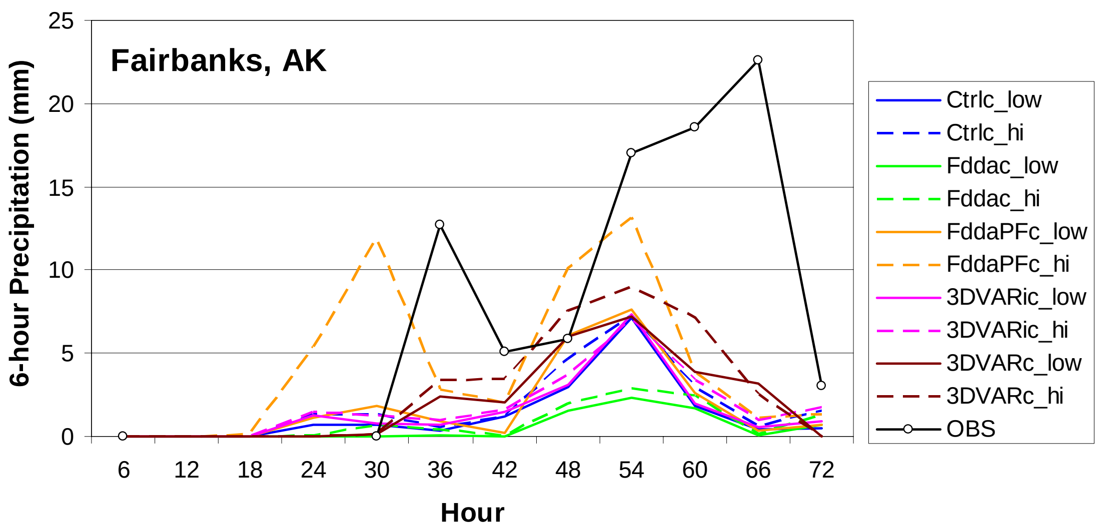

Figure 7 Observed and modeled time series of 6-hour precipitation for Fairbanks, AK

5.2 3DVAR vs. Newtonian Nudging

From the previous analysis we may also note differences in performance between the various data assimilation approaches used. We briefly discuss those in this section.

From Figure 4, it is apparent that the change of resolution has different impacts on the different experiments, though many of these differences are small, varying in sign and not statistically significant through the simulation period. Figure 5 indicates better skill from experiments 3DVARc and FddaPFc compared to experiments Fddac and 3DVARic. Moreover, Figure 7 provides evidence that experiment Fddac produces less precipitation at Fairbanks for this case, while experiment 3DVARc produced more precipitation and for a longer period than the other experiments, while experiment FddaPFc caught both of the rainfall maxima.

6. SUMMARY AND DISCUSSION

The previous analysis suggests the following conclusions:

- High resolution (15 km) improved the forecasts of surface temperature, humidity, and wind fields, in terms of domain-wide averaged statistics of absolute RMSE and bias, compared to the low resolution (45 km). For this extreme rain event, high resolution experiments have better skill with respect to the forecast of frequency of precipitation occurrences in terms of the ETS and Bias scores, and have better forecast in the precipitation amount indicated by both spatial distribution and station time series. Better timing of the rainfall in the high resolution experiments is also shown from station time series.
- Although the impacts are less significant, the above analysis implies some capability of the MM5/3DVAR system for performing data assimilation on the extreme rain event with respect to precipitation forecast discussed in section 5.2., in addition to the capability of performing data assimilation over the Arctic region (as discussed in the companion paper of Tilley et al. 2005).
- As discussed above, the MM5/3DVAR data assimilation system shows less significant impacts on the simulation of the extreme rain event, which may be due to the following three reasons: 1) the same conventional data set has already been used in experiments other than the 3DVAR runs via other objective analysis schemes; 2) The data assimilated is still too sparse over the whole domain to introduce large improvements on the forecasts; 3) the background error used in the 3DVAR analysis is a results from coarse resolution global data set, and therefore a customized background error may be a critical need for further 3DVAR assimilation efforts. We are working on a customized background error for our local MM5 model use instead of the global MM5 background error; results will be shown at the conference if complete.

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