**JP2.11** **Application of A Mesoscale 3DVAR System at High Latitudes As a Step Towards Arctic Reanalysis**

Jeffrey S. Tilley
*Regional Weather Information Center,University of North Dakota, Grand Forks, ND 58202*

Xingang Fan
*Geophysical Institute/University of Alaska Fairbanks, Fairbanks, AK 99775*

John E. Walsh
*International Arctic Research Center/University of Alaska Fairbanks, Fairbanks, AK 99775*

## 1. Motivation: Early ERA-40 Assessment

Recent workshops and papers have highlighted the shortcomings of existing reanalyses (e.g., NCAR/NCEP, ERA-15, ERA-40) for application to the Arctic and Antarctic. For example, Serreze et al. (2004) note that while the European Centre for Medium Range Weather Forecasting (ECMWF) ERA-40 provides generally good depictions of the mean spatial patterns and interannual variability of Arctic precipitation and is a significant improvement over the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, ERA-40 offers no significant improvement over the earlier ERA-15 effort by ECMWF. The reasons for this are unclear. A tendency for ERA-40 precipitation to be too low in appears to be related (at least in part) to precipitation spin-up problems. As evaluated for the Mackenzie basin, spin up and bias seem to be closely tied to the analysis increments of total column water vapor (Betts et al. 2003).

Regarding other aspects of ERA-40, the net cloud radiative forcing over the Arctic Ocean in ERA-40 is qualitatively in accord with observations, being positive (clouds cause surface warming) except during summer, when clouds are associated with surface cooling (J. Walsh, pers. comm..). Nevertheless, the annual cycle in total cloud fraction over the Arctic, at least for winter, is in poor agreement with both direct observations and satellite retrievals ERA-40 shows a fairly even distribution of cloud fraction (over 80%) across the Arctic Ocean. By contrast, observations and satellites indicate that cloud fractions are highest over the Atlantic side of the Arctic Ocean and less over the central Arctic Ocean. The summer cloud cover distribution in ERA-40 is better, showing cloud fractions greater over the Arctic Ocean as compared to land areas.

An assessment of ERA-40 performance over Antarctica (Bromwich and Fogt 2004), where traditional data sources (e.g., rawinsondes) are sparse, indicates that prior to about 1979, errors in ERA-40 surface and upper-air fields are very large, but they are much smaller in later years. The improvement corresponds to the advent of the modern satellite era. Earlier work by Bromwich et al. (2002) identified a cold bias in ERA-40 tropospheric temperatures over the Arctic Ocean, with a corresponding low bias in 500 hPa geopotential heights, which has been traced to sub-optimal assimilation of Total Ozone Vertical Sounder/High-resolution Infrared Sounder (TOVS/HIRS) satellite data. While a fix has been incorporated in ERA-40 for 1997 onwards, the cold bias is still present in earlier years, yielding a spurious non-climatic jump in the ERA-40 record.

It is clear that even with many improvements in reanalysis methodology that have occurred between the original NCEP/NCAR (-1) reanalysis project and the more recent ERA-40 project, less than optimal reanalyses are being achieved. The effort described herein represents the early stages of what is planned to be a new effort in Arctic reanalyses, utilizing the most state-of-the art data assimilation, analysis and modeling system that is current feasible.

In what follows, we first discuss the methodology of our early experiments utilizing the Penn State mesoscale 3 dimensional variation assimilation and modeling system (MM5/3DVAR; Barker et al, 2004), including a brief description of the cases examined and evaluation strategies.

**2. Methodology**

In part because a regional Arctic reanalysis needs to adequately reproduce not only larger scale climatological trends but specific regional events, we have conducted experiments on both a pan-Arctic domain and a regional Alaska domain, which is the focus of the case studies (e.g., Fan et al, 2004). Both of these domains are shown in Figure 1. The Pan-Arctic domain (Figure 1a) covers all areas poleward of 55ºN, while the Alaska domain (Figure 1b) focuses on the western Arctic and has been the outer domain for the real-time MM5 runs conducted at UAF since 2002 (e.g., Tilley and Krieger 2003). Each domain is configured for two sets of experiments, one set at relatively low resolution (60 km for the Pan-Arctic domain, 45 km for the Alaska domain), one set at relatively high resolution (30km for the Pan-Arctic domain, 15 km for the Alaska domain), in order to examine the sensitivity of MM5/3DVAR performance on horizontal resolution. Detailed exploration of this issue is provided in a companion paper (Fan et al., 2005) for a summertime heavy rain event during 2003.

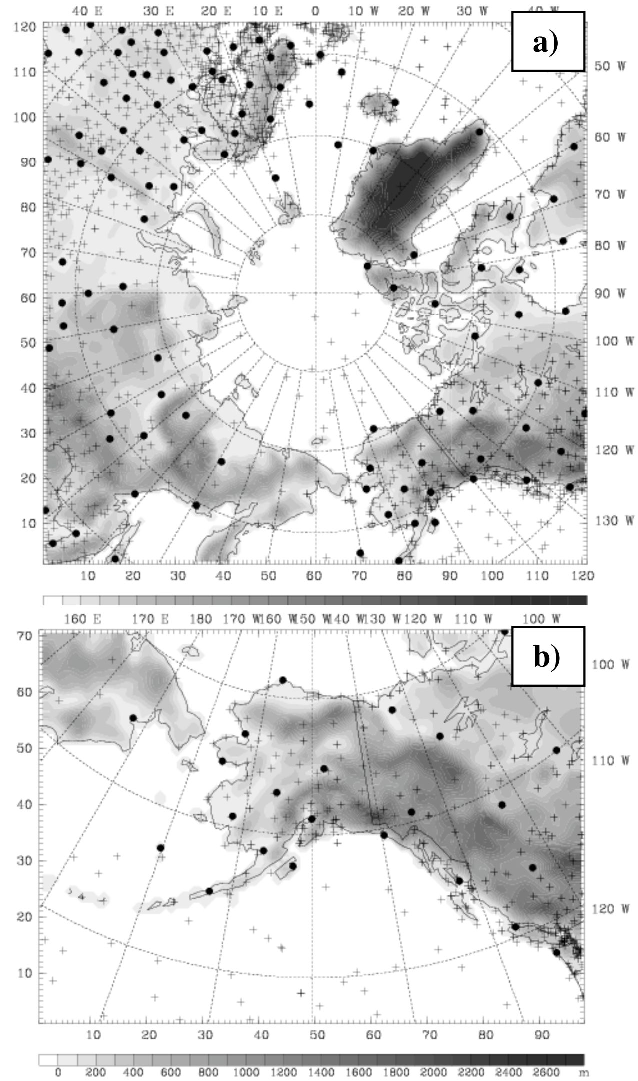


*Figure 1. Domains used in the MM5/3DVAR experiments. a) Pan-Arctic domain; b) Alaska domain. In both figures, solid circles indicate locations of upper air sounding stations. Small '+' symbols indicate locations of surface meteorological stations.*

In this study, periods for study were divided into two classes: those periods considered "generic" (not characterized by unusual storm activity,) and those periods considered to contain "extreme events" (strong storms or other unusual synoptic or mesoscale systems). An example of the latter is presented in the companion paper by Fan et al. (2005). In this paper we restrict our attention to the so-called "generic" periods. Table 1 summarizes the

| Season | Case Name | Domain name | Domain Grid Spacing | Domain Grid Size | 72hrDuration Starting at |
|---|---|---|---|---|---|
| **Spring** | **Asr1** | AK | 45 km | 71x98 | 00 UTC 16 Apr. 2002 |
| **Spring** | **Asr1h** | AK | 15 km | 211x292 | 00 UTC 16 Apr. 2002 |
| **Summer** | **Asr2** | PARC | 60 km | 121x121 | 00 UTC 14 Jul. 2002 |
| **Summer** | **Asr2h** | PARC | 30 km | 241x241 | 00 UTC 14 Jul. 2002 |
| **Fall** | **Asr3** | AK | 45 km | 71x98 | 00 UTC 14 Oct. 2002 |
| **Fall** | **Asr3h** | AK | 15 km | 211x292 | 00 UTC 14 Oct. 2002 |
| **Winter** | **Asr4** | PARC | 60 km | 121x121 | 00 UTC 14 Jan. 2003 |
| **Winter** | **Asr4h** | PARC | 30 km | 241x241 | 00 UTC 14 Jan. 2003 |

Table 1. Characteristics of the case studies constituting the so-called "generic" periods. PARC denotes the Pan-Arctic domain (Fig. 1a), while AK denotes the Alaska domain (Fig. 1b).

characteristics of these "generic" period case studies. In all experiments, the same suite of physical parameterization options available within MM5 are utilized. In particular, this includes the Grell (1993) cumulus scheme, the NOAH land surface model (e.g., Chen and Dudhia (2001), MRF planetary boundary layer scheme (Hong and Pan 199x), the CCM2 radiative transfer scheme (Hack et al, 1993) with modifications by Cassano et al (2001) and the Reisner-1 mixed phase microphysical scheme (Reisner et al, 1998) that does not consider graupel. In the Reisner-1 scheme, the Fletcher (1962) ice nuclei concentration formulation has been replaced with that following Meyers et al (1992). Sea ice concentration is specified initially; the evolution of the sea ice is dependent primarily on sea surface temperature, though its abledo and other surface properties are allowed to interact with the atmospheric boundary layer. This is a simpler sea ice treatment than has previously been reported in Zhang and Tilley (2003).

In addition, to examining the resolution sensitivity via different cases, experiments are performed to examine the efficacy of different approaches to the data assimilation. These experiments are denoted here and in subsequent sections as follows:

- *Control*: initial and boundary conditions are specified from the larger scale fields using the standard MM5 preprocessing suite of programs. No data assimilation is done outside the preprocessing suite of programs and a 72-hr free forecast is conducted.
- *FDDA:* The standard MM5 Newtonian-nudging (e.g., Stauffer and Seaman 1990) based option for data assimilation is utilized, either in a cycling mode followed by a free forecast (FDDAc) or in a continuous fashion (the default).
- *3DVARi:* The MM5 3DVAR scheme is utilized only to provide an enhanced analysis of initial and boundary conditions, as an alternative to the standard MM5 preprocessing suite. No data assimilation is performed after the initial time.
- *3DVARc/a:* The MM5 3DVAR scheme is utilized in a cycling mode at 6 hr intervals. After the initial time, the MM5 model is run in a free forecast model for 6 hours; the resulting forecast (referred to hereafter as 3DVARc) serves as the new background field for the variational assimilation of observations at that point in the forecast, and a new analysis (referred to hereafter as 3DVARa) is generated. From this new analysis, a free forecast is performed

for another 6 hours, and the cycle repeats to a maximum of 72 hours.

In all of the experiments discussed in this paper, the background error fields for MM5 are obtained the application of the so-called "NMC-method" (e.g., Parrish and Derber 1992) to a series of simulations of the NCAR global version of the MM5 modeling system (Dudhia and Bresch 2002). Though a full discussion of the NMC-method and the resulting fields is beyond the scope of this paper, essentially the assumption is made that the background errors can be characterized by differences of 24- and 12-hour model forecast fields (valid at the same time) averaged over a suitable period (from one to three months). The NCAR global background fields are generated from approximately one month of forecasts and are intended as a general "climatological" set of background fields. We recognize that such a set of background fields is not ideal for an Arctic reanalysis and as part of our efforts we intend to generate new background fields for at least the Alaska regional domain based on archived forecasts from the UAF MM5 real-time system. If results from comparison experiments using those background fields are complete, we will present them at the conference.

As part of our initial runs with the MM5 3DVAR system, we explored the sensitivity of the simulations and the analysis increments to several tuning parameters within the 3DVAR system. Specifically, we examined the sensitivity to the background error variance and length scale scaling parameters. Partly as a result of these tests, and considering the fact that the default values of these parameters are specified for 12-hour forecast/assimilation cycles, we have reduced the values of these parameters from the standard values by 33-50%. As will be seen shortly, the resulting analysis increments appear to be of reasonable magnitude with this adjustment and all remaining experiments discussed within this paper will utilize the reduced values for these scaling parameters.

In all experiments presented in this paper, only conventional surface and upper-air observations are ingested. Such initial experiments serve a tri-fold purpose: 1) to allow us to gain experience with the MM5 3DVAR system before moving on to work with more complex satellite-based datastreams such as AVHRR, TOVS and MODIS; 2) to motivate the use of such satellite datasets as crucial elements of an Arctic reanalysis by illustrating the shortcomings of an effort that does not use these data sources; and 3) to provide a baseline of results upon which improvements to the system can be measured.

In the following section we illustrate only a brief sample of the results of our experiments thus far. Additional results are presented in the companion paper by Fan et al (2005), and newer results will be presented at the conference.

## 3. Selected Results

In examining the simulation results, we undertake a tri-part strategy. The first involves investigating the structure of not the analysis fields themselves, but the increments to the background analysis introduced by the various data assimilation strategies. Figures 2a and 2b illustrate a sample of such structure in the analysis increment fields of temperature and nonhydrostatic perturbation pressure for summer case Asr2h (30 km resolution on the Pan-Arctic domain). Figures 2c and 2d show the corresponding full analysis fields for comparison. Inspection of Figures 2a and 2b suggests meso-a to synoptic scale structures in the increment fields, some of which appear to be associated with individual systems and some of which appear to be associated with major topographic features (such as the

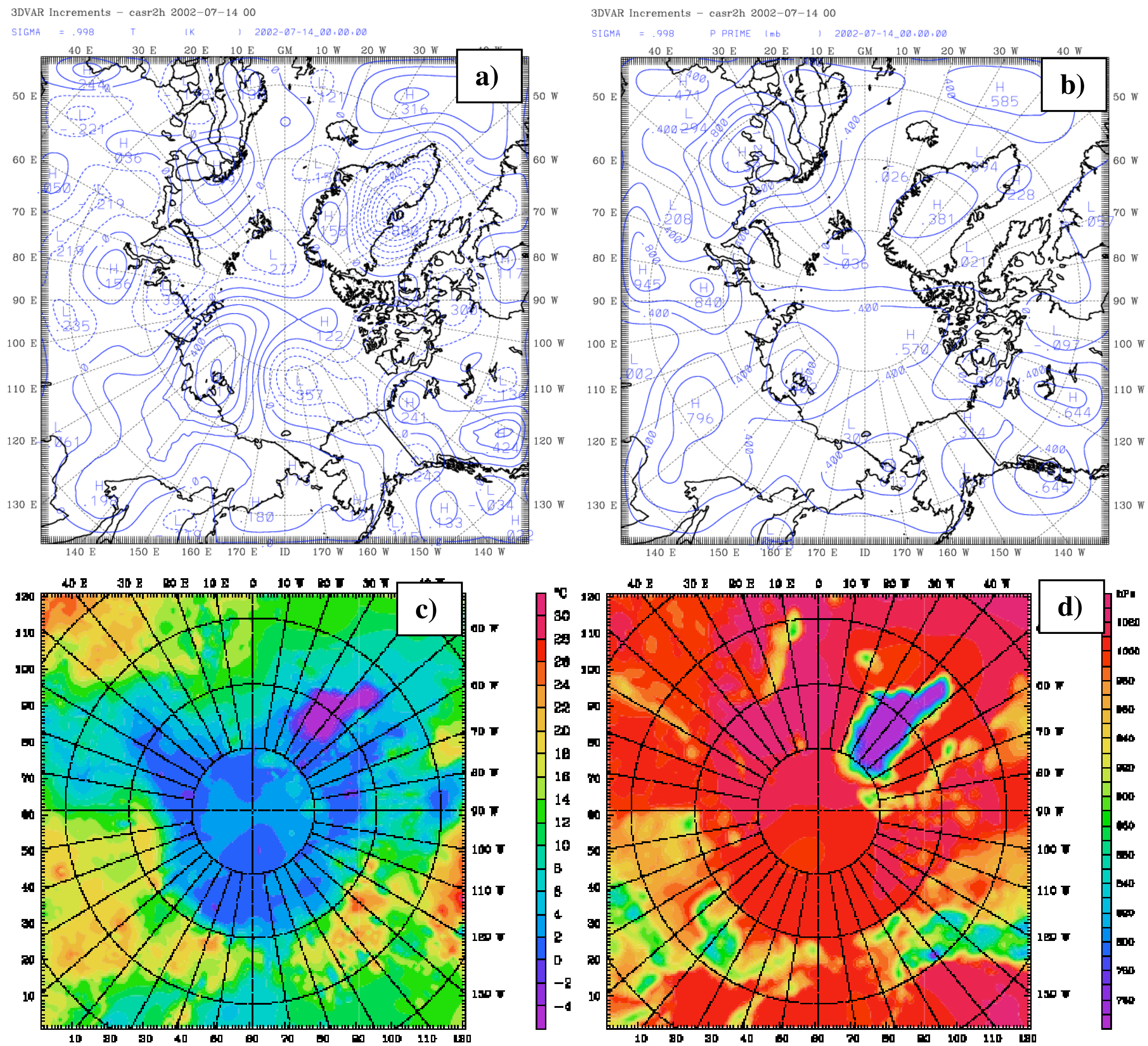


*Figure 2. Analysis increments (a,b, contours) and full fields (c,d, solid colors) of the temperature (a,c, oC) and pressure (b,d, hPa) fields for summer case Asr2h, valid at 00 UTC 14 July 2002.*

Greenland Ice Sheet). Similar results have been seen for the other cases and for both resolutions in each case. Further, the vertical structure of the increment fields (not shown) also suggests at least meso-$\alpha$, if not synoptic scale structure to the analysis increment fields. Magnitudes of the increments (as shown above in Figure 2) are significant though small at the initial times.

Inspection of analysis increment fields at later times (not shown) shows that they do tend to grow with time, which is consistent with a typically increasing error of the model solution at longer forecast ranges. However, we note that little-to-no meso-$\beta$ scale structure is seen in the analysis increment fields either initially or as the simulation proceeds. This is not consistent

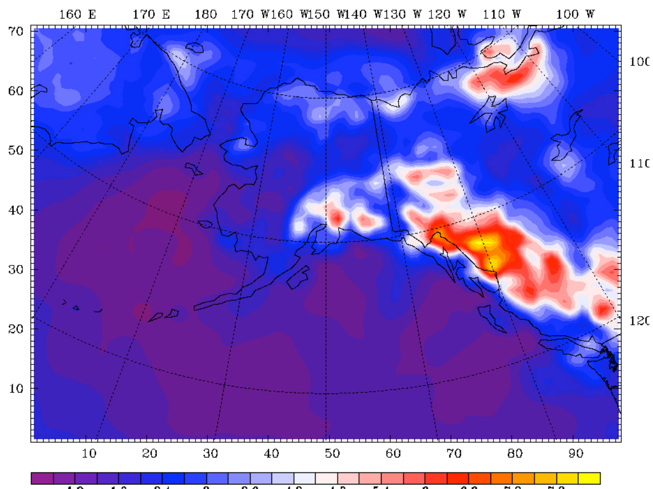

*Figure 3. Averaged JJA 2002 surface temperature errors ($^oC$) over the 45 km Alaska domain from the UAF real-time system.*

with our own experience with the UAF real-time MM5 system. As an example, Figure 3 presents the mean JJA 2002 averaged surface temperature errors for the Alaska domain (at the same resolution as the low resolution runs performed here). It is clear that while some of the error field structure is of a similar spatial scale to that seen in the analysis increment fields above (particularly over the North Pacific Ocean and Bering Sea, as indicated in areas with the coldest colors in Figure 3), that other error structures exist, especially near the surface, that are strongly tied to terrain, even over long period averages. The fact that such patterns do not show up in the analysis increment fields suggests two possibilities: 1) the data being ingested are not sufficient to capture the topographic influences and are thus not reflected in the variational adjustments, or 2) the global background error fields do not properly capture the terrain influences and thus are suboptimal for our applications. We hope to conduct some additional tests this fall with background error fields derived from the UAF real time system (again using the 'NMC-method") to examine these possibilities in more detail.

The second and third foci of our validation effort are similar, both involving computation of domain-averaged statistics; in particular, we compute such statistics for both the analysis increment fields and for the full analysis fields themselves. In the case of the analysis increment fields, comparison of increments over time and between various 3DVAR experiments allows us to evaluate the impact of individual sources of data as we incorporate them into the data assimilation framework. As our experiments thus far only focus on conventional data sources, this approach to validation currently provides only limited information, and is discussed briefly in our companion paper (Fan et al. 2005), but will be invaluable as our efforts proceed.

In the remainder of this section we focus on the third part of our validation approach, that being computation of domain-averaged measures of skill for the various experiments. In computing such measures for a 3DVAR system, it is important to distinguish what is being evaluated and in what manner. In a cycling 3DVAR system, for a given forecast time it is possible to evaluate both the model forecast that is used as the background first guess for the 3DVAR procedure and the resulting 3DVAR analysis. Different information can be obtained by the separate evaluations. Validation of the forecast fields provides a measure of the utility the previous 3DVAR analysis to properly constrain the model solution as it evolves during the cycle (and in some ways, the quality of the first guess fields); validation of the resulting analysis provides information on the ability of 3DVAR system to provide a close match to the real observed state while still maintaining three dimensional dynamic and thermodynamic consistency among the physical fields. In our case, this latter comparison presents a small dilemma, namely the fact that the same observations that go into the 3DVAR analysis are used in the validation procedure, leading to dependencies in the validation process that lessen the robustness of the statistics. Some of these concerns can be avoided by conducting parallel data denial experiments in which some observations are excluded from the 3DVAR analysis. Those data, alone or in combination with the other observations, then comprise a more independent verification data set. Such experiments are planned for the 2004-05 winter and will be reported on at the conference to the extent they are completed.

Figure 4 shows a sample of the type of statistics we are examining for Spring case. The statistic in question is the domain-averaged absolute bias, (Abs Bias) defined in the usual sense by:

$$\text{Abs Bias} = (1/N) \sum_i (X_i - X_i^o) \qquad (1)$$

where $X_i$ represents the forecast/analyzed value of a variable at (or interpolated to) an observation location, and $X_i^o$ represents the observed value of a variable at that location. N represents the total number of observations available.

What is actually shown in Figure 4 is a bias difference statistic for the surface temperature field. The domain-averaged absolute bias is computed for both the control case (Ctrlc) and for the individual experiments. These statistics are then differenced in order to show the relative performance of the various experiments. Positive values mean the experiment has a greater bias than the control; negative values imply a smaller bias than the control. In the figure, comparisons are made between the Control experiment, the cycled nudging experiment and the analysis obtained through the 3DVAR procedure. Clearly,

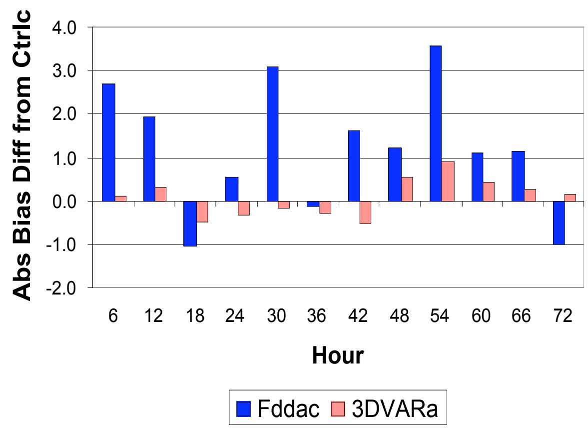


*Figure 4. Differences in domain-averaged absolute temperature biases ($^o$C) between the Control simulation and experiments FDDAc and 3DVARa for the Spring high resolution case. See text for interpretation.*

Figure 4 indicates substantially larger differences in bias between the control and the nudging (FDDAc) experiment compared to the differences in bias between the control and the 3DVAR experiments. At most forecast times, the nudging experiment shows a greater positive bias than the control, particularly during the nighttime and early morning hours (hrs 6, 12, 30,54,60); there is also a slight tendency towards a negative bias, relative to the control, during the late morning hours (e.g., hrs 18, 72) in the nudging experiment. By contrast, a period of reduced bias, relative to the control experiment, is seen in the 3DVAR results for roughly a 24 hour period extending from 18 UTC 16 April 2002 to 18 UTC 17 April 2002. Further investigation into the spatial patterns of the biases is ongoing in order to determine if there are specific areas dominating the bias in a systematic fashion, indicative of model physical parameterization issues that need to be addressed. In addition, we also keep in mind the relatively small number of stations used in the verification. We will present any results that may clarify this issue further at the conference.

## 4. Summary

The above only represents a very small sample of the results and evaluation either completed to date or in progress. Initial results are modestly encouraging though point to a clear need for any (and/or all) of the following: (1) additional data in an Arctic reanalysis beyond operationally available conventional surface and upper air observations; (2) additional work to evaluate the degree to which forecast model deficiencies contribute to a given analysis increment structure. These results are certainly not a surprise but it is important that they be reconfirmed by our effort. Additionally, and as expanded on in the companion paper by Fan et al. (2005), we have noticed that the resolution utilized in the MM5/3DVAR system is a significant factor to consider. Again, this result is not entirely surprising, especially to the high latitude mesoscale modeling community, which has seen in numerous other studies (e.g., Powers et al, 2003) the benefits of higher resolution in properly capturing meso-β to meso-γ scale structures depicted in observational records (and well known anecdotally by trained observers as well as local residents). What remains to be addressed is whether the resolutions we utilize here (as the high-resolution experiments) is sufficient, with all possible data sources, to produce a new Arctic System Reanalysis superior to those currently in existence. We expect to determine an answer to this question as our work proceeds.

*Acknowledgment: This work is supported by NOAA"s Office of Arctic Research under contract # NA17RJ1224.*

## 5. References

Barker, D. M., W. Huang, Y.-R. Guo, A. J. Bourgeois, and Q. N. Xiao,2004: A three-dimensional variational data assimilation system for MM5: implementation and initial results, *Mon. Weather Rev., 132*, 897-914.

Betts, A.K., J.H. Ball and P. Viterbo, 2003: Evaluation of the ERA-40 surface water budget and surface temperature for the Mackenzie River basin. *J. Hydrometeor.*, **4**, 1194-1211.

Bromwich, D.H., and R.L. Fogt, 2004: Strong trends in the skill of the ERA-40 and NCEP/NCAR Reanalyses in the high and middle latitudes of the Southern Hemisphere, 1958-2001. *J. Climate,* in press.

Bromwich, D.H., S.-H. Wang and A.J. Monaghan, 2002: ERA-40 representation of the Arctic atmospheric moisture budget. *ERA-40 Project Report Series 3. Workshop on Re-Analysis, 5-9 November, 2001*, European Center for Medium Range Weather Forecasts, pp. 287-297.

Cassano, J. J.., J. E. Box, D. H. Bromwich, L. Li, and K. Steffen, 2001: Evaluation of Polar MM5 simulations of Greenland's atmospheric circulation. *J. Geophys. Res.,* **106**, 33867-33890.

Chen, F., and J. Dudhia, 2001: Coupling an advanced land surface hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model description and implementation, *Mon. Weather Rev.*, **129**, 569-585

Dudhia, J. and J. F. Bresch, 2002: A global version of the PSU-NCAR mesoscale model. Mon. Wea. Rev., **130**, 2989-3007.

Fan. X., J. E. Walsh and J. S. Tilley, 2005: Simulation of an Arctic extreme rain event using MM5 / 3DVAR at different horizontal resolutions. *Preprints, 8th Conference on Polar Meteorology and Oceanography*, AMS, San Diego, CA, 9-13 January. Available on CD-ROM from Amer. Met. Soc.

Fletcher, N. H, 1962: *The Physics of Rainclouds*, Cambridge Univ. Press, London, 390pp.

Grell, G. A. 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.* **121**, 764-787.

Hack, J. J., B. A. Boville, B. P. Briegleb, J. T. Kiehl, P. J. Rasch, and D. L. Williamson, 1993: Description of the NCAR Community Climate Model (CCM2). *NCAR Technical Note*, NCAR/TN-382+STR, 120 pp.

Meyers, M. P., DeMott, P. J., and W. R. Cotton, 1992: New primary ice-nucleation parameterizations in an explicit cloud scheme. *J. Appl. Meteor.*,**31,** 708-721.

Parrish, D. F., and J. C. Derber, 1992: The National Meteorological Center's Spectral Statistical Interpolation analysis system. *Mon. Wea. Rev.*, **120**, 1747-1763.

Powers, J. G., A. J. Monaghan, A. M. Cayette, D. H. Bromwich, Y-H. Kuo and K. W. Manning, 2003: Real-time mesoscale modeling over Antarctica. *Bull. Amer. Met. Soc.*, **84**(11), 1533-1546.

Reisner, J., R. J. Rasmussen, and R. T. Bruintjes, 1998: Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Quart. J. Roy. Meteor. Soc.*, **124B**, 1071-1107.

Serreze, M.C., A. Barrett and F. Lo, 2004: Northern high latitude precipitation as depicted from atmospheric reanalyses and satellite retrievals. *Mon. Wea. Rev.*, in press.

Stauffer, D. R . and N. L. Seaman, 1990: Use of four-dimensional data assimilation in a limited-area mesoscale model. Part 1: Experiments with synoptic-scale data. *Mon. Wea. Rev.*, **118**, 1250-1277.

Tilley, J. S. and J. Krieger, 2003: The real-time Arctic MM5 modeling system: Characteristics and performance for short-range Alaska regional and local forecast applications. *Preprints, 7th Conference on Polar Meteorology and Oceanography,* AMS, Hyannis, MA. 12-16 May. 14 pp. Available on CD-ROM from the Amer. Met. Soc.

Zhang, J. and J. S. Tilley, 2003: Arctic storm simulation with the Arctic MM5 model: Performance validation. *Preprints, 7th Conference on Polar Meteorology and Oceanography,* AMS, Hyannis, MA. 12-16 May. 7 pp. Available on CD-ROM from the Amer. Met. Soc.