EVALUATION OF A RAPIDLY RELOCATABLE HIGH-RESOLUTION NUMERICAL MODEL AND DATA ASSIMILATION SYSTEM FOR METEOROLOGICAL NOWCASTING

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1. INTRODUCTION

Penn State has developed an automated, globally relocatable numerical modeling system that can be used for mesoscale nowcasting and short-term predictions and operated by someone with little meteorological / numerical modeling training. In many regions of the world, there is a vital need for accurate, up-to-the-minute meteorological information, for example, in remote mountainous areas where there is a military conflict, or in populated regions where there is the potential threat of bioterrorism. Use of global or regional model products for this purpose is very limiting in terms of representing the mesobeta / mesogamma-scale meteorology. This new system is based on a triply nested mesoscale model (MM5) optimized for parallel performance on a Linux-based PC running C-shell scripts to automate the execution sequence. The system ingests available observations using four-dimensional data assimilation (FDDA) and produces computer-generated *"nowcasts"* or short-term forecasts of local meteorology (wind, temperature, humidity, clouds, precipitation, etc..) for a user-defined region.

2. METHODOLOGY

We have conducted extensive testing of the prototype system over the Southern Great Plains ARM CART site in the summer of 2001 and over the east coast of the US during the winter of 2002. This paper presents an overview of the summer intensive observing period (IOP) utilizing standard WMO data and special ARM CART data sources.

Statistical evaluation is performed over a “virtual target region” including the ARM CART site and using all data over a region within about 100 km of Purcell, OK (boundary facility 6) from 1-18 August 2001. The verification soundings include Purcell, and also the sounding data withheld from the system at Norman OK and Fort Sill OK. Surface data include standard WMO data as well as ARM CART SMOS and THWAPS surface sensors.

Statistical skill scores are presented for a data-starved pure predictive form of the nowcast system (Exp. CNTL) and compared to that using FDDA (Exp. FDDA). Both inner domains (12-km and 4-km resolutions) are evaluated over the virtual target region. The evaluation performed here is unique in that none of the real-time data at a given verification time are used by the FDDA system at *that* time. Two of the soundings are withheld from the system at all times for truly independent verification purposes (e.g., Norman OK and the special US Army sounding data launched at Fort Sill, OK), whereas all other data have no direct influence on the nowcast model products at their valid time. In this way, the true concept of FDDA is put to the test in that the time-integrated effects of *previous* data assimilations on the high-resolution model forecasts determine the statistics.

3. NOWCAST MODEL DESCRIPTION

To address the need for timely high-resolution meteorological guidance for a wide variety of applications, a versatile nowcast/prediction system has been developed at the Pennsylvania State University, and is referred to here as the *Relocatable Nowcast / Prediction System (RNPS).* The RNPS is designed around a full-physics version of the non-hydrostatic Penn State/NCAR mesoscale model, MM5 (Grell et al. 1994). Triply nested grids of 36-, 12- and 4-km are used in the RNPS, each having 30 layers in the vertical direction. The model top is at 50 hPa. The outermost domain covers an area of 3600 X 3600 km. The nested 12-km domain covers 1500 X 1500 km and the 4-km domain covers 500 X 500 km. For this evaluation, the domains are centered over southwestern OK (Fig. 1).

The model physics for resolved-scale precipitation includes explicit prognostic equations for the mixing ratios of cloud water/ice (q_c) and rain/snow (q_r). Sub-grid deep convection is parameterized on the 36-km and 12-km domains using the Kain-Fritsch scheme. All precipitation processes are assumed to be resolvable on the 4-km domain (no parameterized convection). Turbulence is represented in the RNPS using a 1.5-order closure scheme that explicitly predicts the turbulent kinetic energy (TKE) (Shafran et al. 2000, Stauffer et al. 1999). Long- and short-wave radiation contributions to temperature tendencies are calculated using a full-column broadband two-stream method. The current version of the system uses the RRTM for the longwave radiation (Seaman et al. 2002).

Figure 2 shows a simplified schematic diagram indicating the main program functionality and the flow of data through the RNPS. Processing of the initial conditions and boundary conditions (IC/BCs) is shown at the top of the figure and is based currently on real-time global-model fields supplied from the US Navy's NOGAPS model. A "Conveyor Belt" module is used to store the incoming NOGAPS fields and select for pro-

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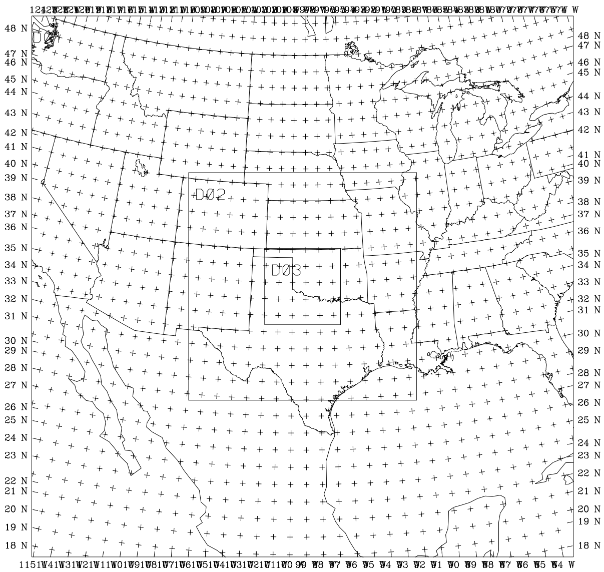

Figure 1. Location of the 36-km, 12-km and 4-km domains of the RNPS for the OK IOP.

cessing those needed by the MM5 for the current time. The IC/BC Generator allows the RNPS to be initialized at any current wall clock time. Meanwhile, a real-time data stream, such as UNIDATA, supplies the incoming observations (lower part of Fig. 2). The GATEKEEPER module selects for processing only the newest observations that have arrived during the past 30 minutes. These new data are quality-checked in the RAWINS-QC module by comparing the observations against the latest model solutions (interpolated to pressure levels by the INTERPB module) and through "buddy checks" against data from nearby sites. The RNPS performs FDDA to reduce numerical errors by blending new observations directly into the MM5 solutions as the model runs using the "observation-nudging" technique of Stauffer and Seaman (1994). The PREPOBS/CHRONOBS module performs the final preparation of the quality-checked data for use in the MM5's FDDA system by projecting to the model's grids and collecting all observations processed during the previous 4 h (the maximum data "staleness" allowed in the RNPS).

The MM5 within the RNPS has been optimized for rapid execution on PCs using the Linux operating system. The RNPS currently runs in real time on an inexpensive dual-processor 933-MHz PC computer and produces new meteorological nowcasts of current conditions every 30 minutes. Each 30-minute nowcast segment requires a total of ~26-28 minutes of wall-clock time for all three domains. (Current processor speeds reduce this time by at least a factor of two.) Once a nowcast segment is completed the model automatically pauses to allow the wall clock to catch up before beginning the next 30-minute segment. The result is a continuous stream of highly detailed numerical nowcasts that provide timely guidance about meteorological conditions as they develop over some target area.

4. EVALUATION OF RESULTS

Tables 1 and 2 summarize statistical performance of the RNPS for nowcast sequences lasting less than 24 hours during the OK IOP. Two types of statistics are shown for vector wind difference (VWD), wind speed and direction (Table 1) and for temperature, mixing ratio and sea-level pressure (Table 2). The mean absolute error (MAE) gives the magnitude of the most typical model error for a given variable, and the mean error (ME) gives the model bias for the variable. Note that the verification is performed within the 100-km radius virtual target region inside the two respective domains (12-km and 4-km). Thus, the statistics reported here can also be compared directly between the two domains.

The statistical skill is generally similar between the 12-km and 4-km domains for this relatively flat verification region. Subjective comparison of RNPS fields suggests that the 4-km domain does indeed produce finer-scale meteorological structures, for example, those associated with frontal boundaries (not shown). Table 1 shows that MAE VWD errors at the surface are reduced via FDDA on the two domains by 18 – 20 percent, with the MAE wind speeds (directions) showing reductions of about 20-21 percent (7-10 percent). (Maximum error reductions for winds above the surface are around 5 – 15 percent.). Figure 3 shows that the error growth in the 4-km surface wind field following cold start of the system from NOGAPS

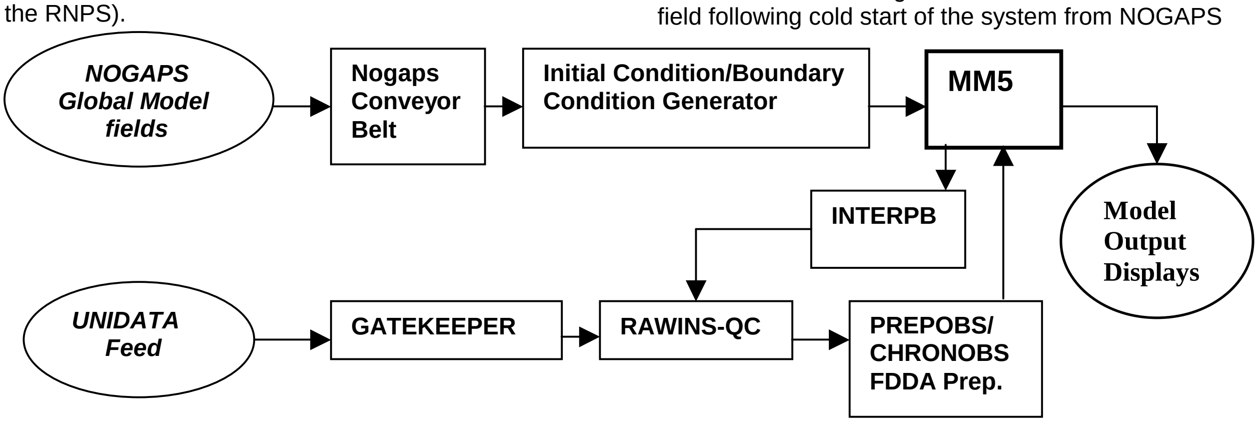

Figure 2. Schematic showing data flow through the RNPS

	MAE VWD (m/s)	MAE Wind Spd (ms^{-1})	ME Wind Spd (ms^{-1})	MAE Wind Dir (deg)	ME Wind Dir (deg)
Stratosphere (10500 – 20000 m AGL)					
4 km CNTL	**5.08**	2.91	-0.47	26.41	**7.98**
12 km CNTL	**5.07**	2.87	-0.46	26.37	**7.84**
4 km FDDA	5.14	**2.83**	**0.22**	**26.35**	9.88
12 km FDDA	5.08	**2.71**	**0.22**	**26.10**	9.40
Upper Troposphere (5000 – 10500 m AGL)					
4 km CNTL	4.07	2.49	**-0.05**	18.81	8.33
12 km CNTL	4.07	2.49	**-0.04**	18.68	7.94
4 km FDDA	**3.89**	**2.47**	0.12	**16.79**	**6.79**
12 km FDDA	**3.84**	**2.38**	0.14	**16.99**	**6.59**
Lower Troposphere (1000 – 5000 m AGL)					
4 km CNTL	3.13	1.82	-0.36	**29.00**	**1.54**
12 km CNTL	3.14	1.76	-0.42	29.37	**1.66**
4 km FDDA	3.13	**1.72**	**0.08**	29.13	3.77
12 km FDDA	**3.06**	**1.67**	**0.04**	**27.66**	3.18
Boundary Layer (80 – 1000 m AGL)					
4 km CNTL	3.63	2.08	**0.28**	27.36	**-0.13**
12 km CNTL	3.63	2.03	**0.25**	28.03	**-0.18**
4 km FDDA	**3.41**	**1.81**	0.68	**26.21**	8.73
12 km FDDA	**3.35**	**1.75**	0.56	**25.63**	7.36
Surface Layer (40 m AGL)					
4 km CNTL	3.09	2.01	1.04	36.66	2.35
12 km CNTL	3.09	1.99	0.96	37.67	2.29
4 km FDDA	**2.54**	**1.61**	**0.61**	**33.93**	**-0.65**
12 km FDDA	**2.48**	**1.58**	**0.49**	**34.01**	**-0.44**

Table 1. Statistical evaluation of the RNPS wind fields over the period 1-18 August 2001 for all applications less than 24 h. Bold entries denote the better statistical score for CNTL versus FDDA for each domain.

	MAE T (^oC)	ME T (^oC)	MAE q_v (gkg^{-1})	ME q_v (gkg^{-1})	MAE SLP (hPa)	ME SLP (hPa)
Stratosphere (10500 – 20000 m AGL)						
4 km CNTL	1.97	1.52	0.01	0.01	N/A	N/A
12 km CNTL	1.98	1.51	0.01	0.01	N/A	N/A
4 km FDDA	**1.34**	**0.98**	0.01	0.01	N/A	N/A
12 km FDDA	**1.33**	**0.96**	0.01	0.01	N/A	N/A
Upper Troposphere (5000 – 10500 m AGL)						
4 km CNTL	0.87	0.36	0.39	-0.23	N/A	N/A
12 km CNTL	0.86	0.38	0.39	-0.23	N/A	N/A
4 km FDDA	**0.79**	**0.35**	**0.37**	**-0.17**	N/A	N/A
12 km FDDA	**0.77**	**0.37**	**0.38**	**-0.15**	N/A	N/A
Lower Troposphere (1000 – 5000 m AGL)						
4 km CNTL	1.24	**0.01**	1.76	-0.91	N/A	N/A
12 km CNTL	1.23	**0.09**	1.78	-1.12	N/A	N/A
4 km FDDA	**1.04**	0.15	**1.53**	**-0.46**	N/A	N/A
12 km FDDA	**0.99**	0.22	**1.51**	**-0.60**	N/A	N/A
Boundary Layer (80 – 1000 m AGL)						
4 km CNTL	1.73	-1.20	1.69	-0.15	N/A	N/A
12 km CNTL	1.73	-1.25	1.63	-0.26	N/A	N/A
4 km FDDA	**1.61**	**-1.08**	**1.56**	**0.04**	N/A	N/A
12 km FDDA	**1.66**	**-1.21**	**1.53**	**0.00**	N/A	N/A
Surface Layer (40 m AGL)						
4 km CNTL	2.30	-0.27	1.89	**-1.43**	1.07	-0.16
12 km CNTL	**2.05**	**-0.57**	1.88	-1.45	1.08	-0.19
4 km FDDA	**2.29**	**-0.11**	**1.86**	-1.45	**0.89**	**-0.10**
12 km FDDA	2.16	-0.58	**1.78**	**-1.36**	**0.90**	**-0.11**

Table 2. Statistical evaluation of the RNPS mass fields over the period 1-18 August 2001 for all applications less than 24 h. Bold entries denote the better statistical score for CNTL versus FDDA. for each domain

initial conditions, is reduced due to the continuous FDDA.

Table 2 shows that the mass fields, which are not directly assimilated here at the surface or within the PBL for reasons discussed in Stauffer et al (1991), are also generally improved by FDDA. The maximum reductions in MAE for temperature, mixing ratio and SLP due to FDDA are 33 percent (0.6 C), 15 percent (0.3 g kg^{-1}) and 17 percent (0.2 hPa), respectively.

Overall, Exp. FDDA generally outperformed Exp. CNTL during the OK IOP, indicating that the blending of previous observations into the forward integrating real-time nowcasts has a positive effect for reducing the current model errors. This is significant because the realtime nowcast system required redesign of the FDDA weights and parameters since it can only use observations *after* their valid times, rather than both before and after their valid times as in research applications (e.g., Stauffer and Seaman 1994)

5. SUMMARY AND FUTURE DIRECTIONS

A real-time relocatable nowcast/prediction system has been constructed and demonstrated to have potential benefits for assisting decision makers to anticipate and respond to short-term meteorological variability at very fine (4-km) resolution. Further work is expected to allow assimilation of new data types (such as satellite cloud- and vapor-tracked winds) in real time, coupling to a plume-dispersion model for tracking airborne materials, such as smoke plumes, and post-processing to reduce remaining errors in the model-generated products (Seaman et al. 2002). Moreover, the current 30-minute nowcasts can be augmented to produce short-range forecasts.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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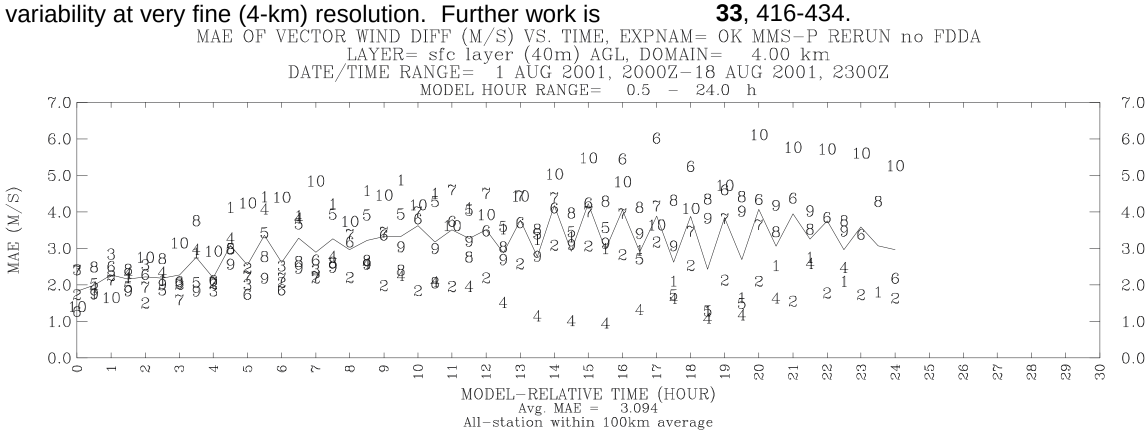

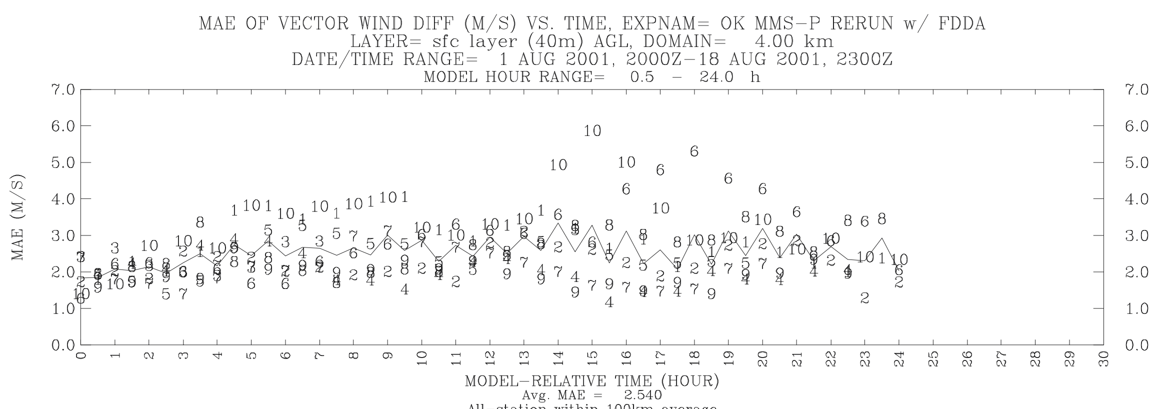

Figure 3. Time series of VWD MAE statistics (ms^{-1}) at the surface for Exps. CNTL (no FDDA) and FDDA in terms of model-relative time (h) since cold-start initialization. Numbers indicate average virtual target region VWD MAEs for individual 30-minute nowcasts during the first 24 h for each of 10 cases during 1 – 18 August 2001, and the solid line denotes the 10-case average statistics at each model-relative time.