4.2   AN OBJECTIVE VERIFICATION OF THE NORTH AMERICAN MESOSCALE MODEL FOR KENNEDY SPACE CENTER AND CAPE CANAVERAL AIR FORCE STATION

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1. INTRODUCTION

The 45th Weather Squadron (45 WS) Launch Weather Officers (LWO's) use the 12-km resolution North American Mesoscale (NAM) model (MesoNAM) text and graphical product forecasts extensively to support launch weather operations. However, the actual performance of the model at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) has not been measured objectively. In order to have tangible evidence of model performance, the 45 WS tasked the Applied Meteorology Unit (AMU; Bauman et al, 2004) to conduct a detailed statistical analysis of model output compared to observed values. The model products are provided to the 45 WS by ACTA, Inc. and include hourly forecasts from 0 to 84 hours based on model initialization times of 00, 06, 12 and 18 UTC. The objective analysis compared the MesoNAM forecast winds, temperature (T) and dew point (T_d), as well as the changes in these parameters over time, to the observed values from the sensors in the KSC/CCAFS wind tower network shown in Table 1. These objective statistics give the forecasters knowledge of the model's strengths and weaknesses, which will result in improved forecasts for operations.

2. BACKGROUND

The 45 WS requested the data sets be stratified by year, warm season (May-September), cool season (October-April), month and model initialization time. They also requested verification the model forecasts for the current operational version of the MesoNAM. This paper will address the following statistics requested by the 45 WS:

- Bias (mean difference),
- Standard deviation of Bias, and
- Root Mean Square Error (RMSE).

3. WIND TOWER DATA

The current version of the operational MesoNAM became available in August 2006.

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Table 1. Towers, launch activities and sensor heights at KSC and CCAFS used in the objective analysis to verify the MesoNAM forecasts.

Tower Number	Supported Activity and Facility	Sensor Heights
0002	Delta II (LC-17)	6 ft, 54 ft, 90 ft
0006	Delta IV (LC-37)	54 ft
0108	Delta IV (LC-40)	54 ft
0110	Atlas V/Falcon (LC-41)	54 ft, 162 ft, 204 ft
0041	Atlas V (LC-41)	230 ft
393/394	Shuttle/Constellation (LC-39A)	60 ft
397/398	Shuttle/Constellation (LC-39B)	60 ft
511/512/513	Shuttle Landing Facility	6 ft, 30 ft

Therefore, the period of record (POR) for this data set starts with the first cool season month of October 2006. The KSC/CCAFS wind tower data were acquired for the period October 2006 to April 2009 from the AMU archive, and the AMU wind tower quality control (QC) software was used to remove erroneous observations from the dataset. The statistical analysis software S-PLUS® (Insightful Corporation 2007) was used to process the wind tower data. Scripts were written in S-PLUS to import and modify the QC'd wind tower observation files to remove unneeded time periods and sensor heights from the dataset for each tower. The locations of the towers used for the verification are shown on the map of KSC/CCAFS in Figure 1.

Since the tower data were reported every 5 minutes and the MesoNAM forecasts were hourly, the 45 WS requested the AMU calculate the mean value for each observed parameter from the tower data at the top of every hour using the observations from 30 minutes prior and 30 minutes after the hour. The S-PLUS scripts were written to reformat the tower data and calculate the mean values in this manner.
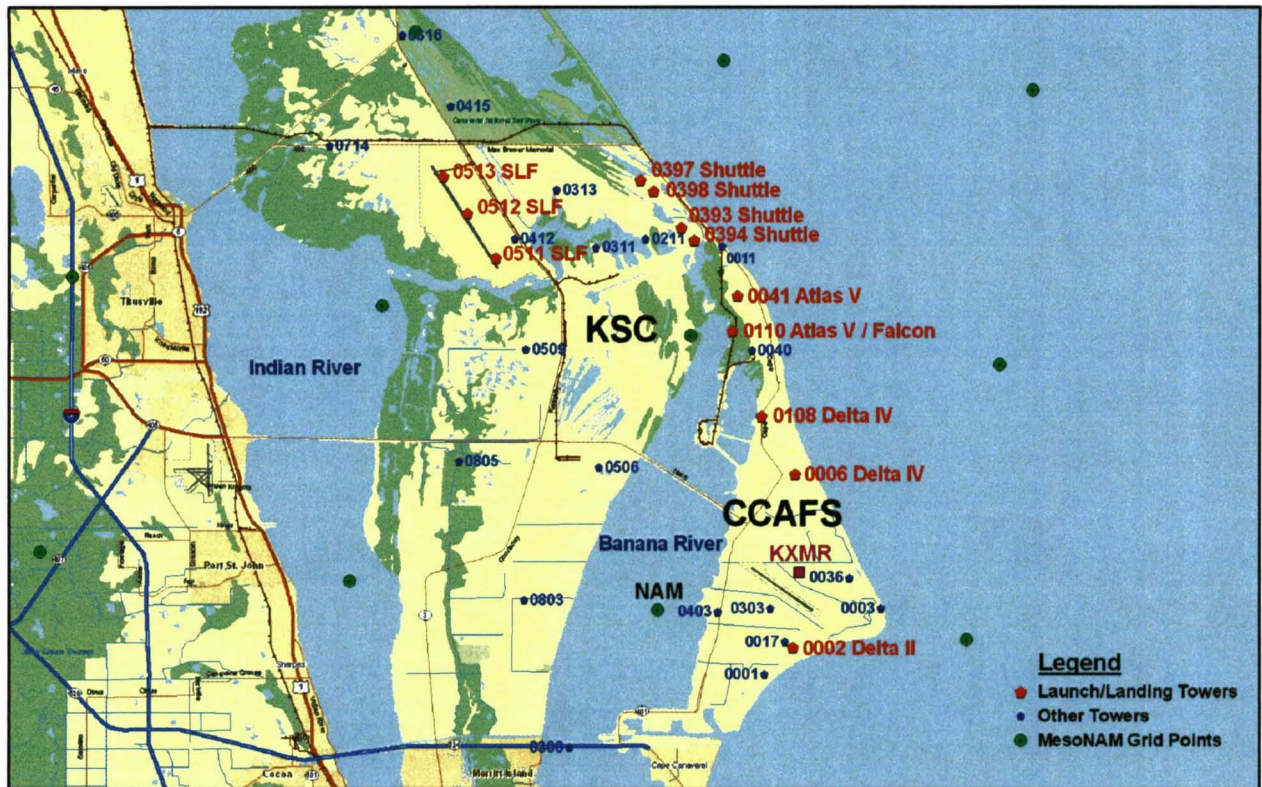
Figure 1. Map of KSC/CCAFS showing the locations of the wind towers used to verify MesoNAM forecasts (red pentagons labeled with tower number and the supported launch activity), the locations of the MesoNAM model grid points (green circles with black dot) and CCAFS weather station (magenta square labeled KXMR).

4. MESONAM FORECAST PRODUCTS

The AMU requested and obtained the archived MesoNAM forecasts from ACTA, Inc. The current operational version of the MesoNAM is the 12-km Weather Research and Forecasting (WRF) model. Based on the seasonal stratifications requested by the 45 WS and model availability, the MesoNAM forecasts were evaluated beginning with the October 2006 data, the first cool season month in the data set. The POR included three cool seasons: 2006-2007, 2007-2008 and 2008-2009; and two warm seasons: 2007 and 2008.

The MesoNAM forecast files were provided to the AMU as space-delimited text files. Each file was based on a single model initialization time and was valid at a single point extracted from the model forecasts. This point was identified as "KXMR" in each file and represents the location of the CCAFS weather station, which is located near the center of CCAFS and is identified in Figure 1 by the magenta square. The closest model grid point, which represents the point data used by the 45 WS, is located 5.8 km southwest of KXMR over the Banana River. It is shown in Figure 1 as a green circle with a black dot and labeled "NAM".

An inventory of the MesoNAM files in the POR revealed 128 missing files, or model runs, out of a possible 3772 files for the 943 days. Some days were missing less than four model runs while others were missing all four model runs. This resulted in a total of 910 days containing at least one model run.

5. FILE FORMATTING

Microsoft Visual Basic scripts were written to import the MesoNAM files into Microsoft Excel spreadsheets and reformatted to match the wind tower observation spreadsheets. This included converting the temperature and dew point from Celsius to Fahrenheit and moving rows and columns in the MesoNAM spreadsheets to match the wind tower spreadsheets. Visual Basic scripts were written to create an Excel workbook for each of the 910 days with at least one model run. Each workbook included up to four worksheets, one for each available model run, containing combined wind tower observations and MesoNAM data for each sensor on every tower. This resulted in a total of 24,570 workbooks.

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6. VERIFICATION STATISTICS

Verification statistics were calculated once the files were properly formatted and stratified. First the model bias was calculated for each model forecast against every observation. The means and standard deviations of the model bias for all stratifications (e.g., one month) as well as the root mean square error (RMSE) were calculated using the following equations:

$$Bias_{Mean} = \frac{1}{n}\sum_{i=1}^{n}(f_i - o_i)$$

Where:

n = number of available model forecasts in any given stratification,

f = MesoNAM forecast of T, T_d, wind speed or wind direction, and

o = observed T, T_d, wind speed or wind direction from each tower/sensor height.

$$STDEV_{Bias} = \sqrt{\frac{\sum(x - \bar{x})^2}{n}}$$

Where:

n = number of available model forecasts in any given stratification,

x = model bias of each forecast,

$\bar{x}$ = mean bias of each forecast period in any given stratification.

$$RMSE = \sqrt{MSE}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(f_i - o_i)^2$$

Where:

n = number of available model forecasts in any given stratification,

f = MesoNAM forecast of T, T_d, wind speed or wind direction, and

o = observed T, T_d, wind speed or wind direction from each tower/sensor height.

6.1. Temperature and Dew Point Example

Figure 2 shows a graph of the model bias of T and T_d from a 1200 UTC model initialization at Tower 0020 at a sensor height of 6 ft for the month of January in the POR. Preliminary results indicate a periodic fluctuation was present in the model bias of T as can be seen in Figure 2. This result is consistent among the first three towers and all sensor levels analyzed as of the writing of this paper. The periodic fluctuation was observed in all four model runs per day. In January, the model had a positive T bias and a negative T_d bias. The biases also decreased with forecast hour, with T coming closer to 0, but T_d becoming more negative.
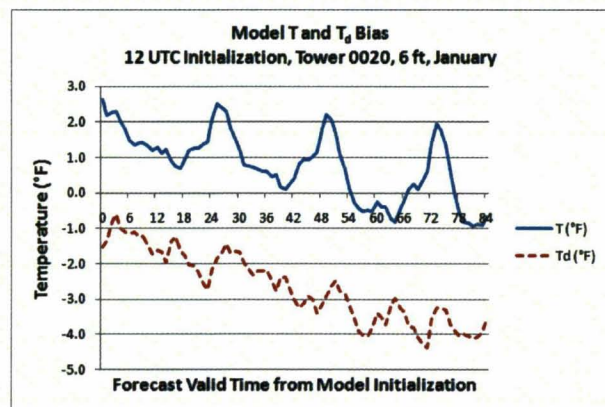

Figure 2. Graph of T and T_d model bias from a 1200 UTC model initialization at Tower 0020 and sensor height of 6 ft for January. The blue line is T and the red dashed line is T_d.

Figure 3 shows the model bias of T and T_d from a 1200 UTC model initialization at Tower 0020 at a sensor height of 6 ft for the month of May in the POR. The T bias was more negative than January and displayed a similar periodic fluctuation. The model T_d bias was also negative in May.
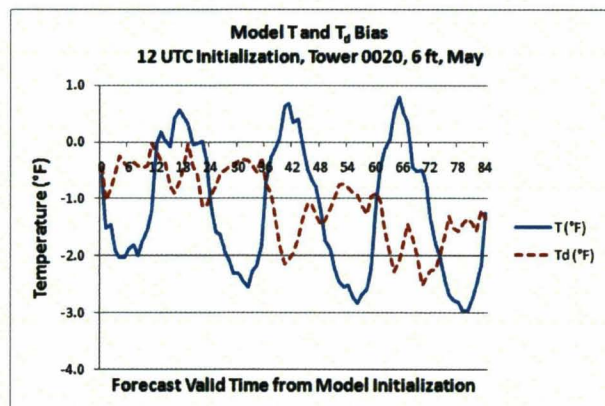

Figure 3. As in Figure 2 but for May.

The model standard deviation and RMSE of T and T_d are shown in Figure 4 and 5, respectively, for a 1200 UTC model initialization at Tower 0020 at a sensor height of 6 ft for the month of January. Both graphs indicate the model performance degraded with time through the 84-hr forecast. This preliminary result of model degradation with time was also consistent among the three towers evaluated against the model thus far.
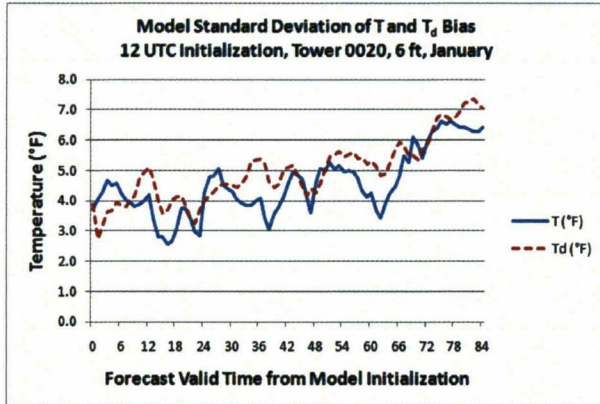

Model Standard Deviation of T and T_d Bias
12 UTC Initialization, Tower 0020, 6 ft, January

Figure 4. As in Figure 2 but for standard deviation of bias.

Model T and T_d RMSE
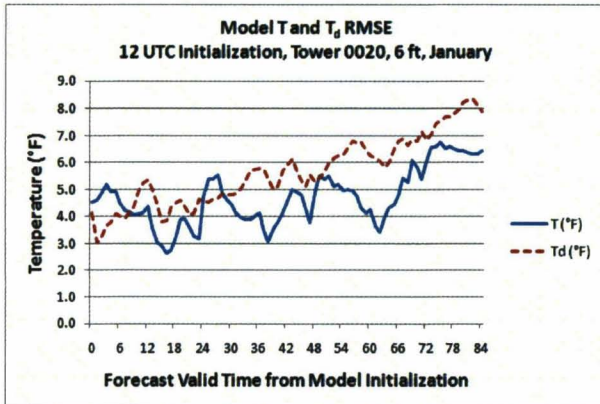12 UTC Initialization, Tower 0020, 6 ft, January

Figure 5. As in Figure 2 but for RMSE.

6.2. Wind Speed and Direction Example

Figures 6, 7 and 8 show the graphs of wind speed bias, standard deviation of bias and RMSE, respectively from a 1200 UTC model initialization at Tower 0020 at a sensor height of 54 ft for the month of January in the POR. These results indicate the MesoNAM forecasted wind speed 4–5 kt too high throughout the entire 84 hour model forecast period for January. Preliminary results indicate the MesoNAM also forecasted wind speed too high at the other three towers evaluated thus far. Unlike T and Td, the wind speed forecast error did not increase significantly throughout the 84-hr forecast period but remained fairly constant.
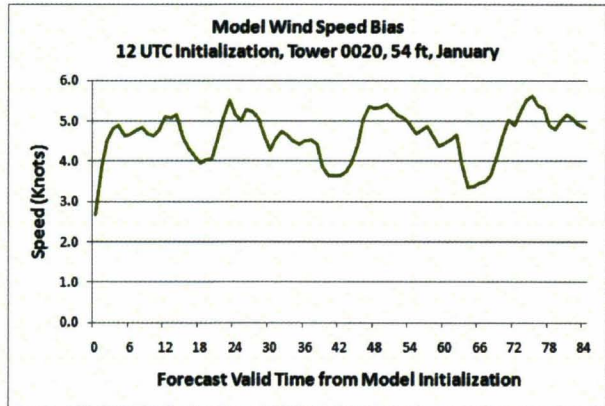

Model Wind Speed Bias
12 UTC Initialization, Tower 0020, 54 ft, January

Figure 6. Graph of model wind speed bias from a 1200 UTC model initialization at Tower 0020 and sensor height of 54 ft for January.

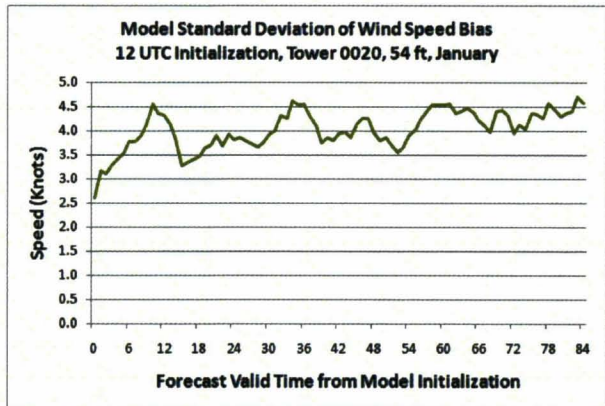**Model Standard Deviation of Wind Speed Bias**
12 UTC Initialization, Tower 0020, 54 ft, January

Figure 7. Same as in Figure 6 but for standard deviation.

Model Wind Speed RMSE
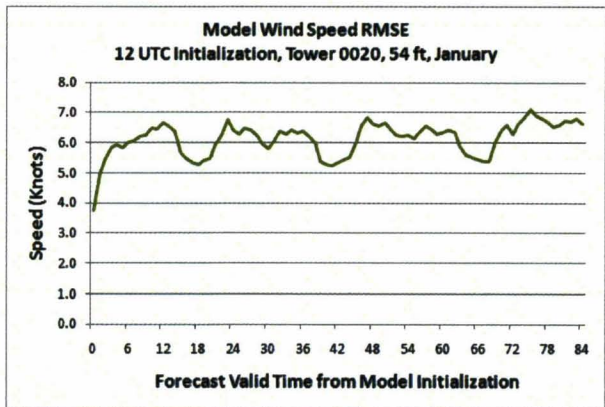12 UTC Initialization, Tower 0020, 54 ft, January

Figure 8. Same as in Figure 6 but for RMSE.

Figures 9, 10 and 11 show the wind direction graphs of bias, standard deviation of bias and RMSE, respectively from a 1200 UTC model initialization at Tower 0020 at a sensor height of 54 ft for the month of January in the POR. The MesoNAM bias of wind direction was more negative, or to the right, of the observed winds. The standard deviation shows the bias was highly variable between 30 and 60°.

Model Wind Direction Bias
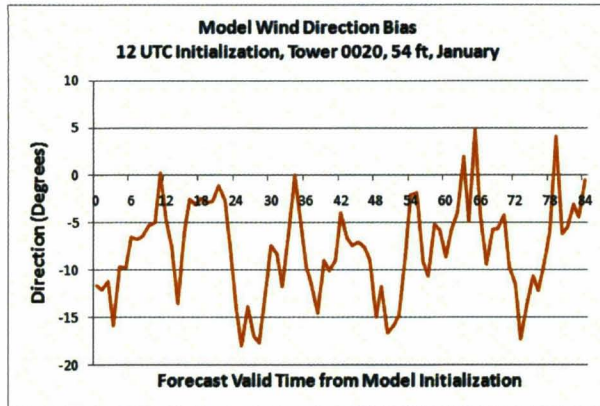**12 UTC Initialization, Tower 0020, 54 ft, January**

Figure 9. Graph of model wind direction bias from a 1200 UTC model initialization at Tower 0020 and sensor height of 54 ft for January.

There was also a slight degradation in the wind direction forecast through the 84-hrforecast period for this tower as shown in the standard deviation of the bias and RMSE in Figures 10 and 11.

Model Standard Deviation of Wind Direction Bias
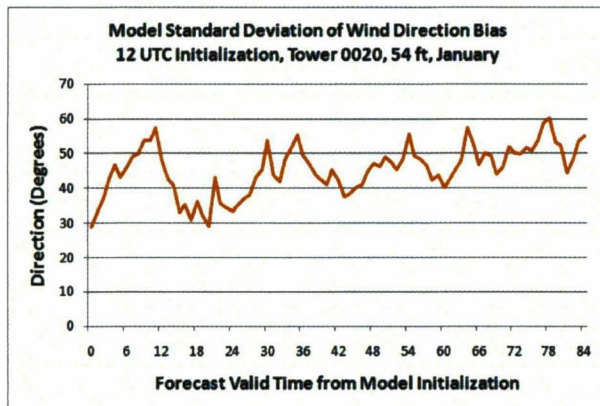**12 UTC Initialization, Tower 0020, 54 ft, January**

Figure 10. As in Figure 9 but for standard deviation of bias.

7. FUTURE WORK

In addition to the statistics presented in this paper, the 45 WS has requested conducting hypothesis tests for bias = 0, RMSE = 0 and if the composited bias and RMSE = 0. Also, if justified by the sample size, the data will be stratified by 45°, 90° and 180° with the sector directions oriented to maximize discrimination between onshore and offshore flow.

Model Wind Direction RMSE
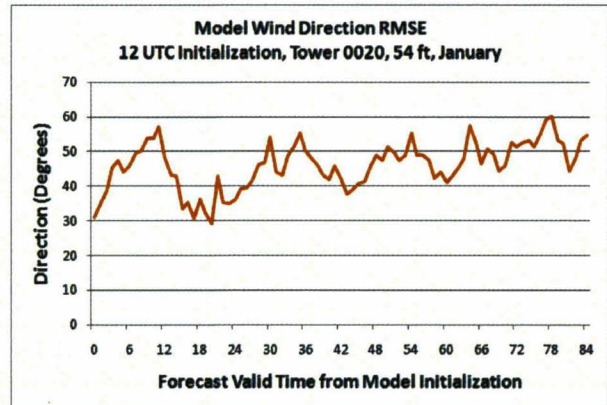**12 UTC Initialization, Tower 0020, 54 ft, January**

Figure 11. As in Figure 9 but for RMSE.

In order to present the data to the LWO's in a manageable and user-friendly manner, a graphical user interface may be developed. A total of 9,240 graphs would be generated based on the statistics being calculated for the monthly and seasonal stratifications for all sensors on all towers. The number of graphs could exceed 36,000 if the sample size is significant enough to stratify the data by sector.

8. REFERENCES

Bauman, W. H., W. P. Roeder, R. A. Lafosse, D. W. Sharp, and F. J. Merceret, 2004: The Applied Meteorology Unit – Operational Contributions to Spaceport Canaveral. Preprints, 11th Conference on Aviation, Range, and Aerospace Meteorology, Amer. Meteor. Soc., Hyannis, MA, 4-8 October 2004, 24 pp.

Insightful Corporation, 2007: S-PLUS® 8 for Windows® User's Guide, Insightful Corp., Seattle, WA, 584 pp.

NOTICE