Comparison and Evaluation
of
Operational Mesoscale Models MM5 and BFM
over
White Sands Missile Range (WSMR)

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I. Introduction

The White Sands Missile Range (WSMR) weather station, "C" station, is now using the fifth-Generation NCAR / Penn State Mesoscale Model (MM5) as a tool for short-range (24 h) weather forecast. MM5 is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model to predict mesoscale and regional-scale atmospheric circulations. Details about the model can be found on its internet MM5 home page : http://www.ucar.edu/mm5/mm5-home.html. Forecasts are routinely made twice a day initialized at 0000 UTC and 1200 UTC over the model domain covering WSMR and surrounding area. These forecasts and the Surface Atmosphere Measuring System (SAMS) data are being archived by C station.

The Battlescale Forecast Model (BFM), developed at the U. S. Army Research Laboratory (ARL), is used to make short-range forecast of atmospheric conditions in the Integrated Meteorology System (IMETS) and the Computer Assisted Artillery Meteorology (CAAM) system [1]. BFM is designed to forecast atmospheric conditions over a battlescale area (500 km x 500 km or less area). Detail of the BFM is described by Henmi and Dumais[2],[3]. The BFM is globally relocatable except for high latitude regions, and has been used for different parts of the world. The BFM uses, for prognostic calculations, the Higher order Turbulence Model for Atmospheric Circulation (HOTMAC) developed by Yamada [4].

Archived data of MM5, SAMS, and the BFM forecast over WSMR domain provide excellent data sets with which to evaluate and compare MM5 and BFM. There have been several reports of mesoscale model comparison studies [5, 6], but the past studies were based on the results of a limited number of cases. The present study is based on forty-two, 24-hr forecast calculations of MM5 and BFM compared with observational results.

The purpose of this report is to present the results of this study.

In Section II, archived MM5 and SAMS data, along with BFM applications to WSMR are discussed. Comparison methods are introduced in section III, while the results of this study are shown in Section IV. Section V summarizes the present study.

II. MM5, SAMS Data, and BFM Forecast Data

1. MM5 data

The WSMR MM5 forecasts are done on three nests :

grid	grid numbers	grid distance (km)
1	84 x 98	30
2	67 x 71	10
3	61 x 61	3.3

and 31 vertical layers are used. The vertical σ-coordinate used in MM5 is defined as [4]:

$$\sigma = \frac{p_0 - p_t}{p_s - p_t} \quad \textbf{(1)}$$

where p_s and p_t are the surface and top pressures, respectively, of the reference state and are independent of time. p_0 is the reference state pressure and dependent on height only.

The initial and time-dependent lateral boundary values for model forecast calculations are provided by the forecast data of Eta model run by the National Center for Environmental Prediction (NCEP). The center of all the model domain is located at 33.0° N and 106.0° W.

The grid 3 domain is located to cover the WSMR. Grid 3 data were interpolated to the locations of the SAMS sites, and the interpolated data, PSAMS, are archived. PSAMS data are composed of hourly forecasts over 12 hour forecast period initialized at 0000 and 1200 UTC, and include temperature and relative humidity values at the 2 m level and wind speed and direction at the 10 m level. Hourly data are displayed at 1 through 11, and 13 through 23 UTC. Few or no data at 0, 12, and 24 UTC are given in data set. The surface data were obtained by extrapolating the data at the lowest level of model (about 40 m above ground surface) to the surface level, using the similarity theory relationships [7], [8]. These surface data are statistically compared to the SAMS data.

2. SAMS Data

The locations of the WSMR SAMS sites are shown in Figure 1. Figure 1 was obtained from the internet home page of WSMR Weather Station (http://weather.wsmr.army.com).

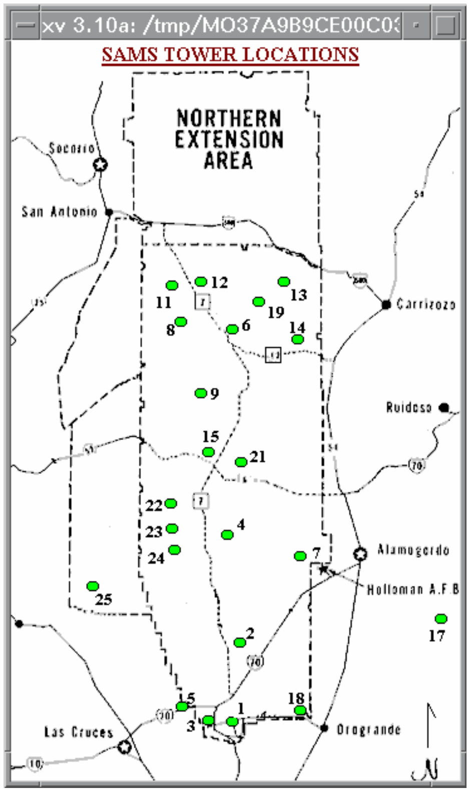

Figure 1 Map showing the locations of WSMR SAMS

3. BFM Data

BFM is applied to a domain similar to the MM5 Grid 3 area, The BFM domain consists of 51 x 51 grid points with a grid spacing of 3.33 km: this means a total model area of 166.7 x 166.7 km. The model vertical depth was set to 7 km above the highest elevation point in the domain and includes 16 layers. Forecast calculations are made twice daily initialized at 00 and 12 UTC.

Figure 2 shows terrain data for the area of 533.3 x 533.3 km which contains the model domain at the central area. Also shown are the locations of input data for initial and lateral boundary conditions. In the figure, N represents the location of the Naval Operational Global Atmospheric Prediction System (NOGAPS) forecast data points. The data are given at every 1 degree in both latitudinal and longitudinal directions. U represents the radiosonde stations. The data obtained at El Paso (located at 31.90° N and 106.70° W), and Albuquerque (located at 35.05° N and 105.62° W) are used.

The NOGAPS data were obtained through the internet homepage of the Master Environmental Library (MEL) addressed at:

http://www-mel.nrlmry.navy.mil/homepage.html

Horizontal wind vector components, temperature, dew point temperature, and geopotential height at 13 different pressure levels (1000, 975, 925, 900, 850, 700, 500, 400, 300, 250, 200,

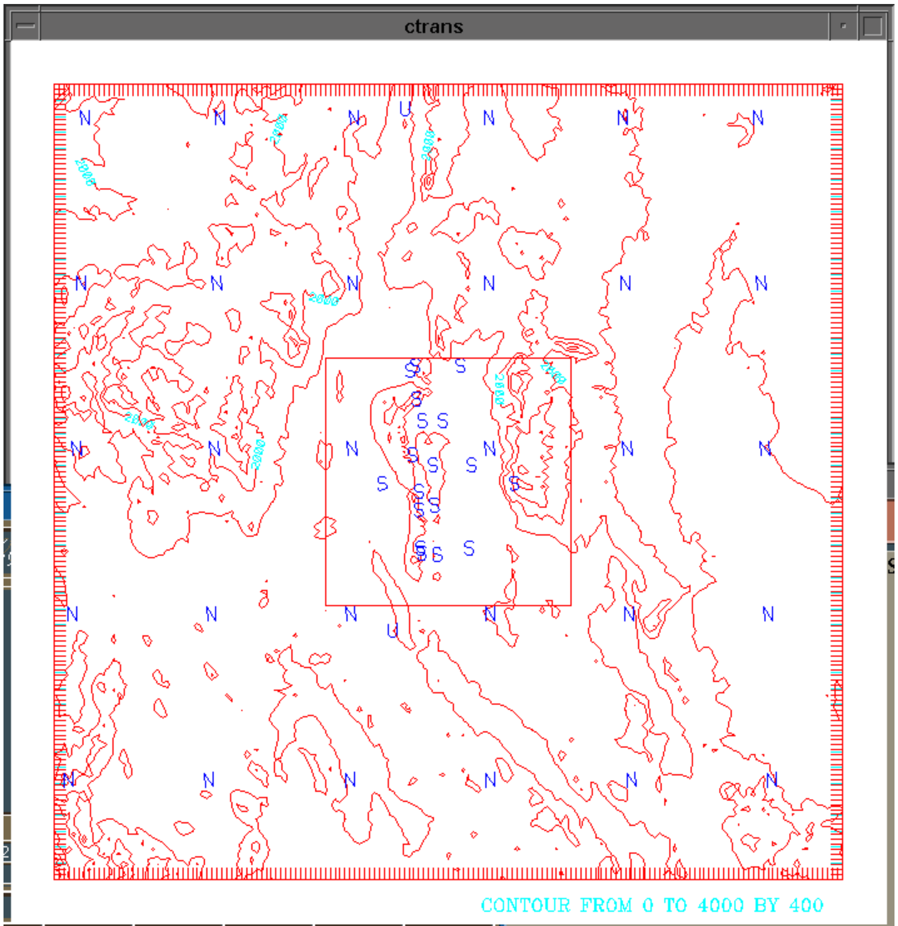

Figure 2 Contour plot of terrain data for the area covering of 533.3 x 533.3 km, centered at 32.8°N and 106.3°W. BFM model domain is located in the central area. Also shown are the locations of input data for initial and lateral boundary conditions. N, represents NOGAPS data points, U upperair, ans S SAMS stations.

150, and 100 mb) are obtained for the forecast periods of 0, 6, 12, 18, and 24 hours. These data are interpolated to the 161 x 161 grid with the grid spacing of 3.33 km at each pressure level for the above forecast periods. With the exception of the 0 hour data, the data is vertically interpolated from the pressure levels to the BFM's height levels to produce three-dimensional fields of the input data. At 0 hours, the NOGAPS data and upper air sounding data are composited, and interpolated to the BFM vertical levels [2].

The BFM vertical coordinate z^* is defined as: **(2)**

$$z^* = \overline{H}\frac{z - z_g}{H - z_g}$$

where z is the Cartesian vertical coordinate, z_g the ground elevation, $\overline{H}$ the material surface top of the model in the z^* coordinate, and H is the corresponding height in the z coordinate defined by H= $\overline{H}$ + $z_{g\,max}$. $z_{g\,max}$ is the maximum value of terrain elevation in the BFM model domain. The data fields covering the 51 x 51 grid points are used for forecast calculation. Details of the data analysis is described in [2].

Forecast calculation of the BFM is done as follows: Suppose a forecast calculation is initialized at time t_0. Pre-calculation will start at time t_0 -3 hour, and for 3 hours from t_0-3 to t_0 to t_0 the model fields are dynamically adjusted to the initial fields by the nudging method. The hourly lateral boundary condition data between two different forecast periods are calculated by a linear interpolation method. Fromt time t to t + 1, the data for t + 1 hour are assimilated in for 1 hour, and this process is repeated for an entire forecast period.

For the present study, surface data are not used for initialization.

After the forecast calculation is completed, the following bilinear interpolation is conducted to obtain the BFM data at the SAMS locations. Suppose a SAMS location (x', and y') is surrounded by four BFM grid points. An interpolated value φ' of an arbitrary variable φ at (x', y') is calculated using a bilear interpolation method as:

$$\varphi_1=\varphi(i,j)+ (x'-x)\cdot[\varphi(i+1,j)-\varphi(i,j)] \quad \textbf{(3)}$$
$$\varphi_2 =\varphi(i,j+1)+(x'-x)\cdot[\varphi(i+1,j+1)-\varphi(i,j+1)] \quad \textbf{(4)}$$
$$\varphi'(x',y') =\varphi_1 + (y'-y)\cdot[\varphi_2 - \varphi_1] \quad \textbf{(5)}$$

Here (i,j) is the southwest grid point of the four grid points surrounding a SAMS location (x',y'), and (x, y) is the distance location for the grid point (i,j). φ(i,j) is an arbitrary variable at (x,y).

Figure 3 shows the terrain elevation data for BFM, covering the domain of 51 x 51 grid points with grid spacing of 3.33 km. In the figure, the locations of SAMS stations are represented by the station number. As can be seen in the figure, the majority of the SAMS are located in the central portion of the model domain, and are not distributed evenly. Only a few stations are placed in the mountainous areas. Thus, the data set is, by no means, ideal for mesoscale model evaluation. The results obtained in the present comparison study should be regarded as qualitative.

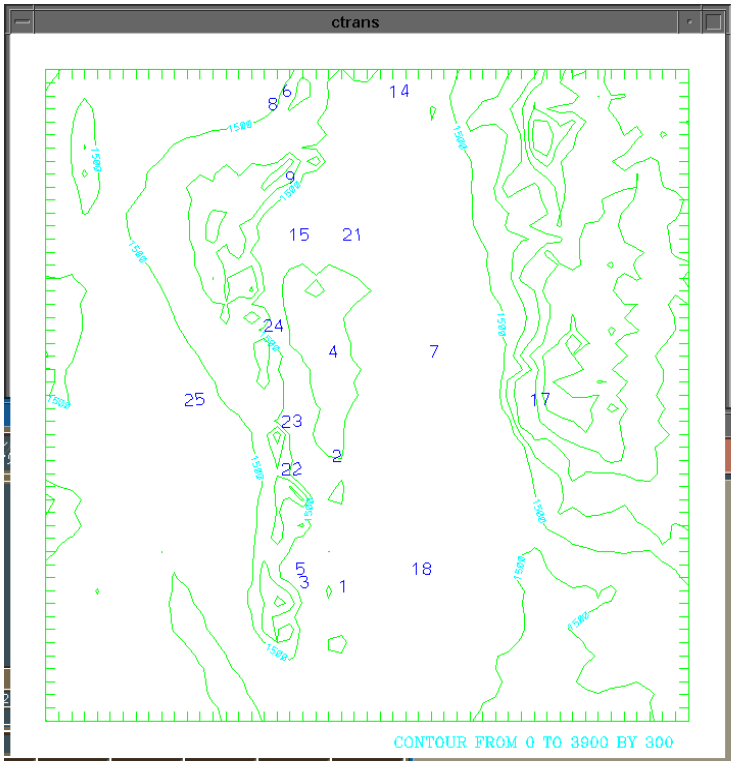

Figure 3 BFM model domain covering the area of 51 x 51 grid points with grid spacing of 3.33 km, centered at 32.8°N and 106.3°W.

III. Statistical Parameters

The following statistical parameters between the forecast data (MM5 and BFM) and the observed data (SAMS) are calculated using the data for 42 days in the period between April 1 and May 31, 1999. Statistical parameters are calculated for temperature, relative humidity, wind speed and vector components at every forecast hour.

1. Mean Difference

$$MD = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n}(x_{p,i,j} - x_{o,i,j})}{m \cdot n} \qquad \textbf{(6)}$$

Here the subscripts $_o$ and $_p$ represent observation and prediction, respectively. The subscript i_I represents the i^{th} SAMS station, and the subscript $_j$ the j^{th} forecast day. N is the number of SAMS the stations, and m the total number of forecast days. A nonzero MD indicates bias. For instance, if MD value is positive, it indicates that the model tends to overforecast.

2. Mean Absolute Difference

$$AD = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n}\left|x_{p,i,j} - x_{o,i,j}\right|}{m \cdot n} \quad (7)$$

3. Root Mean Square Error

$$RMSE = \sqrt{\frac{\sum_{j=1}^{m}\sum_{i=1}^{n}(x_{o,i,j} - x_{p,i,j})^2}{m \cdot n}} \quad (8)$$

Good agreements between observation and forecast are, in general, related to smaller values of AD and rmse.

4. Root Mean Square vector Error (rmsve)

$$RMSVE = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}[(u_{o,i,j} - u_{p,i,j})^2 + (v_{o,i,j} - v_{p,i,j})^2]}{m \cdot n}} \quad (9)$$

This parameter measures the differences of both wind speed and direction. Again, good agreements of wind vectors are related to small values of the rmsve.

5. Correlation Coefficient

$$CC = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} y_{o,i,j} \cdot y_{p,i,j}}{\sqrt{\sum_{j=1}^{m}\sum_{i=1}^{n} y^2{}_{o,i,j} \cdot \sum_{j=1}^{m}\sum_{i=1}^{n} y^2{}_{p,i,j}}} \quad (10)$$

Here, , and $y_{p,i,j} = x_{p,i,j} - \overline{x_p}$. $\overline{x_o}$ and $\overline{x_p}$ are the means of observed and forecast values, respectively**.**

IV. Comparison of MM5 and BFM Forecast

As has been mentioned, the MM5 forecast data of surface parameters PSAMS are composed of two subsets of 12 hour forecast calculation. Therefore, in the following, the corresponding data subsets of BFM are used for comparison. In the following results, the data for the stations 5 and 9 are excluded due to:

1. The locations of the station 5 is incorrectly given [5], resulting in poor interpolation results of both MM5 and BFM for wind parameters .

2. For the station 9, both MM5 and BFM consistently calculated the temperature warmer than observed values. The terrain elevation height for the station 9 is 2,709 m. The height reduced from the terrain elevation data for BFM is 1,963 m, 746 m lower than the real height. The poor forecast of temperature for the station 9 by the BFM may be caused by this discrepancy of height. For MM5, the terrain elevation data set is not available, but a similar reason may have applied to the poor forecasts.

1. Scatter Diagrams of forecast versus observation

Figures 4 through 8 show the scatter diagrams of forecast calculation versus observation. In these figures, (A) is for MM5 forecast, and (B) for BFM.

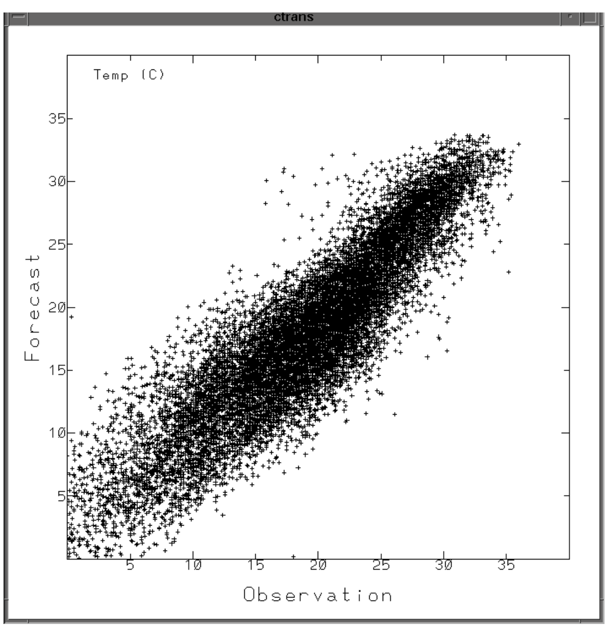

Figure 4 (A) Scatter diagrams of MM5 forecast vs. SAMS observation for temperature.

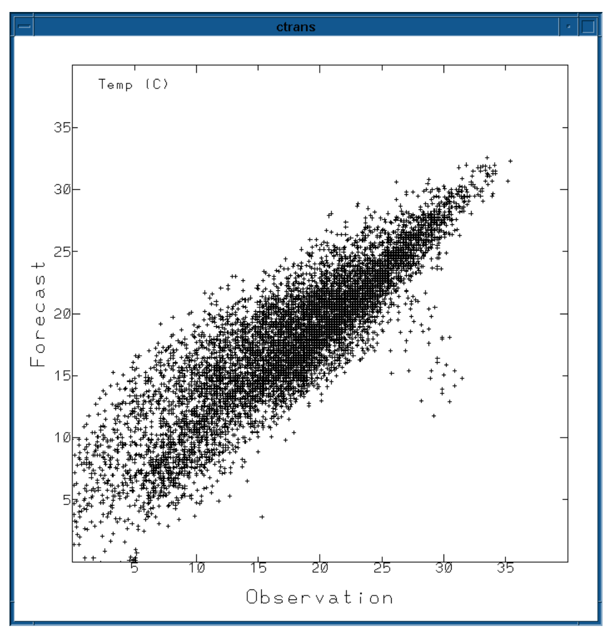

Figure 4 (B) Same as Figure 4 (A), except for BFM forecast vs. SAMS observation.

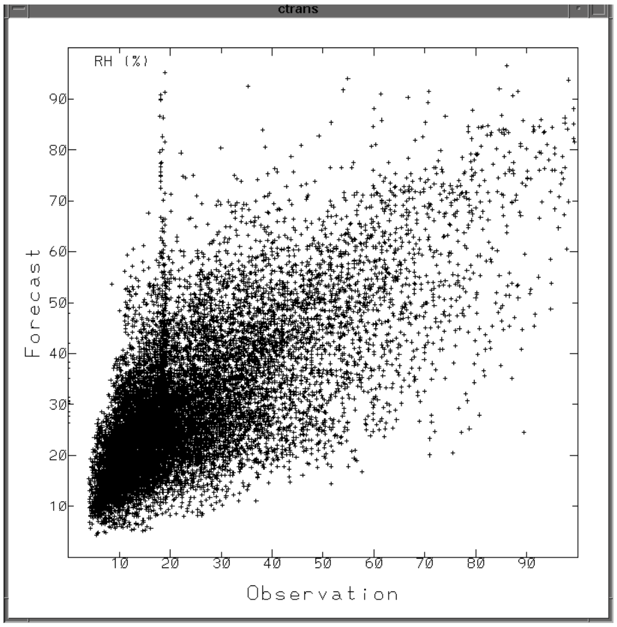

Figure 5 (A) Scatter diagram of MM5 forecast vs. SAMS observation for relative humidity.

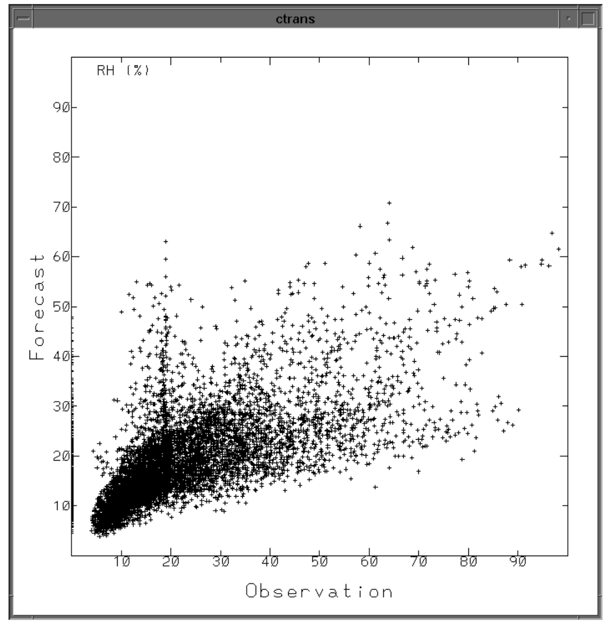

Figure 5 (B) Same as Figure 5 (A), except for BFM. forecast vs. SAMS observation.

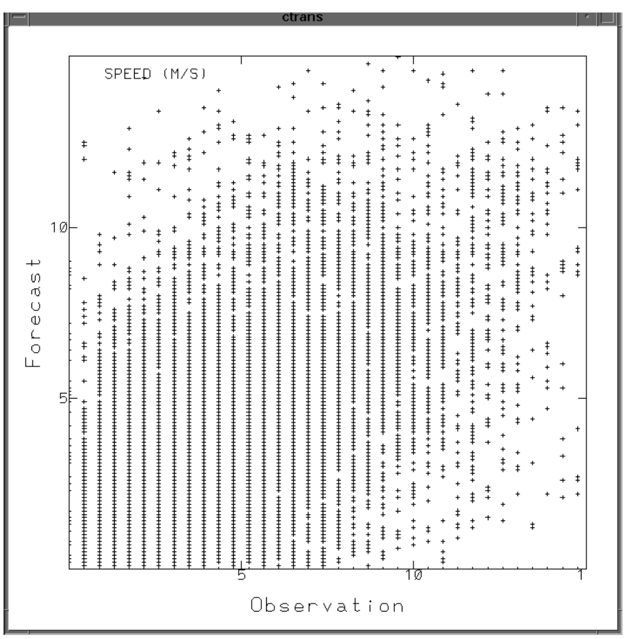

Figure 6 (A) Scatter diagram of MM5 forecast vs, SAMS observation, for wind speed.

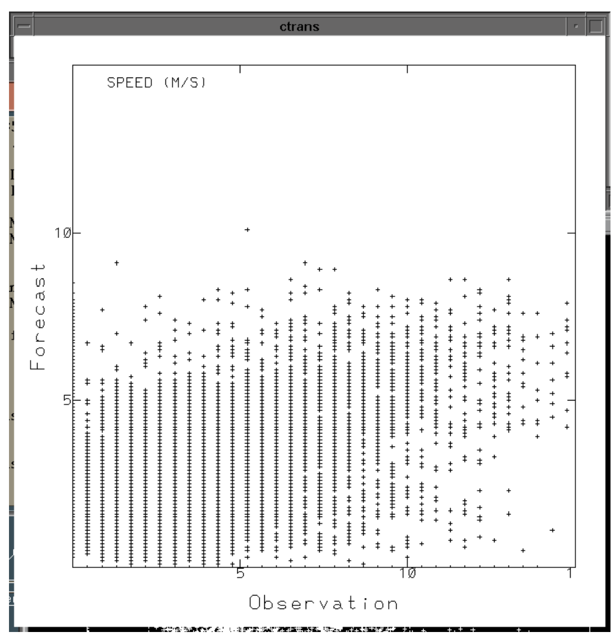

Figure 6 (B) Same as Figure 6 (A), except for BFM forecast vs, SAMS observation.

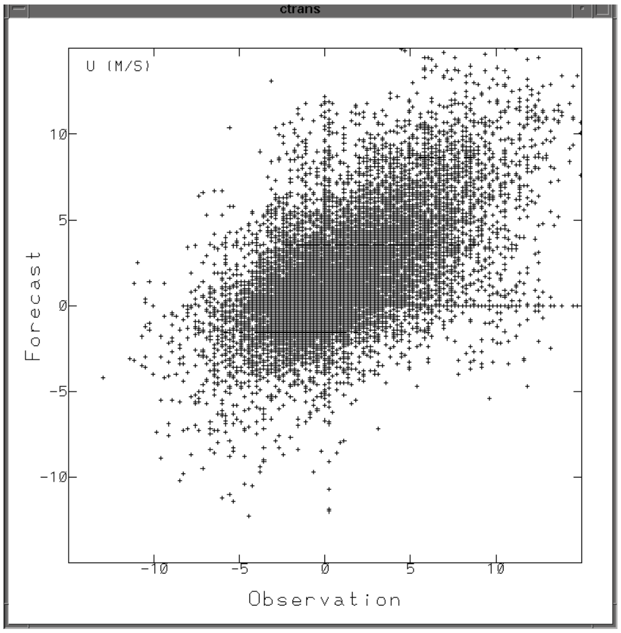

Figure 7 (A) Scatter diagram of MM5 forecast vs. SAMS observation, for wind vector component, u.

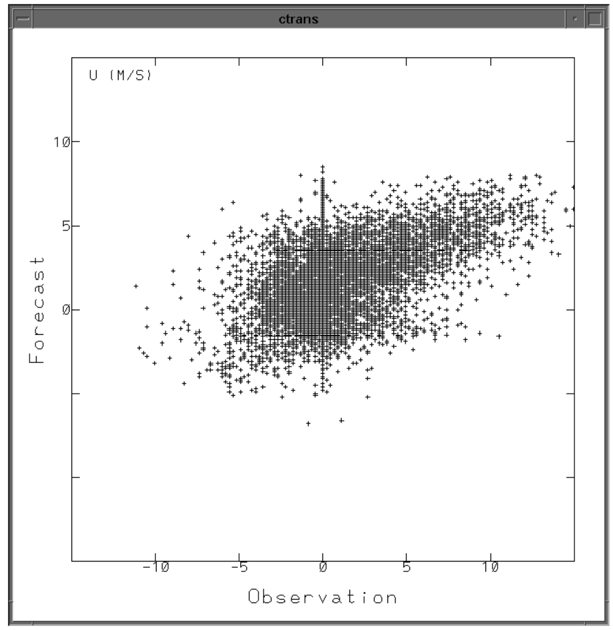

Figure 7 (B) Same as Figure 7 (A), except for BFM forecast vs. SAMS observation.

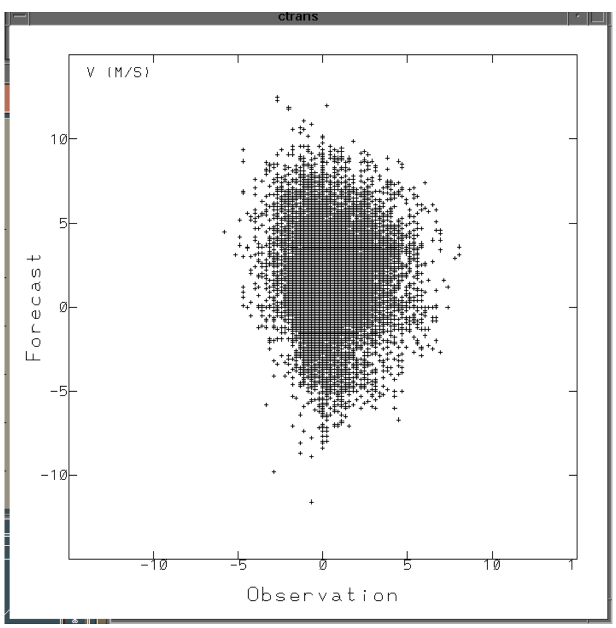

Figure 8 (A) Scatter diagram of MM5 forecast vs. SAMS observation, for wind vector component, v.

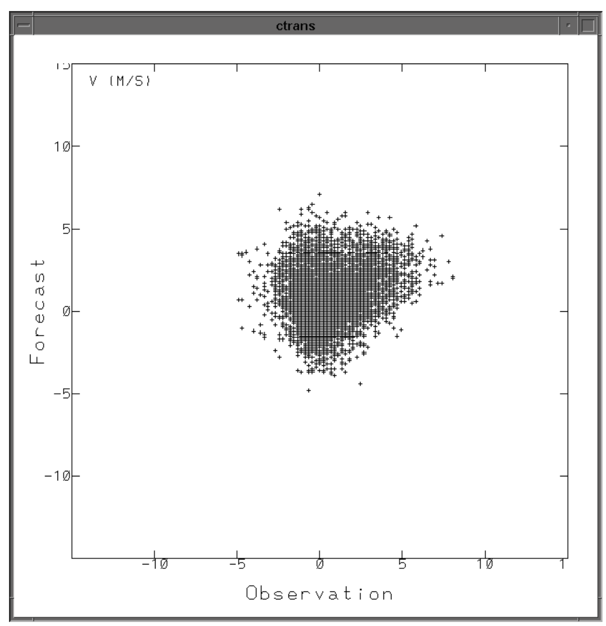

Figure 8 (B) Same as Figure 8 (B), except for BFM forecast vs. SAMS observation.

parameter	MM5 vs. SAMS	BFM vs. SAMS
Temperature (C)	.90	.97
R.H. (%)	.72	.83
Wind speed (m/sec)	.48	.64
u (m/sec)	.56	.55
v (m/sec)	-.009	.28

Table 1. Correlation coefficients between forecast and observation.

These scatter diagrams are composed of all the data points including 16 SAMS stations, for 24 hours, and 42 forecast days. The correlation coefficients between the model forecast and the SAMS observation are calculated as appears in Table 1.

The following trends in the data can be seen:

(1) From Figure 4 (A) and (B), there is good agreement for temperature between forecasts and observation for both MM5 and the BFM with the correlation coefficients of .90 and .97, respectively.

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(2) Reflecting dry atmospheric conditions over WSMR and the study period of April and May, 1999, data points of relative humidity are concentrated in lower left part of Figure 5 (A) and (B).

The figures show some scatter, indicating that both models have difficulties in simulating the moisture parameter near the ground surface. The correlation coefficient for BFM forecast versus SAMS observations is 0.83, slightly better than the MM5's 0.72.

(3) For wind speed, the correlation coefficient between BFM and SAMS is greater than those between MM5 and SAMS, but Figure 6 (B) clearly shows that BFM tends to underforecast the surface wind speed.

(4) For wind vector component, u, the correlation coefficient between MM5 and SAMS is similar to BFM's, but for wind vector component, v, it is slightly negative for MM5.

2. Time series of Statistical Parameters

MD, AD, RMSE, and RMSVE are calculated every hour of the 24-h forecast period using 42 days of forecast data. For the MM5 forecast, PSAMS data files contain very few data at 00, 12, and 24 UTC. In Figures 9 through 14, the values for MM5 are drawn with thin lines, and those for BFM with thick lines.

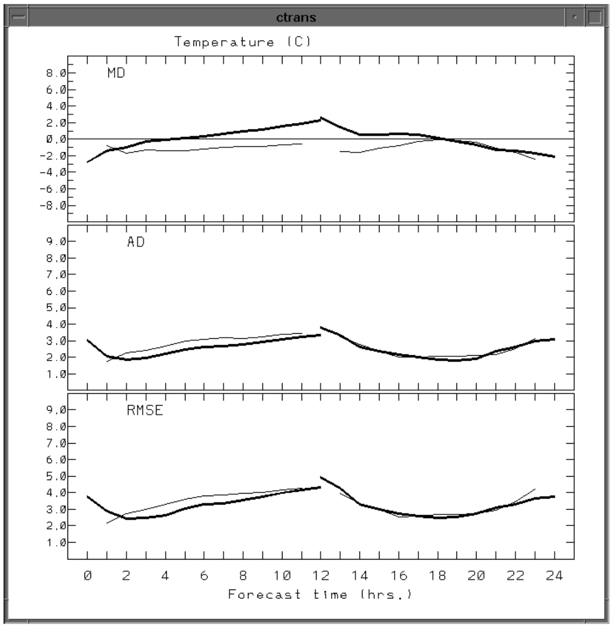

Figure 9 Time series of the statistical parameters, MD, AD, and RMSE for temperature. Thin lines: MM5, thick lines:BFM

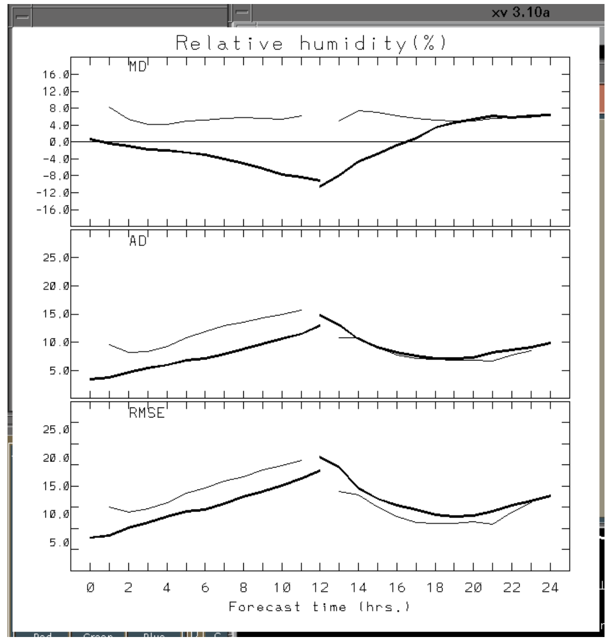

Figure 10 Sams as Figure 9, except for relative humidity.

Inspection of these figures reveals that AD and RMSE vary proportionally. Therefore, in the following, AD is chosen for consideration. The following can be seen from these figures:

1. For surface temperature, the statistics of both models are very similar, except that MM5 underforecasts temperature slightly, and that BFM overforecasts the temperature. Mean absolute differences for both models are about 3.0° C.

2. MM5 forecasts produces a slightly higher relative humidity than observation throughout the 24-h forecast period. As shown in the previous section, the BFM tends to produce a lower relative humidity than observed from the evening to morning hours, and slightly higher values in the afternoon. For the forecast period from 00 to 12 UTC, the BFM produced smaller AD than MM5, and for the second 12-h period, both models produced similar AD values. The AD ranged within 15 percent.

3. MD, AD, and RMSE of wind vector components u and v, and wind speed respectively in Figures 11, 12, and 13, and the RMSVE in Figure 14. Figure 13 show that both MM5 and BFM underpredicted wind speed throughout the entire forecast period. The under-prediction of wind speed is more significant for BFM than by the MM5. The RMSVE values of MM5 are greater than those of BFM throughout the 24 forecast period. This is mainly due to larger errors of MM5 in calculation of the y-component of wind vector v.

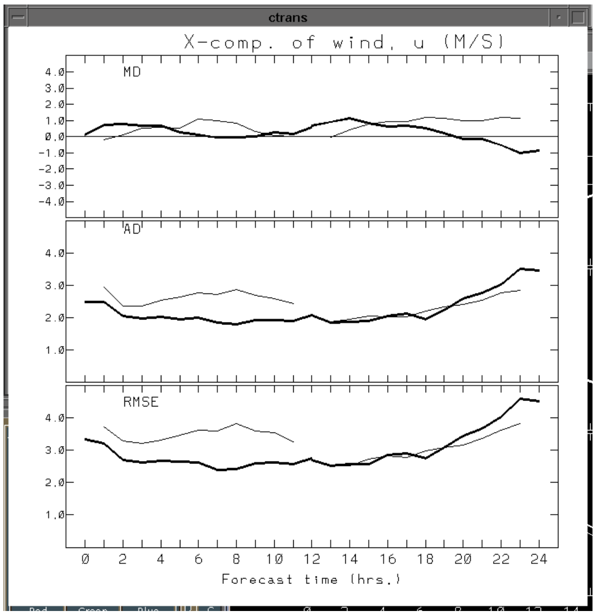

Figure 11 Same as Figure 9, except for wind vector component, u.

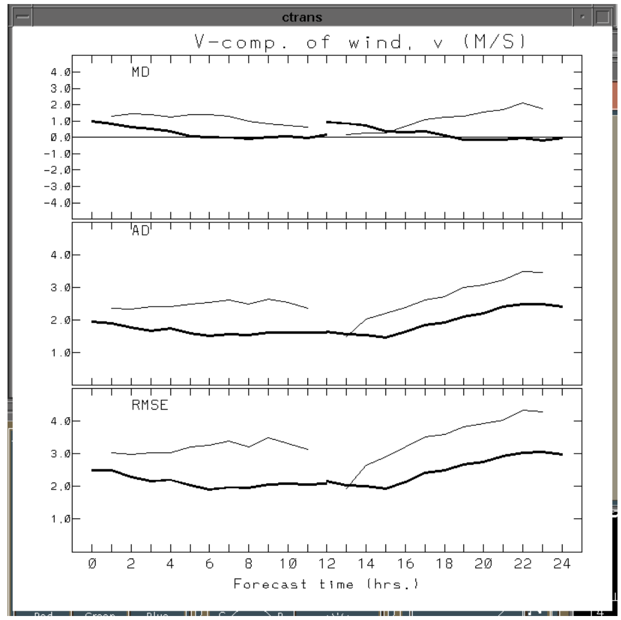

Figure 12 Same as Figure 9, except for wind vector component, v.

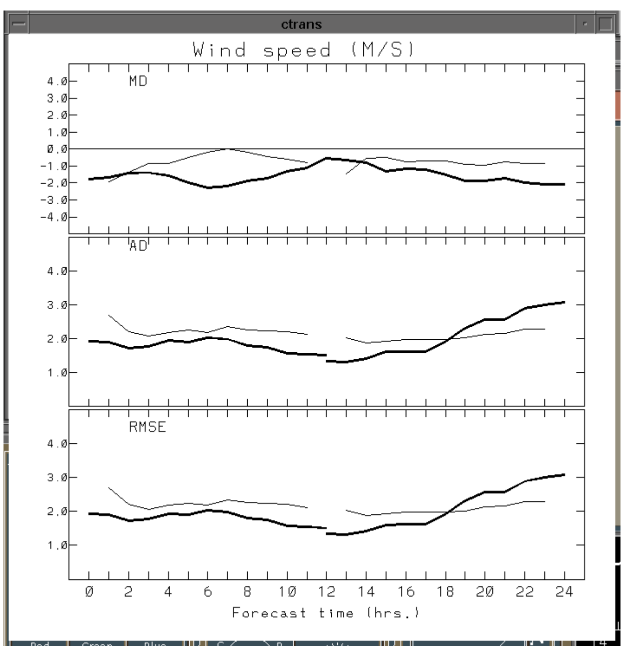

Figure 13 Same as Figure 9, except for wind speed.

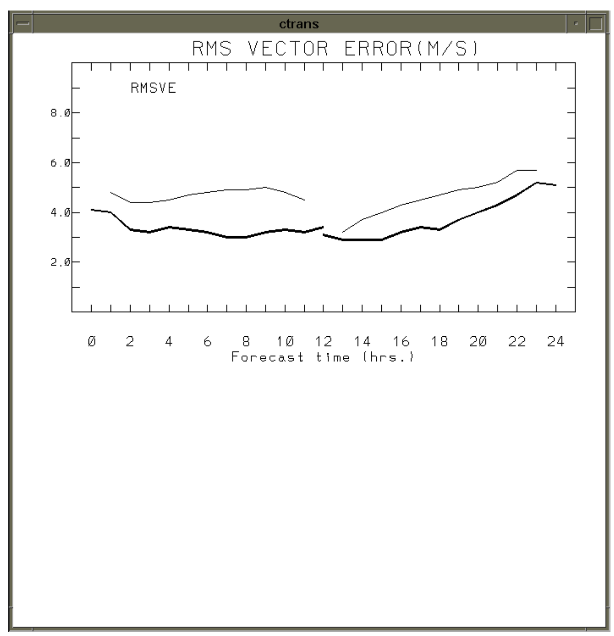

Figure 14 Time series of the RMSVE.

4. In a study of the BFM during June and July, 1998, over three different model domains (Colorado, Washington, and Florida) encompassing 500 x 500 km area with grid spacing of 10 km by Henmi[10], the AD values for surface temperature are in the range of 2 to 3° C, which are similar to the AD values obtained by both MM5 and BFM in this study. However, for wind speed, the above study showed AD smaller than 1 m/sec, and RMSVE in the ranges of 2 to 3 m/sec for three different model domains. The present study shows that by the BFM AD values are in the range of 2 to 3 m/sec, and RMSVE in the range of 4 to 5 m/sec. In a BFM evaluation study over Colorado which covers a 500 x 500 km with a grid spacing of 10 km, Knapp and Dumais [11] obtained the results of AD of 3.0° C for temperature and 1.8 m/sec for wind speed. Both results are similar to the results of the present study for temperature, but smaller for wind speed. At this point, it is not clear why both MM5 and BFM calculations over WSMR with a 3.33 km grid spacing have resulted in larger values of AD and rmsve than in the previous studies.

V. Summary

MM5 and BFM forecast data over the WSMR covering the 42 days during April and May, 1999 are statistically compared with SAMS data. MM5 data interpolated to SAMS locations and archived on the computer of WSMR weather station are used for the study. Since the majority of archived daily data of MM5 are composed of two 12 hour forecast data, the BFM calculations were correspondingly done twice a day, initialized at 00 and 12 UTC. Although forecast calculations initialized at both 00 and 12 UTC produced comparable results for the same period of day between 12 and 24 UTC, those initialized at 12 UTC produced slight improvement over those initialized at 00 UTC. The data for initialization and time-dependent boundary conditions were provided by the U.S. Navy's NOGAPS 0, 6, 12, 18, and 24 hour forecast data, and upper air sounding data at El Paso and Albuquerque.

The following results are obtained from the present study:

1. From the scatter diagrams of forecast and observed data for all of the forecast days, it can be seen that the surface temperature forecast by both MM5 and BFM produced good agreement with SAMS data. On the other hand, both MM5 and BFM showed difficulty in forecasting the relative humidity at the surface. The scatter diagram of wind speed for BFM versus the observations shows that the model tends to under-forecast wind speed. The correlation coefficients for wind speed, and vector wind components (u and v) for both models are comparable, except that the correlation coefficient of v for MM5 is negative.

2. The time series of statistical parameters of both the MM5 and BFM for temperature are very similar, except that MM5 under-forecasts and BFM over-forecasts slightly. It may be concluded that both MM5 and BFM predicted the surface temperature fields over the WSMR model domain reasonably well. The BFM tended to produce a lower relative humidity than observed from the evening to the morning hours and slightly higher values in the afternoon, whereas MM5 tended

to produce a slightly higher relative humidity than observed throughout the 24 hour forecast period.

3. Wind speeds predicted by the BFM are less than those observed throughout the 24-h forecast period. However, probably due to poor performance of MM5 in simulating the y-component of wind vector, v, the RMSVEs for BFM are smaller than those for MM5 throughout the 24 hour forecast period.

4. The majority of SAMS stations in WSMR are located in the valley areas and are not distributed evenly in the model domain. Observed data at a few mountain stations are influenced by localized effects that could not be resolved by the grid spacing (3.33 km) used in the present study. Therefore, this study's statistics should be regarded as qualitative.

5. Up to this time, the BFM has been mainly used with grid spacings greater than 5 km. This study is the first systematic attempt to use the terrain elevation data with grid spacing of 3.33 km. It is encouraging to see that a hydrostatic and a single-nested forecast model, the BFM, has produced comparable statistical results of surface meteorological parameters to the non-hydrostatic and triply-nested MM5.

6. The present study was performed for the period of April and May over WSMR. Further study is needed to cover different seasons and model domains, particularly the winter season in which synoptic scale weather patterns are important to local weather.

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