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Evaluation Study of Mesoscale Models MM5 and BFM Over the Model Domains of Utah Using Surface Meteorological Data by Mesowest

by Teizi Henmi

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Executive Summary

The forecast skills of the Penn State/National Center for Atmospheric Research Mesoscale Model version 5 (MM5), and the Battlescale Forecast Model (BFM) were statistically evaluated by comparing the model forecasting data with surface observation data obtained from the University of Utah Mesowest cooperative. The evaluation study was made for two different periods: January-March 2002, and April-June 2002.

The MM5, with quadruple-nests of 67.5, 22.5, 7.5, and 2.5 km grid increments, all of which have 51x51 grid points centered near Salt Lake City, UT, was set for computation on the U.S. Army High Power Computer. The forecast data of domains 3 and 4, with grid increments of 7.5 and 2.5 km (respectively), are compared with the observation data in each domain. The BFM forecasting calculations were made separately over two model domains with grid increments of 5 and 2.5 km, both centered on Salt Lake City, UT.

The major findings of this study include the following:

1. There are no significant statistical differences in forecast results between MM5 domains 3 and 4. Likewise, the forecast results of the BFM for the two grid increments of 5 and 2.5 km are statistically similar.
2. Both MM5 and the BFM produce better forecast results for surface temperature than for dew point temperature, and have difficulties producing good forecast results for wind vectors.
3. For all of the surface meteorological parameters, MM5 produced statistically better forecast results than the BFM over the complex terrain of Utah.
4. Both MM5 and the BFM showed better forecasting statistics for the period of April-June 2002 than for the period of January-March 2002.

1. Introduction

The Battlescale Forecast Model (BFM), developed at the U.S. Army Research Laboratory (ARL), has been extensively used to make short-range forecasts of atmospheric conditions as a component of the Integrated Meteorological System (IMETS). The BFM uses, for prognostic calculation, a hydrostatic model called the Higher Order Turbulence Model for Atmospheric Circulation (HOTMAC), which was developed by Yamada and Bunker (1989). The HOTMAC was used for prognostic calculation because of its numerical stability, which allows operational forecasting calculations to be made without failure. HOTMAC was also chosen because of its short computational time requirement. A 24-h forecast calculation over a battlescale area, such as 500x500 km^2, could be completed by BFM within one hour on a workstation computer having a single processor.

With advancements in both computer hardware and software, such as the availability of a parallel computer with distributed memory and Message Passage Interface (MPI), applications like non-hydrostatic models with many different physics options are becoming possible. Thus, it is important to evaluate how a non-hydrostatic model, such as the Pennsylvania State University/National Center for Atmospheric Research (NCAR) Mesoscale Model version 5 (MM5), performs over areas of complex terrain. For comparison, the BFM is also evaluated in this study.

In a previous study, the forecast skills of the BFM were compared to those of MM5 by applying the models to the domain of White Sands Missile Range (WSMR), NM, which covers an area of 167x167 km, 51x51 grid points with grid spacing of 3.33 km (Henmi, 2000). Meteorological parameters forecasted by the models were compared with observed data. The comparison study showed that the forecast skills of the BFM are comparable to those of the MM5. Surface temperature forecasted by both the BFM and MM5 agreed well with observed values. Both the BFM and the MM5 showed difficulties for forecasting the relative humidity. In forecasting wind parameters, both models tended to predict wind speed less than that observed, but BFM calculations produced lower wind speed than the MM5. The BFM resulted in better forecasts than the MM5 for wind direction.

In operational mode on the IMETS, the BFM has been extensively used over the model domain of 500x500 km^2 with grid spacing of 10 km. A statistical evaluation of the BFM in operational mode was conducted for cases during a 30-day period over three different model domains (Colorado, Washington and Florida), which had different terrain complexities and climates (Henmi, 2000). The model calculations were initialized with three different sets of initial conditions:

1. NOGAPS + upper air data + surface data
2. NOGAPS + upper air data
3. NOGAPS

Forecast data for 24-h periods were statistically compared with surface observation data by calculating parameters such as mean difference (MD), absolute difference (AD), root mean square error (RMSE), root mean square vector error (RMSVE), and correlation coefficient (CC).

For all three model domains, the temperature fields of the BFM were statistically better when initialized with (1) and (2) than when initialized with (3). For Colorado and Washington model domains, the BFM showed clear tendencies of forecasting dew point temperature lower than those observed throughout the 24-h forecast period. However, for the Florida model domain, forecasts of dew point temperature were higher than observed.

The three different types of initialization data did not produce significantly different wind fields throughout the 24-h forecast period. The value of MD for wind speed is in the range of 0 to 1 m/sec. The values of AD are also between 0 and 1 m/sec for the three model domains throughout the 24-h forecast period.

For the Colorado and Washington model domains, where the terrain is more complex than in Florida, the use of the BFM improves temperature forecasts over those of the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Navy Operational Regional Atmospheric Prediction System (NORAPS). For the Florida domain, no significant improvements in temperature forecasts are found. Similarly, the BFM produces better wind fields than NOGAPS and NORAPS over Colorado and Washington.

In the recent study of an objective multiyear evaluation of the University of Washington real-time MM5 forecasts, in which forecasts from the 36, 12, and 4 km domains were verified at surface observation locations over western Washington state, Mass et al. states: "Reduction from 36 to 12 km grid increments allows the definition of the major topographic features of the region and their corresponding atmospheric circulations, resulting in a beneficial effect on the evaluation. However, there are only small improvements in verification statistics as grid spacing decreased from 12 to 4 km." (2002).

The purpose of this report is to describe the results of a statistical evaluation of surface forecast data from MM5 domains with grid increments of 7.5 and 2.5 km, and from BFM domains with grid increments of 5 and 2.5 km, all of which are centered near Salt Lake City, UT, and use Mesowest data. The ARL High Power Computer (HPC) parallel computer is extensively used for this study.

2. Description of the Models and Model Domains

2.1 MM5

The model used in this study is the distributed-memory version of the PSU-NCAR MM5. The source code of MM5 was obtained from the MM5 Home page (2001).

The MM5 is based on non-hydrostatic dynamics and features multiple-nest capabilities and many physics options. Details of this modeling system can be found in Dudhia (1993), Grell et al. (1994) and Warner et al. (1992).

For the present study, the following physics options are employed:

1. *Planetary Boundary Layer (PBL)*. The PBL technique that is used in the Medium-Range Forecast (MRF) model of the National Center for Environmental Prediction (NCEP) by Hong and Pan (1996).
2. *Precipitation parameterization*. A simple treatment of cloud microphysics based on Dudhia (1989), in which both ice and liquid phases are permitted for cloud and precipitation, but mixed phases are not permitted.
3. *Cumulus parameterization*. Grell's scheme that is based on rate of destabilization or quasi-equilibrium, simple single-cloud scheme with updraft and downdraft fluxes, and compensating motion determining heating and moistening profile (1994).
4. *Radiation parameterization*. Dudhia's scheme in which long wave and short wave radiation interact with the clear atmosphere, clouds, precipitation, and the ground (1989).
5. *Ground temperature scheme*. Multilayer soil temperature model.

The MM5 quadruple-nested computational grids are depicted in figure 1. All four computational domains have a mesh size of 55x55 grid points, and grid increments of 67.5, 22.5, 7.5, and 2.5 km, respectively, for domains 1, 2, 3, and 4. For the present study, the forecast fields only for domains 3 and 4 are compared with observed data.

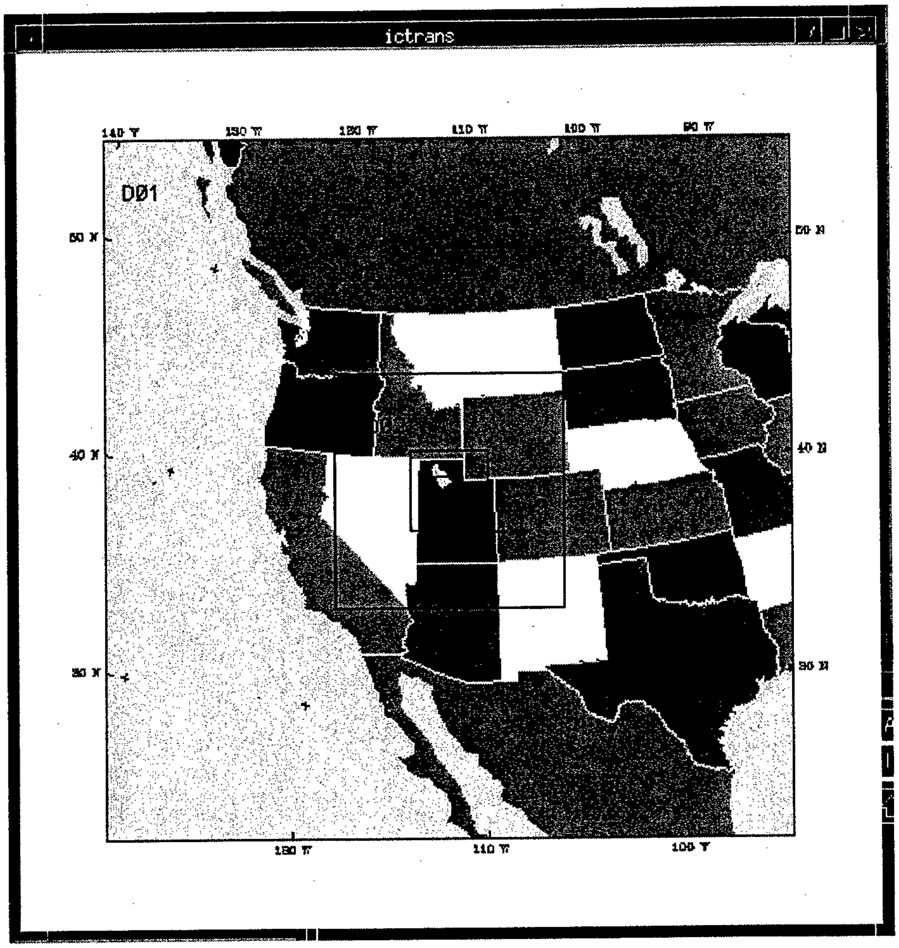

Figure 1. Geographical extents of the four computational domains.

Terrain height contours of domains 3 and 4 are shown, respectively, in figures 2 and 3. Terrain, vegetation/land use, and soil type data for the model domains are obtained from data archived in the MM5 Internet site.

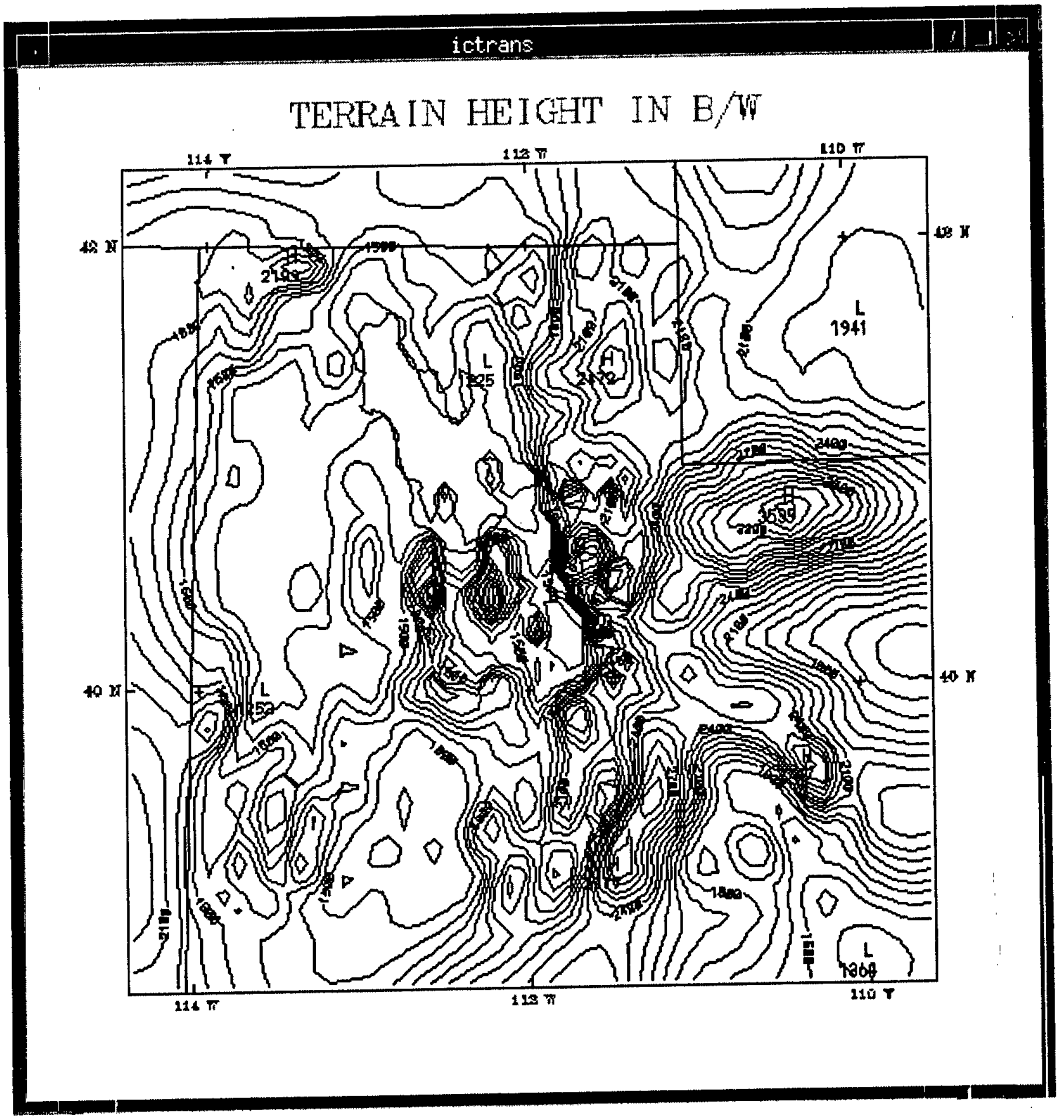

Figure 2. Terrain contours of MM5 domain 3.

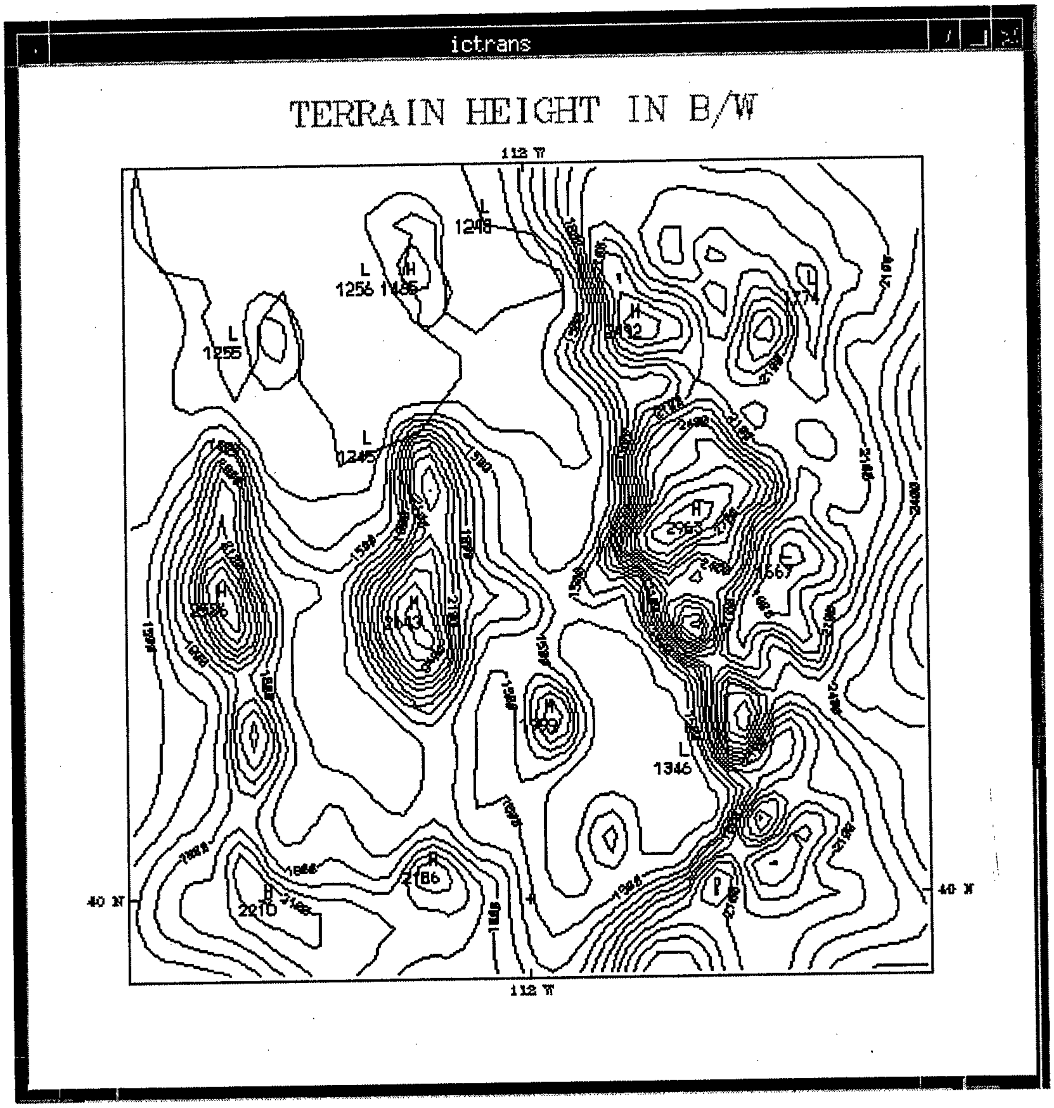

Figure 3. Terrain contours of MM5 domain 4.

2.2 BFM

The BFM is an operational mesoscale forecast model developed by the ARL (Henmi and Dumais, 1998) at WSMR, NM. It has been extensively used to make short-range forecasts of atmospheric conditions as a component in the IMETS. The BFM uses, for prognostic calculation, the HOTMAC, developed by Yamada and Bunker (1989). In operational mode on the IMETS, the BFM has been extensively used over a model domain of 500x500 km with grid increments of 10 km. So far, there has been no evaluation study of the BFM over the domain with grid increment smaller than 5 km for an extended period. In this study, the BFM was used over two domains with 2.5 and 5 km grid increments, centered at Salt Lake City, UT.

Figure 4 shows the terrain contours of the 2.5 km grid increment domain. Figure 5 shows the terrain contours of the 5 km grid increment domain. An inner squared area of 51x51 grid points with 125 km^2 and 250 km^2 are used for the model calculations, respectively, for figures 4 and 5. In these figures, the inner, squared areas represent the BFM model domains. The spots denoted by "N" are the locations of the NOGAPS grid points that are used for initial and time-dependent boundary values, and the spots denoted by "*" represent the Mesowest data points. For model evaluation, data within the squared area is used.

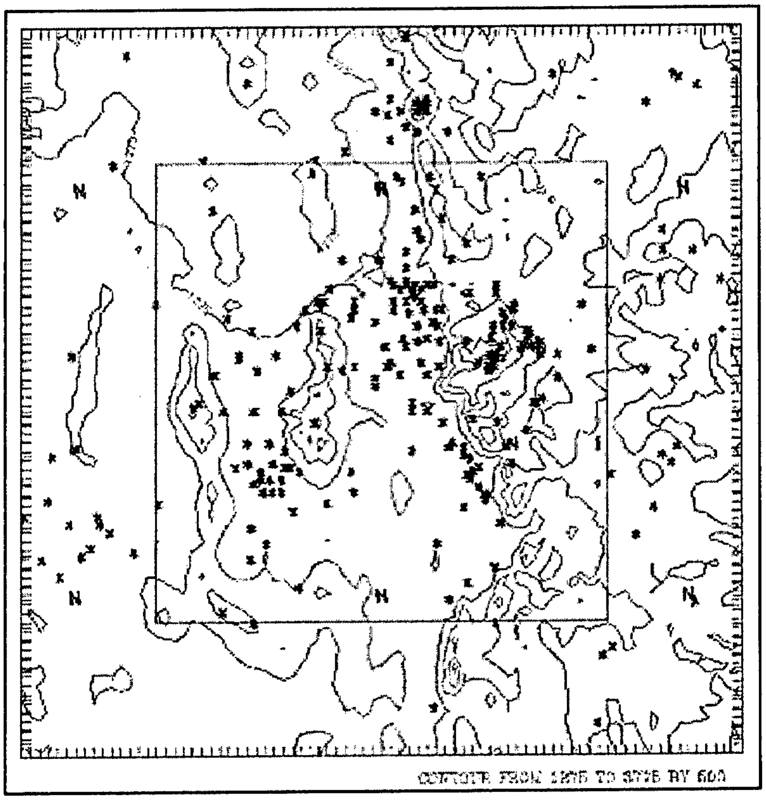

Figure 4. Terrain contours of the BFM model domain
(2.5 km grid increments).

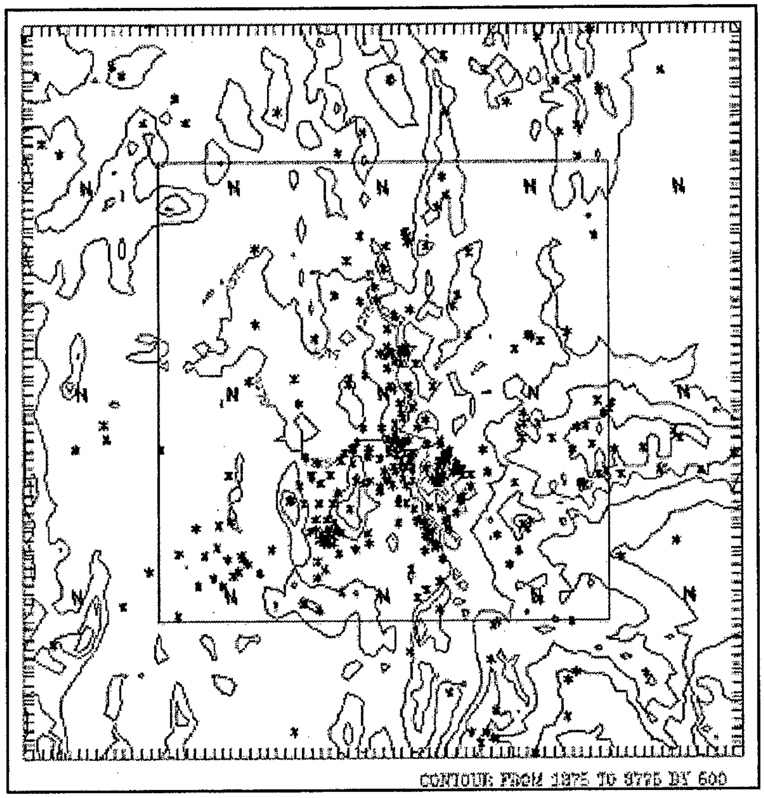

Figure 5. Terrain contours of the BFM model domain
(5 km grid increments).

3. Meteorological Data

There is a large amount of surface observation data available for the model domains that are shown in figures 4 and 5. The data is freely available from the University of Utah Mesowest cooperative.

A Mesowest data file, called "total.dat," contains data in 15-min intervals for a 24-h period for the western United States. A detailed description of Mesowest data can be found in Horel et al. (2002).

A daily data file that contains data only for the even hours of a 24-h period (starting at 00:00 UTC (universal time coordinate)) was created for the areas to be studied. Table 1 displays a portion of the daily data file. Table 1 shows the following (from left to right): station name, day, hour, minute, latitude, longitude, wind direction, wind speed (knot), temperature (°F), dew point temperature (°F), relative humidity (%), and 24-h accumulated precipitation (in this example –9999.0 zero or no report). This data was compared to hourly model forecast data.

Table 1. Portion of the daily data.

BGRUT	2	516	0	0	40.93	-112.56	90.00	7.80	62.00	35.50	37.00-9999.00
BR4	2	516	0	0	41.44	-112.16	148.00	0.90	65.00	27.40	24.00-9999.00
DVB	2	516	0	0	40.62	-111.48	248.00	2.60	56.00	19.70	24.00-9999.00
EMPUT	2	516	0	0	40.61	-111.53	245.00	4.30	45.00	20.30	37.00-9999.00
FPK	2	516	0	0	41.03	-111.84	323.00	13.00	38.00	8.50	29.00-9999.00
FWP	2	516	0	0	40.66	-112.20	244.00	3.50	43.00	17.20	35.00-9999.00
GNI	2	516	0	0	41.33	-112.85	96.00	8.70	62.00	29.40	29.00-9999.00
HAT	2	516	0	0	41.07	-112.59	42.00	7.00	62.00	23.80	23.00-9999.00
LDS1	2	516	0	0	40.77	-111.89	359.00	3.50	63.00	17.50	17.00-9999.00
LMR	2	516	0	0	41.06	-112.89	104.00	0.00	60.00	22.10	23.00-9999.00
LMS	2	516	0	0	41.70	-112.85	148.00	2.60	67.00	20.80	17.00-9999.00
MBY	2	516	0	0	40.61	-111.48	282.00	9.60	48.00	16.50	28.00-9999.00
PCB	2	516	0	0	40.65	-111.51	347.00	1.70	60.00	24.10	25.00-9999.00
PCS	2	516	0	0	40.65	-111.52	266.00	1.70	55.00	20.80	26.00-9999.00
PRP	2	516	0	0	41.26	-112.44	341.00	6.10	53.00	10.60	18.00-9999.00
SB1	2	516	0	0	41.19	-111.84	312.00	3.50	55.00	13.50	19.00-9999.00
SNH	2	516	0	0	40.55	-111.85	340.00	4.30	65.00	26.30	23.00-9999.00
SNI	2	516	0	0	41.20	-111.86	20.00	0.90	50.00	15.60	25.00-9999.00
SNV	2	516	0	0	40.62	-111.51	269.00	0.90	52.00	20.70	29.00-9999.00
SNX	2	516	0	0	41.04	-112.23	48.00	4.30	62.00	27.70	27.00-9999.00
SNZ	2	516	0	0	40.88	-111.87	339.00	0.00	66.00	25.00	21.00-9999.00
TPC	2	516	0	0	40.43	-111.71	192.00	4.30	52.00	23.10	32.00-9999.00
WBU	2	516	0	0	40.71	-111.56	271.00	4.30	61.00	25.00	25.00-9999.00
WCR	2	516	0	0	40.55	-111.32	261.00	7.80	57.00	16.30	20.00-9999.00
KMS	2	516	0	0	40.56	-111.13	253.00	3.50	57.00	18.50	22.00-9999.00
SKY	2	516	0	0	39.58	-111.25	249.00	8.70	52.00	16.30	24.00-9999.00
UT1	2	516	0	0	41.20	-111.11	225.00	10.50	56.10	16.20	20.00-9999.00
UT12	2	516	0	0	40.64	-111.90	0.00	5.80	66.00	21.90	18.00-9999.00
UT20	2	516	0	0	40.75	-111.90	337.50	6.80	66.70	20.80	17.00-9999.00
UT23	2	516	0	0	40.72	-111.90	0.00	7.20	67.60	20.70	16.00-9999.00
UT5	2	516	0	0	40.71	-111.80	270.00	6.00	64.90	17.20	15.00-9999.00
UT7	2	516	0	0	40.48	-111.90	0.00	12.60	65.10	19.90	17.00-9999.00
UT9	2	516	0	0	40.68	-112.26	22.50	15.60	63.10	23.40	22.00-9999.00
SND	2	516	0	0	40.37	-111.59	167.00	7.00	55.00	19.80	25.00-9999.00
QSA	2	516	0	0	40.83	-112.01	5.00	7.00	63.00	22.50	21.00-9999.00
KEM	2	516	0	0	41.76	-110.58	270.00	16.50	54.00	25.60	33.00-9999.00
LGP	2	516	0	0	41.71	-111.71	288.00	10.40	36.00	14.60	41.00-9999.00
CASD	2	516	0	0	39.22	-111.02	257.40	8.80	74.10	28.20	18.20-9999.00
ELMO	2	516	0	0	39.40	-110.81	286.60	5.90	77.00	20.60	12.10-9999.00
FERR	2	516	0	0	39.09	-111.09	359.30	11.60	68.80	17.70	14.10-9999.00
GUNN	2	516	0	0	39.16	-111.81	333.20	11.20	74.60	27.00	17.00-9999.00
LITW	2	516	0	0	39.32	-111.33	339.80	7.20	67.50	33.90	28.80-9999.00
MOLE	2	516	0	0	39.06	-111.14	202.50	10.50	70.90	18.20	13.30-9999.00
CUPC	2	516	0	0	40.36	-111.90	333.40	6.30	67.20	27.40	22.30-9999.00
CUPE	2	516	0	0	40.49	-111.47	255.40	6.30	65.80	25.90	22.00-9999.00
CUPF	2	516	0	0	40.22	-111.11	273.60	11.70	54.60	31.00	40.40-9999.00
CUPG	2	516	0	0	40.37	-111.03	355.30	7.30	54.40	30.30	39.50-9999.00
CUPI	2	516	0	0	40.56	-110.70	354.40	0.00	55.80	14.60	19.40-9999.00
MSI01	2	516	0	0	40.72	-111.86	325.00	5.60	69.70	25.60	19.00-9999.00
BBN	2	516	0	0	40.89	-111.85	330.00	2.60	63.00	17.50	17.00-9999.00
ARAU1	2	516	0	0	40.59	-113.02	40.00	6.10	64.00	13.00	14.00-9999.00
BRAU1	2	516	0	0	40.88	-110.83	90.00	4.30	54.00	19.00	26.00-9999.00

NOGAPS data, which is available for every 1° grid point for the entire world, is used for initialization and time-dependent lateral boundary conditions for both the MM5 and the BFM. The forecast data for the periods of 0, 12, and 24-h, initialized at 00:00 UTC, were obtained at 13 pressure levels from 1000 mb to 100 mb. The data was obtained through the Defense Modeling and Simulation Office, Master Environmental Library Web site.

Upper-air sounding data was obtained from the University of Wyoming Web site.

For this study, these three different data sets for the winter and spring of 2002 were collected, and model calculations for 24-h forecasting were performed for both seasons (Table 2).

Table 2. Dates of archived data sets and model calculations for 24-h forecasting.

Winter, 2002	Spring, 2002
January 15, 22, 23, 24, 25, 28, 29, 30	April 17, 22, 23, 24, 30
February 4, 5, 6, 7, 8, 11, 12, 13, 14, 19, 20, 21, 22, 26, 27,28	May 1, 2, 6, 8, 13, 14, 16, 20, 21, 30 31
March 4, 5, 6, 7, 8, 11, 12, 14	June 3, 4, 5, 10, 11, 17, 18, 19, 20

4. Forecast and Evaluation Methods

4.1 Forecast Method

4.1.1 MM5

The standard method of MM5 initialization (REGRID) is used, which is discussed in the MM5 user's manual (MM5 Home Page, 2001). GRIB-formatted NOGAPS data on pressure levels is read and interpolated to the MM5 grid. For the MM5 calculations, only NOGAPS data is used. The program, INTERP, conducts vertical interpolation, diagnostic computation and data reformatting to generate model initial and lateral boundary conditions, and a lower boundary condition. The data sets are generated separately for four different nested grids.

4.1.2 BFM

From the NOGAPS data, horizontal wind vector components, temperature, dew point temperature and geopotential height at 13 different pressure levels for the forecast periods of 0, 12, and 24-h are interpolated to the 81x81 grid with grid increments of 2.5 or 5 km at each pressure level for the above forecast periods. The data is then vertically interpolated from the pressure levels to the BFM's height levels to produce 4-d fields of the input data for initialization and lateral boundary conditions. In this study, all model calculations were initiated at 00:00 UTC. The 0-h NOGAPS data is composed with upper air sounding data obtained at Salt Lake City. The details of the initialization method are described in Henmi and Dumais (1998).

4.2 Evaluation Method

4.2.1 Data Comparison Method

After the forecast calculation is completed, the following bilinear interpolation is conducted to obtain model forecast data at the surface observation locations.

Suppose a surface observation location (x' and y') is surrounded by four model grid points. An interpolated value, φ', of an arbitrary variable, φ at (x', y'), is calculated using a bilinear interpolation method, such as:

$$\varphi_1=\varphi(i,j)+(x'-x)[\varphi(i+1,j)-\varphi(i,j)]$$
$$\varphi_2=\varphi(i,j+1)+(x'-x)[\varphi(i+1,j+1)-\varphi(i,j+1)]$$
$$\varphi'(x',y')=\varphi_1+(y'-y)[\varphi_2-\varphi_1] \quad (1)$$

where

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

4.2.2 Statistical Parameters

The following statistical parameters between model forecast data and surface observation data are calculated using the data available in the model domains. The parameters are calculated hourly for the entire period. Statistical parameters are calculated for temperature, relative humidity, wind speed and horizontal wind vector components u and v.

Mean Difference (MD):

$$MD=\frac{\sum_{j=1}^{m}\sum_{i=1}^{n}(x_{p,i,j}-x_{o,i,j})}{mn} \quad (2)$$

where

the subscript *o* represents observation and *p* represents prediction. The subscript *i* represents the i^{th} surface station, and the subscript *j* represents the j^{th} forecast day. *n* is the number of surface stations, and *m* is the total number of forecast days.

A nonzero MD indicates bias. For instance, if the MD value is positive, it indicates that the model tends to over-forecast.

Mean Absolute Difference (AD):

$$AD = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n}\left|x_{p,i,j} - x_{o,i,j}\right|}{mn} \tag{3}$$

Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{j=1}^{m}\sum_{i=1}^{n}(x_{o,i,j} - x_{o,i,j})^2}{mn}} \tag{4}$$

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

Root Mean Square Vector Error (RMSVE):

$$RMSVE = \sqrt{\frac{\sum_{j=1}^{m}\sum_{i=1}^{n}[(u_{o,i,j} - u_{p,i,j})^2 + (v_{o,i,j} - v_{p,i,j})^2]}{mn}} \tag{5}$$

This parameter measures the differences of both wind speed and direction. Good agreements of wind vectors are related to small values of the RMSVE.

Correlation Coefficient (CC):

$$CC = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} y_{o,i,j}\, y_{p,i,j}}{\sqrt{\sum_{j=1}^{m}\sum_{i=1}^{n} y_{o,i,j}^{2} \sum_{j=1}^{m}\sum_{i=1}^{n} y_{p,i,j}^{2}}} \tag{6}$$

where

$$y_{p,i,j} = x_{p,i,j} - \overline{x_p}$$

$$y_{o,i,j} = x_{o,i,j} - \overline{x_o}$$

x_o and x_p are the means of observed and forecasted values, respectively.

5. Results

The following section presents statistical parameters that were calculated between model forecast data and surface observation data. For this study, all of the MM5 forecast calculations are done with a 6-h spin-up period. So for the MM5, forecast data is only available between 06:00 and 24:00 UTC. For the BFM, 24-h forecast data between 00:00 and 24:00 UTC is available.

5.1 Statistical Parameters of Daily Data

Table 3 shows the statistical parameters (CC, MD, and RMSE) of surface temperature calculated for the daily data from the period of January-March 2002. Table 4 shows the statistical parameters (CC, MD and the mean wind direction difference between model and observation data (MWDDF)) of wind vector calculated for the daily data from the period of January-March 2002. The results that are displayed in Tables 3 and 4 are for MM5 domain 4 and the BFM of the grid increment of 2.5 km.

Table 3. Statistical parameters calculated for surface temperature.

		MM5			BFM	
Date	**CC**	**MD**	**RMSE**	**CC**	**MD**	**RMSE**
1-15	.06	.7	3.0	.30	2.6	4.4
1-22	.82	.0	2.7	.72	2.6	4.8
1-23	.73	-.7	3.5	.78	2.0	3.6
1-24	.59	-1.6	4.2	.73	1.1	3.4
1-25	-.25	1.9	3.9	.47	1.2	3.2
1-28	.68	1.4	3.1	.78	2.6	3.8
1-29	.63	-.5	3.2	.80	3.2	4.0
1-30	.35	-.7	3.9	.63	2.5	4.3
2-04	.40	.8	4.2	.48	1.8	4.1
2-05	.55	.7	4.5	.56	1.6	4.0
2-06	.53	2.1	4.8	.59	2.3	4.4
2-07	.44	4.0	6.3	.62	.8	3.8
2-08	.63	-1.2	4.1	-.02	-5.2	8.4
2-11	.52	1.1	4.6	.64	.56	3.6
2-12	.58	-.2	3.3	.51	4.2	5.8
2-13	.56	-.3	4.7	.57	6.4	7.7
2-14	.61	.0	2.2	.54	1.4	2.8
2-17	.78	-1.8	3.5	.64	.23	3.4
2-20	.73	-1.0	2.9	.54	-1.3	3.7
2-22	.54	2.0	3.8	.51	-.6	3.6
2-26	.78	-.9	3.9	.65	7.5	8.6
2-27	.81	-1.9	2.6	.69	2.1	3.6
2-28	.70	-.6	3.1	.59	1.6	3.9
3-04	.88	.36	3.0	.69	4.3	5.9
3-05	.81	.6	3.4	.77	-1.0	3.8
3-07	.86	-.7	2.7	.23	-3.5	6.6
3-11	.88	.4	2.6	.77	-.5	3.4

Table 3. Statistical parameters calculated for surface temperature (continued).

3-12	.77	-.6	2.6	.40	-2.3	4.9
3-14	.87	-2.1	3.3	.69	3.3	4.6

Table 4. Statistical parameters calculated for wind vector.

		MM5			BFM	
Date	**CC**	**RMSVE**	**MWDDF**	**CC**	**RMSVE**	**MWDDF**
1-15	.20	3.6	56.9	.15	4.3	64.1
1-22	.11	5.6	43.1	-.18	7.3	55.9
1-23	.21	2.6	65.6	.00	2.9	62.9
1-24	.17	3.3	64.8	.00	3.2	73.6
1-25	.39	4.4	55.0	.13	3.4	55.0
1-28	.20	6.3	52.2	.11	5.8	50.7
1-29	.29	2.8	46.3	-.01	2.6	42.6
1-30	.00	4.2	62.8	.03	2.9	52.8
2-04	.40	2.3	34.5	.07	2.3	41.8
2-05	.06	2.9	58.6	-.04	2.8	45.6
2-06	.26	2.3	70.5	.00	2.6	70.0
2-07	.24	3.9	57.2	.03	2.8	62.3
2-08	.23	7.0	45.2	.07	5.7	69.8
2-11	.31	3.1	54.3	.09	2.7	55.0
2-12	.48	2.8	35.9	.10	3.5	37.6
2-13	.10	3.7	60.7	.03	4.2	79.4
2-14	.51	3.4	42.2	.18	4.0	61.2
2-19	.29	3.0	49.3	.02	4.0	75.0
2-20	.31	4.7	60.8	-.03	4.9	77.5
2-22	.50	3.4	48.8	-.03	3.5	70.0
2-26	.23	3.6	57.3	-.08	4.5	67.4
2-27	.21	4.0	31.1	.08	4.7	53.1
2-28	.41	4.5	50.8	.17	4.6	70.3
3-04	.51	2.6	66.4	.02	3.4	66.2
3-05	.26	4.0	45.2	.10	3.2	61.0
3-07	.19	5.7	43.2	.03	4.0	65.7
3-11	.45	3.29	46.7	-.05	3.9	59.8
3-12	.50	4.0	32.1	.01	9.8	73.2
3-14	.12	4.0	28.6	-.13	4.7	45.8

The values of daily statistical parameters for both temperature and wind vary considerably between days. For surface wind forecasts, the CC values for MM5 are greater than those for the BFM, and the MWDDF values for MM5 are smaller than those for the BFM throughout the period (Table 4). These results indicate that MM5 performed better than the BFM in wind forecasts over the complex terrain of Utah. However, for surface temperature forecasts, statistical parameters for both models are compatible (Table 3). As shown in the appendix, similar results are obtained between MM5 domain 3 and the BFM with 5 km grid increments.

5.2 MM5 Forecast and Observation Data Comparison

Figures 6–15 are scatter diagrams that illustrate the difference between the MM5 forecast data and the observation data for the period of January-March 2002. For each set of figures that follow, MM5 domain 3 with grid increments of 7.5 km is the figure displayed at the top of the page, and MM5 domain 4 with grid increments of 2.5 km is the figure displayed at the bottom.

Diagrams for the period of April-June 2002 can be found in Appendix B. Figures representing the BFM for the periods of January-March and April-June 2002 are included in Appendixes C and D.

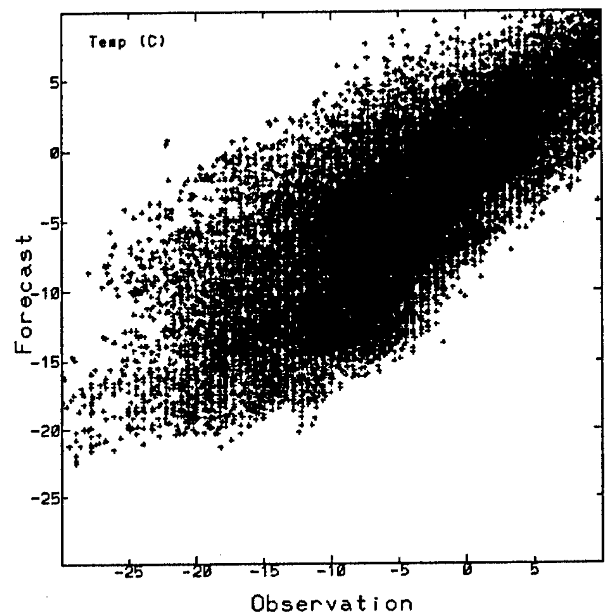

Figure 6. Difference between MM5 forecast and observation: temperature (domain 3).

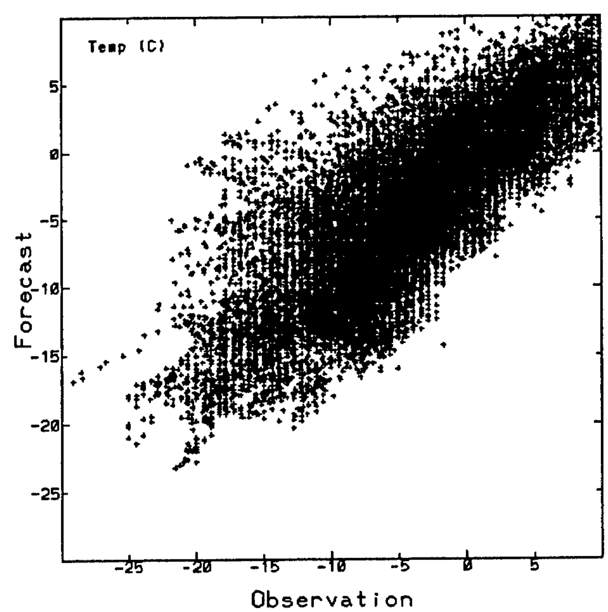

Figure 7. Difference between MM5 forecast and observation: temperature (domain 4).

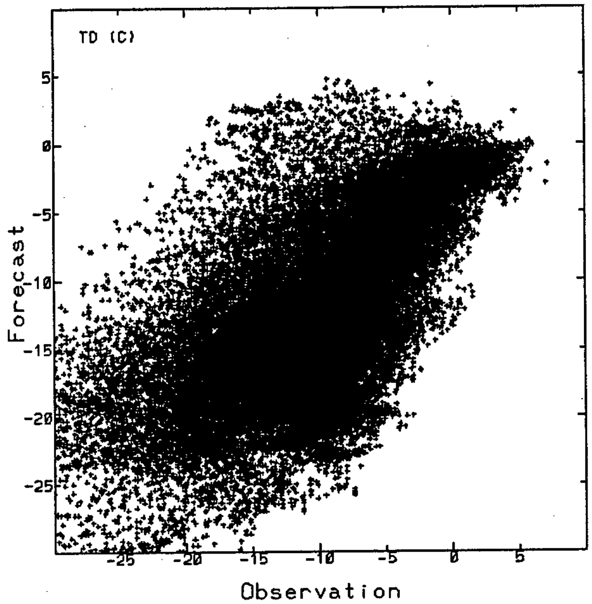

Figure 8. Difference between MM5 forecast and observation: dew point temperature (domain 3).

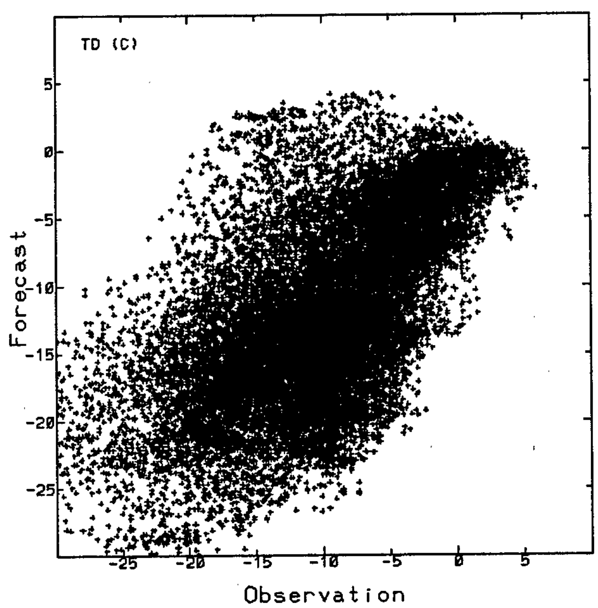

Figure 9. Difference between MM5 forecast and observation: temperature (domain 4).

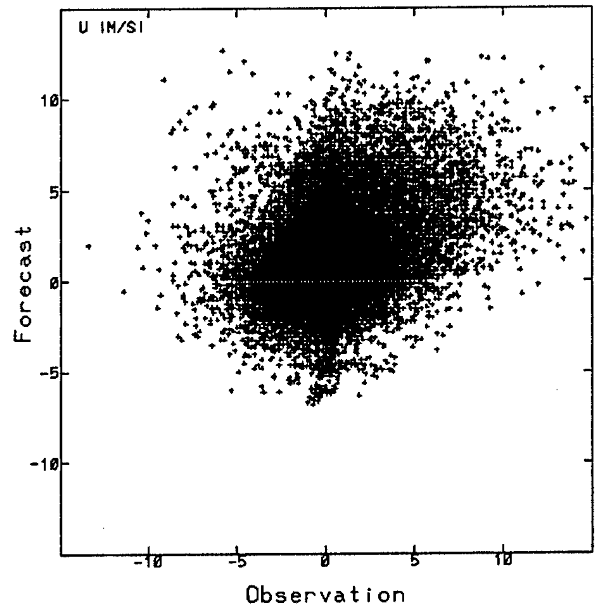

Figure 10. Difference between MM5 forecast and observation: wind vector-x component u (domain 3).

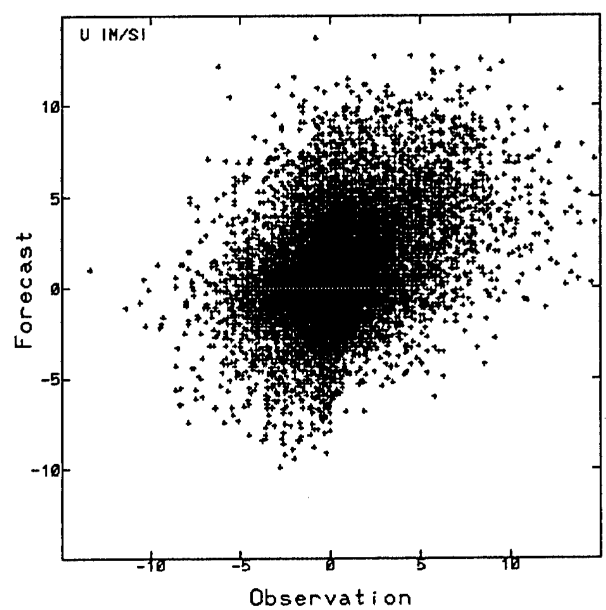

Figure 11. Difference between MM5 forecast and observation: wind vector-x, component u (domain 4).

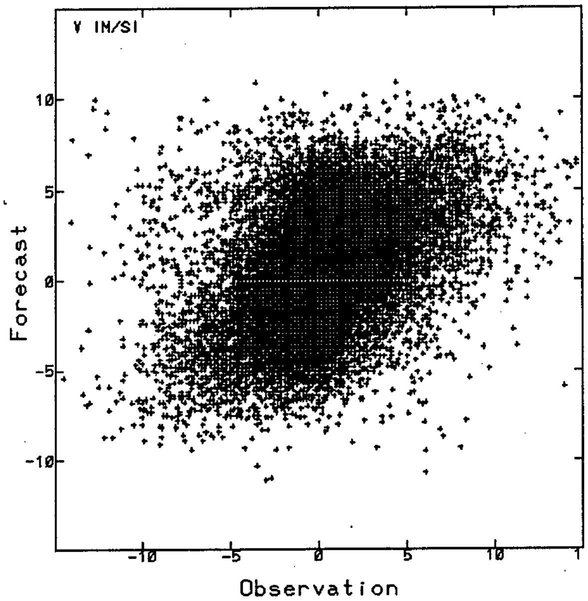

Figure 12. Difference between MM5 forecast and observation: wind vector-y, component v (domain 3).

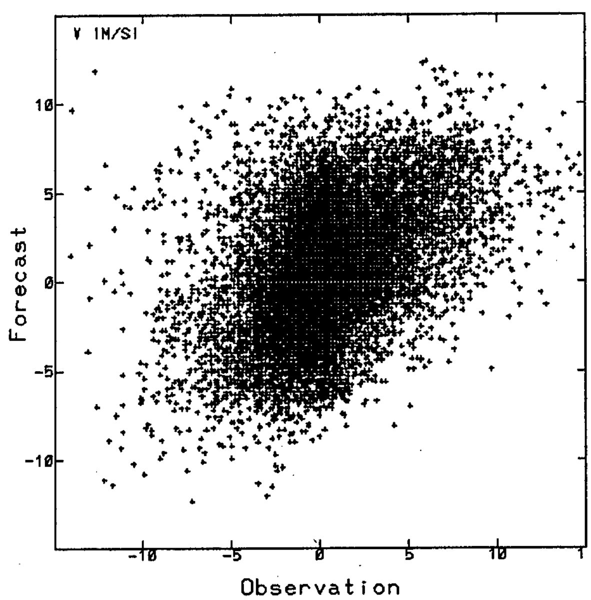

Figure 13. Difference between MM5 forecast and observation: wind vector-y, component v (domain 4).

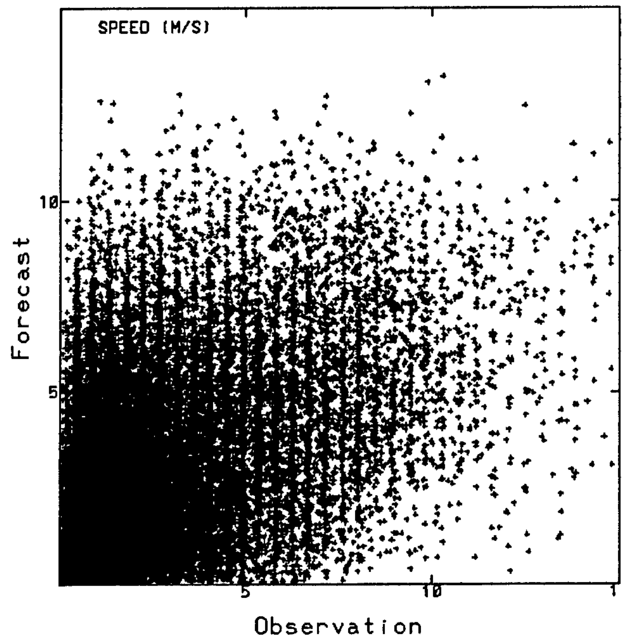

Figure 14. Difference between MM5 forecast and observation: wind speed (domain 3).

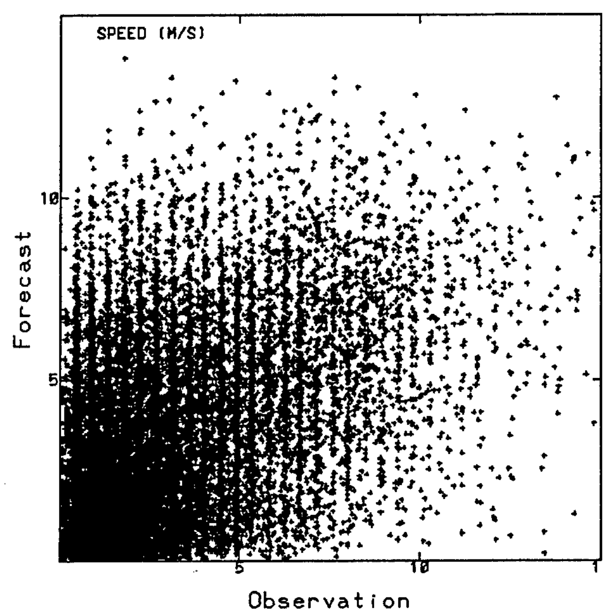

Figure 15. Difference between MM5 forecast and observation: wind speed (domain 4).

Figures 6–15 were obtained by plotting all of the data accumulated including 18 forecast hours during a period of 30 days in January-March 2002. For instance, the figure representing the temperature of MM5 domain 4 (figure 7) contains more than 27,000 points. Similar figures for the BFM can be found in Appendixes C and D.

5.3 Statistical Parameters of Entire Forecasting Periods

Statistical parameters are calculated for the data inclusive of all forecast hours and days during the two seasons. Tables 5, 6, and 7 are calculated for the period of January-March 2002, and Tables 8, 9, and 10 are calculated for the period of April-June 2002. Tables 5 and 8 contain CC, MD, AD, and RMSE of temperature for four different model domains. Tables 6 and 9 contain CC, MD, AD, and RMSE of dew point temperature. Tables 7 and 10 contain the statistical parameters for wind: CC, MD, and AD of wind speed, and RMSVE and MWDDF.

Table 5. Statistical parameters of temperature for different model domains (January-March 2002).

Parameters	**MM5 D3 7.5 km grid**	**MM5 D4 2.5 km grid**	**BFM 5 km grid**	**BFM 2.5 km grid**
CC	.79	.81	.71	.69
MD	.30	-.02	1.5	1.3
AD	3.3	2.9	3.7	3.6
RMSE	4.3	3.9	4.9	4.8
# of Data	43,192	27,042	56,300	35,807

Table 6. Statistical parameters of dew pt temperature for different model domains (January-March 2002)

Parameters	**MM5 D3 7.5 km grid**	**MM5 D4 2.5 km grid**	**BFM 5 km grid**	**BFM 2.5 km grid**
CC	.66	.64	.61	.63
MD	-1.6	-1.9	-2.1	-2.8
AD	4.5	4.6	4.6	4.8
RMSE	5.7	5.9	5.6	5.8
# of Data	42,864	26,830	57,181	36,388

Table 7. Statistical parameters of wind vector for different model domains (January-March 2002).

Parameters	**MM5 D3 7.5 km grid**	**MM5 2.5 km grid**	**BFM 5 km grid**	**BFM 2.5 km grid**
CC of speed	.37	.42	.09	.09
MD of speed	.7	.5	-.4	.0
AD of speed	1.9	1.9	1.9	2.1
RMSVE	4.1	4.1	4.7	5.0
MWDDF	51.2	49.4	62.7	61.2
# of Data	37,177	22,594	47,706	29,420

Table 8. Statistical parameters of temperature for different model domains (April-June 2002).

Parameters	**MM5 D3 7.5 km grid**	**MM5 2.5 km grid**	**BFM 5 km grid**	**BFM 2.5 km grid**
CC	.86	.87	.70	.70
MD	-.62	-.64	-.5	-.4
AD	3.3	3.2	4.5	4.5
RMSE	4.2	4.0	6.1	6.1
# of Data	19,338	13,520	28,007	19,636

Table 9. Statistical parameters of dew point temperature for different model domains (April-June 2002).

Parameters	MM5 D3 7.5 km grid	MM5 2.5 km grid	BFM 5 km grid	BFM 2.5 km grid
CC	.56	.53	.33	.32
MD	4.0	3.8	-2.3	-2.5
AD	5.5	5.4	4.9	5.0
RMSE	7.0	6.9	6.5	6.6
# of Data	19,429	13,573	28,211	19,757

Table 10. Statistical parameters of wind vector for different model domains (April-June 2002).

Parameters	MM5 D3 7.5 km grid	MM5 2.5 km grid	BFM 5 km grid	BFM 2.5 km grid
CC of speed	.28	.25	.07	.02
MD of speed	.37	.50-	-.2	.1
AD of speed	2.0	2.2	2.3	2.5
RMSVE	4.3	4.4	4.7	5.0
MWDDF	57.1	54.4	59.5	61.1
# of Data	17,077	11,737	24,354	16,934

From the data displayed in Tables 5–10, the following can be inferred:

1. Both MM5 and the BFM yielded better forecasting statistics in the period of April-June 2002 than in the period of January-March 2002. This may be caused by the following: over the middle latitude area, the forcing by synoptic weather patterns is more dominant than the forcing by local surface heating/cooling in cold months than in warm months. Synoptic weather forcing is inputted into model calculation as initial and lateral condition values from the NOGAPS forecast data, and local forcing effects are calculated by surface physics routines of the models.
2. There are no significant statistical differences between MM5 domain 3 (grid increments of 7.5 km) and domain 4 (grid increments of 2.5 km). Similarly, the statistical parameters for the BFM of grid increments 5 km and 2.5 km are similar. Reducing the grid increment does not produce a significant improvement of forecast skills for either MM5 or the BFM.
3. For all the meteorological parameters of temperature, dew point, and wind vector, the statistical parameters for MM5 are better than those for the BFM. Note that the amount of data is different for MM5 and the BFM.
4. Both MM5 and the BFM show better forecast skills for temperature than they show for dew point temperature and wind vector.
5. Over the complex terrain of Utah, both MM5 and BFM show low forecast skills for wind vector.

5.4 Time Series of the Statistical Parameters

Every statistical parameter is calculated at each forecast hour using all available data for the period. In this section, figures 16–23 display the time series for MM5 domain 4, and the BFM of 2.5 km grid increment for the period of April-June 2002. For MM5, the data for the time period of 06–23 h are plotted. For the BFM, the data is plotted from 00–24 h. Similar figures are shown in Appendixes A, B, C, and D for other model domains and periods.

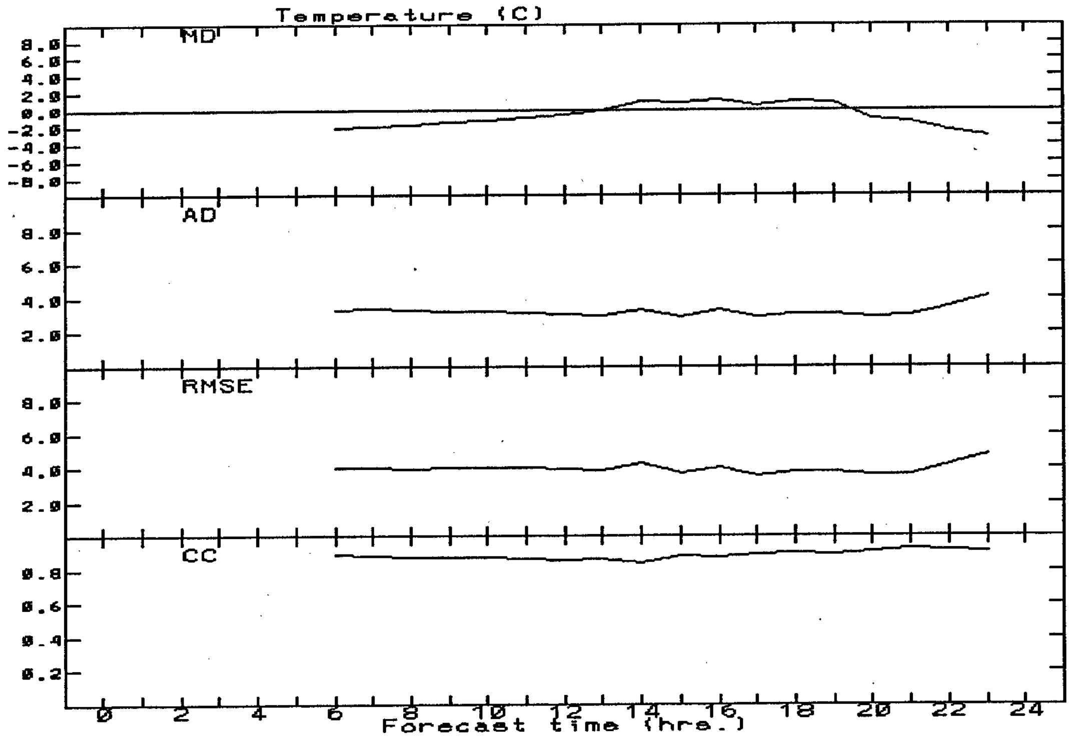

Figure 16. Time series of statistical parameters for temperature (April-June 2002, MM5 domain 4).

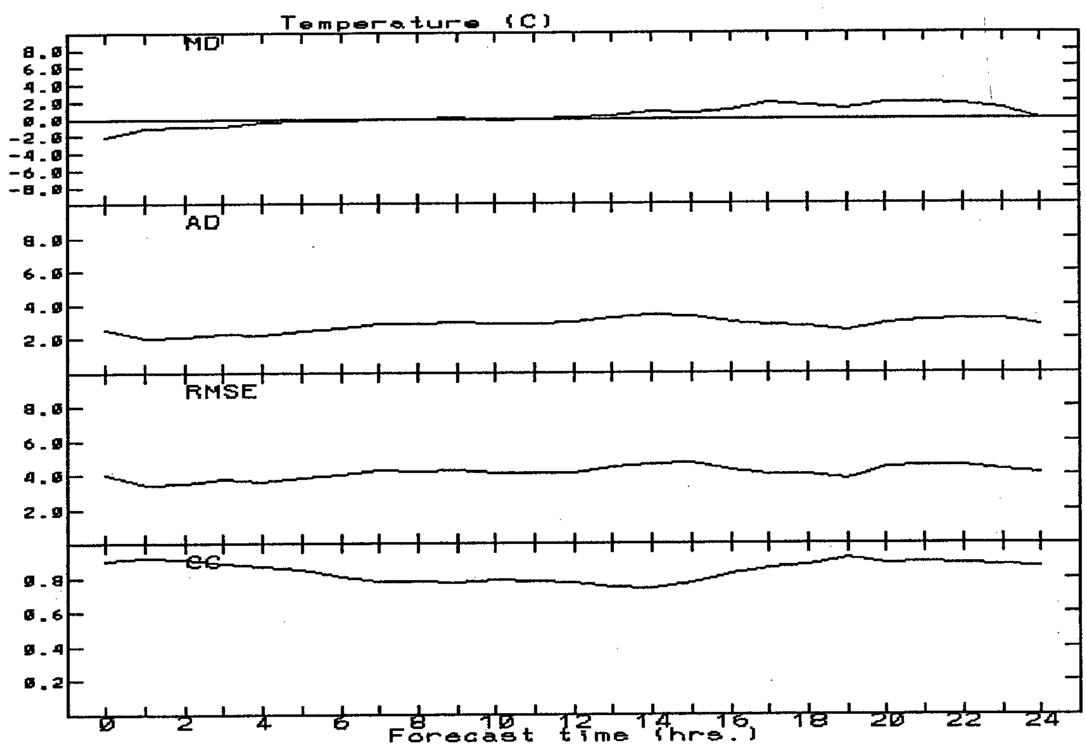

Figure 17. Time series of statistical parameters of temperature (April-June 2002, BFM 2.5 km grid increment).

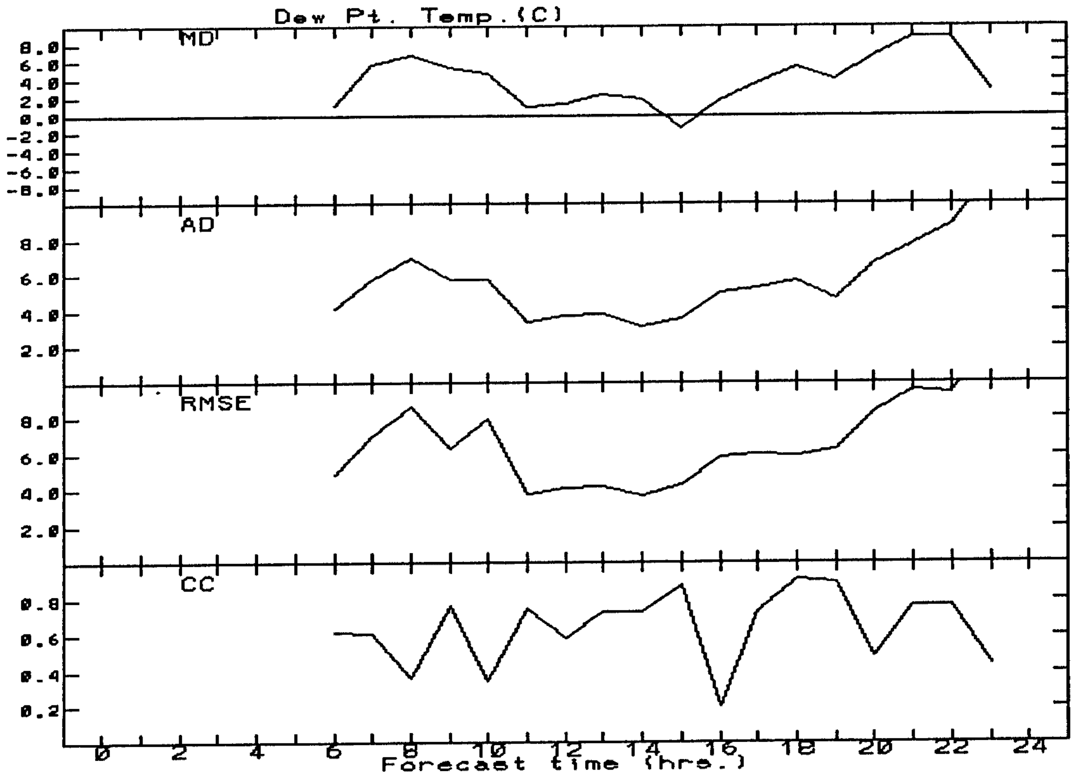

Figure 18. Time series of statistical parameters for dew point temperature (April-June 2002, MM5 domain 4).

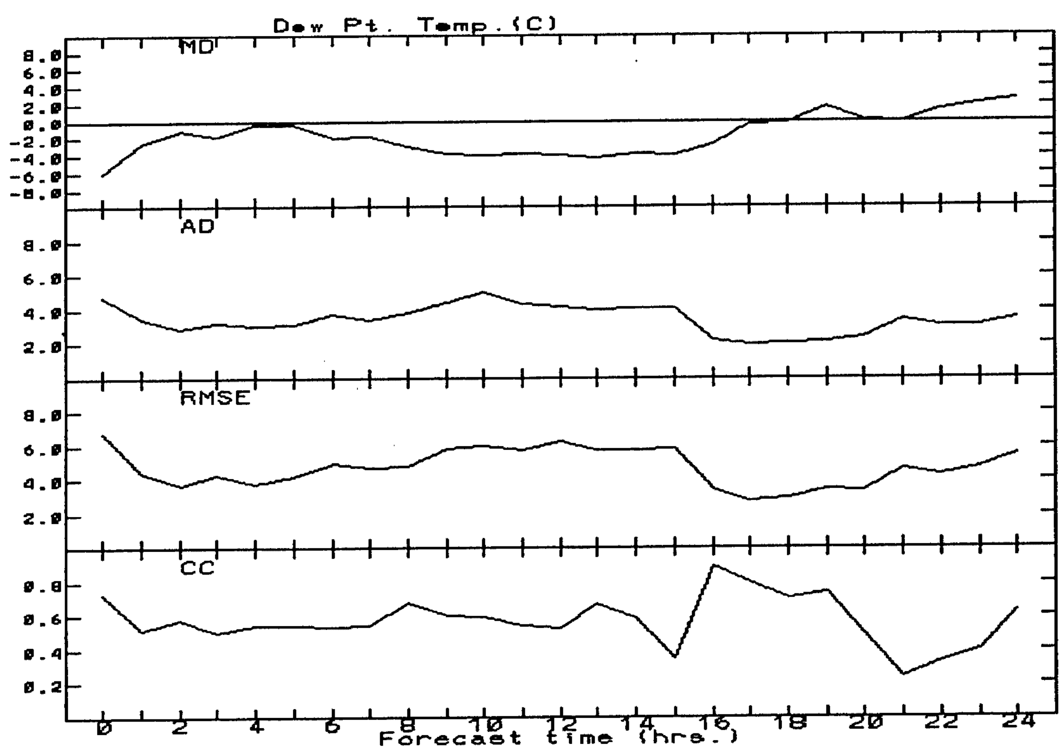

Figure 19. Time series of statistical parameters for temperature (April-June 2002, BFM 2.5 km grid increment).

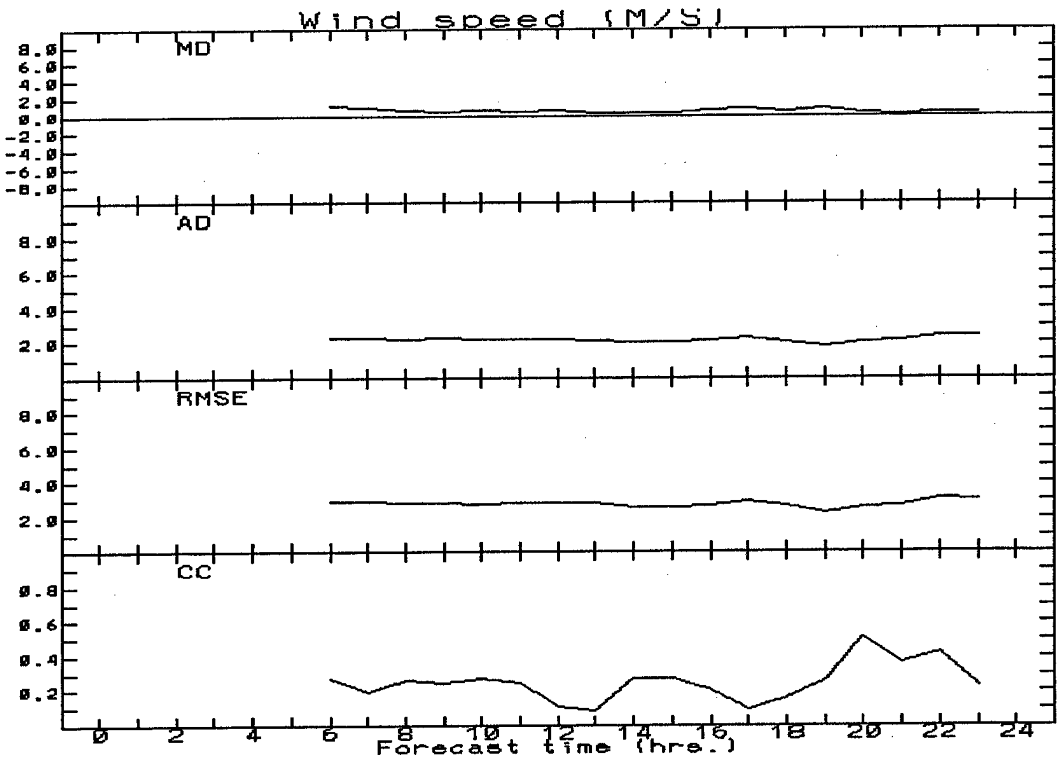

Figure 20. Time series of statistical parameters for wind speed (April-June 2002, MM5 domain 5).

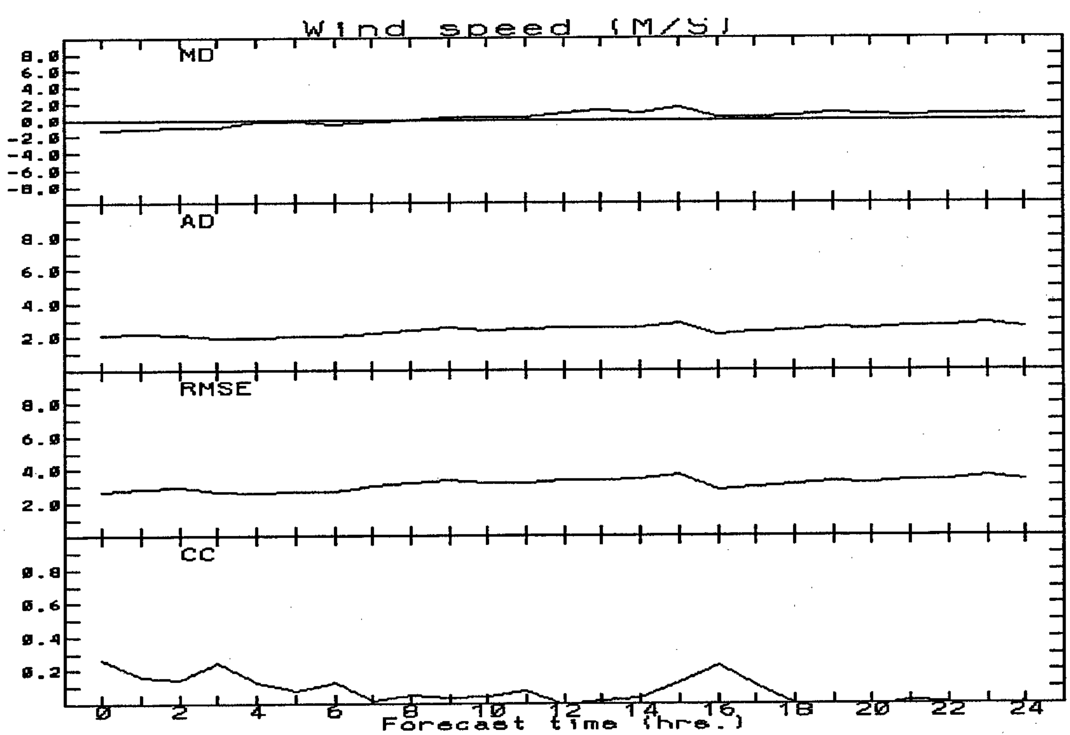

Figure 21. Time series of statistical parameters for wind speed (April-June 2002, BFM 2.5 grid increment).

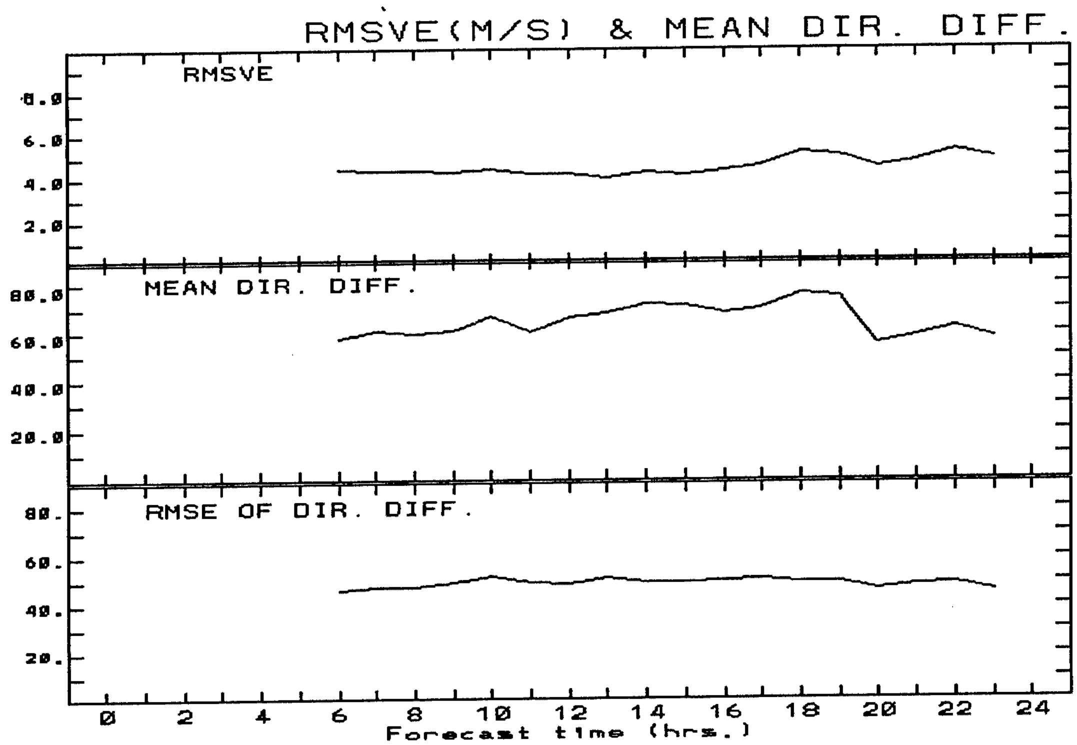

Figure 22. Time series for RMSVE, MWDDF, and RMSE of wind direction difference (April-June 2002, MM5 domain 4).

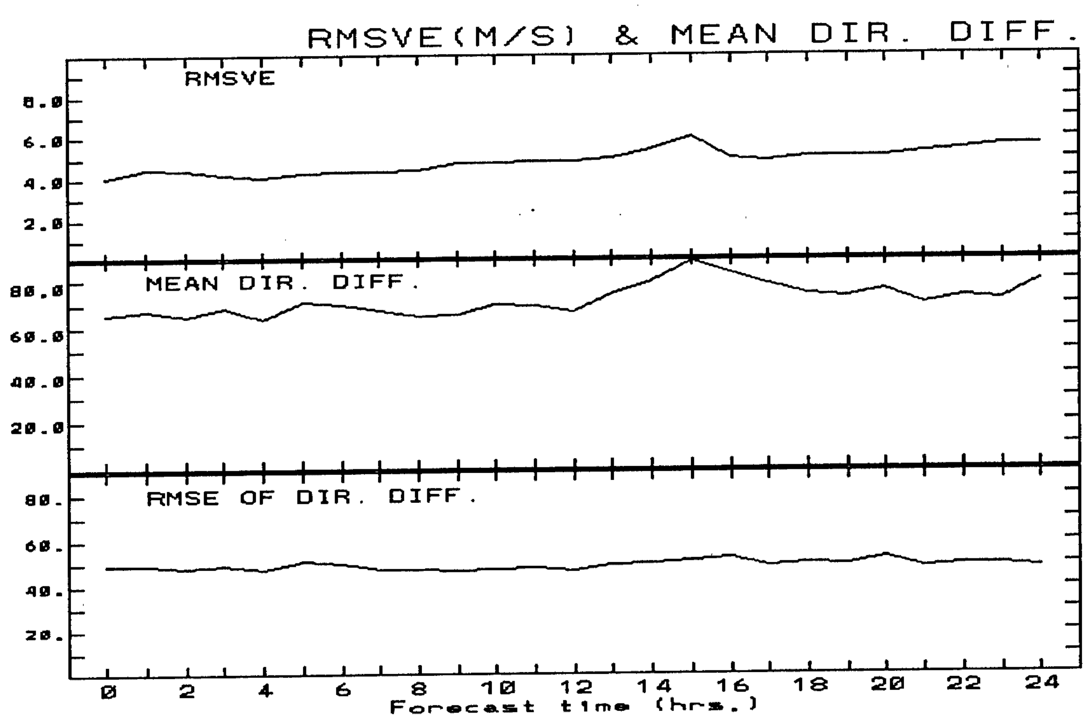

Figure 23. Time series for RMSVE, MWDDF and RMSE of wind direction difference (April-June 2002, BFM 2.5 km grid increment).

From the information displayed in figures 11–18, the following can be seen:

1. For temperature, both the MM5 and the BFM forecast data produced statistically good agreement with observed data, with the AD values around 2 °C and the CC greater than 0.9.
2. Dew point temperatures forecasted by MM5 tend to be greater than the dew point temperatures of the observed data. Dew point temperatures forecasted by the BFM tend to be less than the dew point temperatures of the observed data. For MM5, the modeled atmosphere near the surface tends to be more humid than the observed atmosphere. For BFM, the modeled atmosphere near the surface tends to be less humid than the observed atmosphere. The forecast skills of both MM5 and the BFM, with regards to dew point temperature, are statistically less than those for temperature.
3. The AD values of wind speed for both MM5 and the BFM are between 2 and 3 m/sec, and the RMSVE values are between 4 and 5 m/sec. In the previous study (Henmi, 2000), the AD values of three different climatological areas (Colorado, Washington, and Florida) over a 500x500 km^2 area with grid increment of 10 km were smaller than 1 m/sec, and the RMSVE values were between 2 and 3 m/sec. Lower statistical skills of both MM5 and the BFM for wind vector forecasts over the Utah domains in this study may be attributed to the fact that the observed data used for comparison in Henmi (2000) was obtained at sites such as airports, where the topography surrounding the sites is flat. Thus, the BFM might have simulated wind vector fields over the previous domains better than over the Utah domains.
4. The CC values of MM5 (approximately 0.3) and of the BFM (less than 0.2), and the mean wind direction differences for both models (greater than 60^o) are statistically poor.

Similar findings can be found in the statistics of MM5 domain 3 and the BFM with grid increments of 5 km (see appendixes).

6. Conclusions

Forecast calculations by the MM5 and the BFM mesoscale models were made over the model domains of Utah for two different periods (January-March, April-June 2002).

The mesoscale model, MM5, has quadruple-nested computational grids. All four domains have a mesh size of 55x55 points, and grid increments of 67.5, 22.5, 7.5, and 2.5 km, respectively, for the domains 1,2, 3, and 4. Forecast computations were carried out in parallel modes using 16 processors. The U. S. Army HPC computer was used for this study. For this evaluation study, the forecast data for domains 3 and 4 were compared with observed data.

BFM calculations were made independently over two model domains with grid increments of 5 and 2.5 km, both centered at Salt Lake City, UT. Surface meteorological data forecasted by the models were statistically compared with Mesowest network data.

The major findings of this study included:

1. There are no significant statistical differences in forecast skills between MM5 domain 3 (7.5 km grid increment) and domain 4 (2.5 km grid increment). Similarly, the forecast skills of two BFM (5 and 2.5 km) grid increments are statistically similar. It can be concluded that reducing the grid increment from 7.5 to 2.5 km for MM5, and from 5.0 to 2.5 km from BFM does not produce significant improvement of forecast results.
2. Both MM5 and the BFM produced more accurate forecast results for surface temperature than for dew point temperature and wind vector. The AD values of temperature (approximately 2 °C) produced by both models are compatible with the values reported by Mass et al. (2002). Over the complex terrain of Utah, both MM5 and the BFM have difficulties in producing good forecast results for wind vector. For both models, the MWDDF between forecast and observation was greater than 60°, and absolute wind speed differences were around 2 m/sec for the entire forecast hour. In a similar study over western Washington, Mass et al. (2002) reported that the operational MM5, triply-nested with 36, 12, and 4 km grid increments, produced values of approximately 40° for MWDDF, and approximately 4 knots (~ 2 m/sec) for absolute difference. The terrain complexities of the model domains over Utah may be the reason for these differences.
3. For all of the surface meteorological parameters of temperature, dew point temperature and wind vector, MM5 produced statistically better forecast skills than the BFM.
4. Both MM5 and the BFM showed better forecasting statistics during the period of April-June 2002 than during the period of January-March 2002. During the warmer period of April-June 2002, local heating and cooling effects might have been more significant, influential factors for surface meteorological parameters than during the colder period of January-March 2002. A similar study for the summer season is planned.

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Appendix A Statistical Diagrams Displaying the Difference Between MM5 Forecast Data and Observation Data for the Period of January-March 2002.

This appendix is part of ARL-TR-2928, Evaluation Study of Mesoscale Models MM5 and BFM Over the Model Domains of Utah Using Surface Meteorological Data by Mesowest.

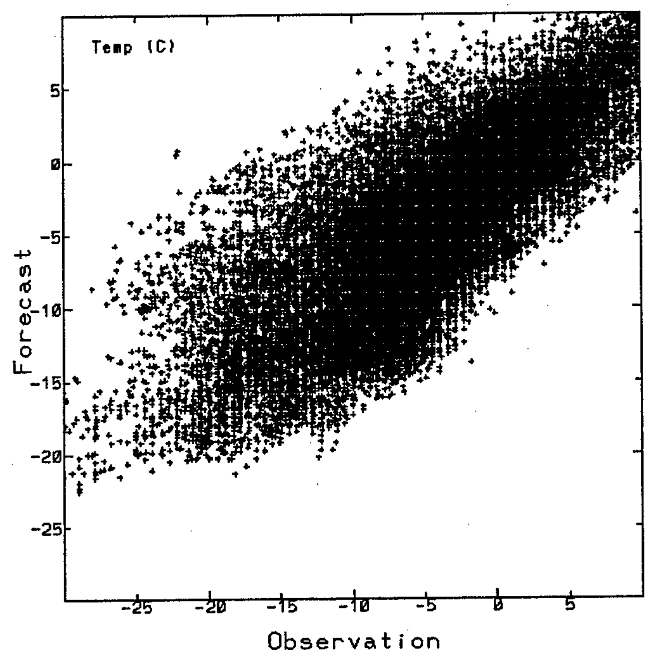

Figure A1. Difference between MM5 forecast data and observation data for temperature (domain 3).

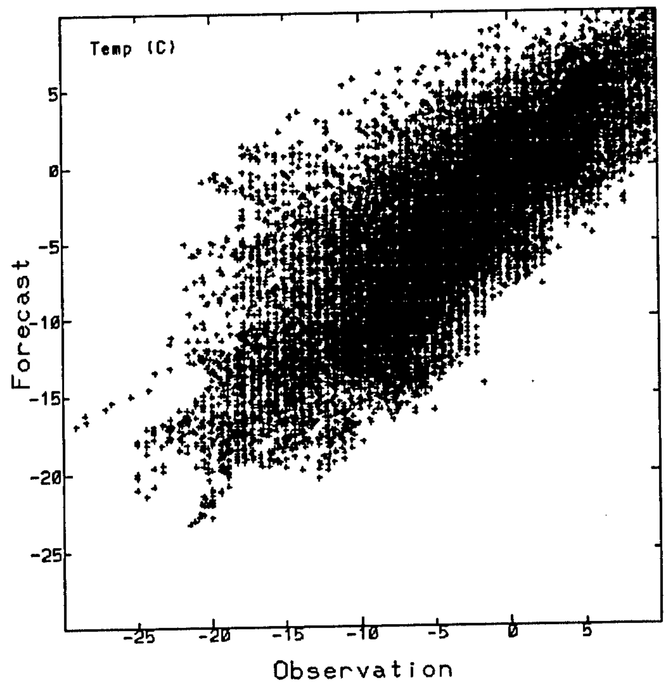

Figure A2. Difference between MM5 forecast data and observation data for temperature (domain 4).

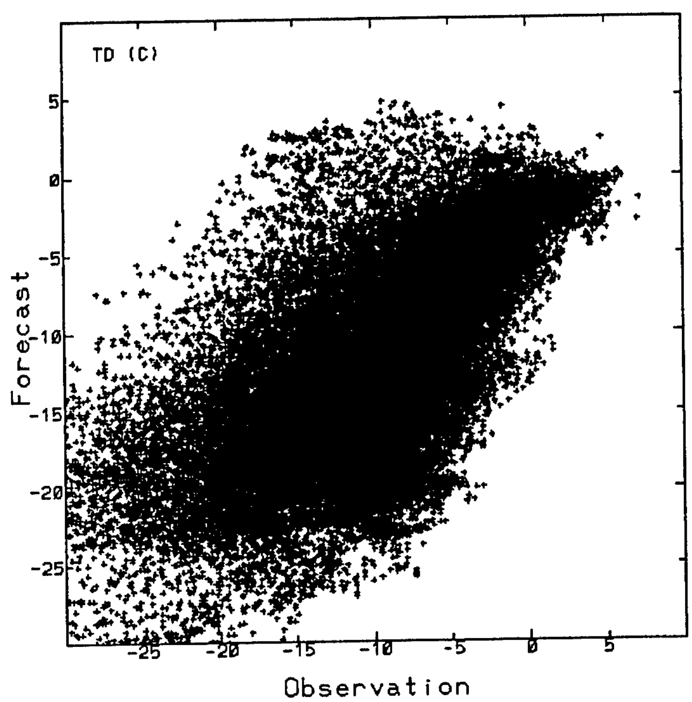

Figure A3. Difference between MM5 forecast data and observation data for dew point temperature (domain 3).

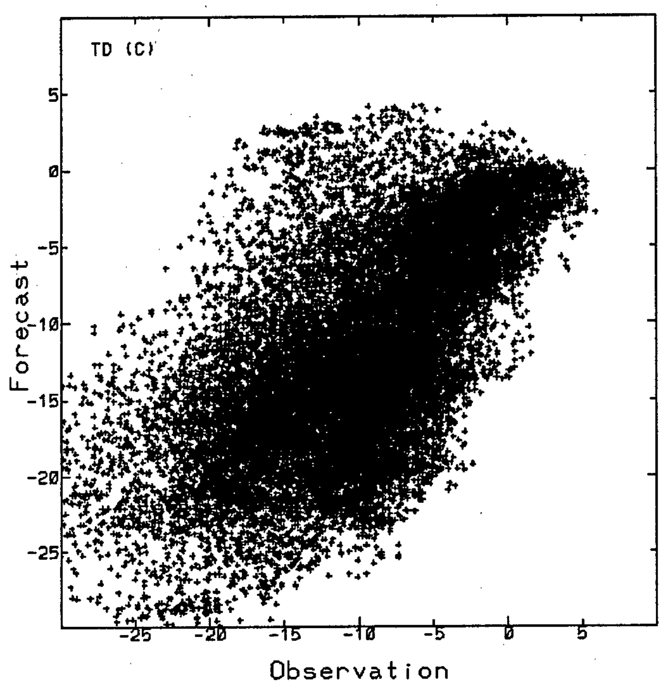

Figure A4. Difference between MM5 forecast data and observation data for dew point temperature (domain 4).

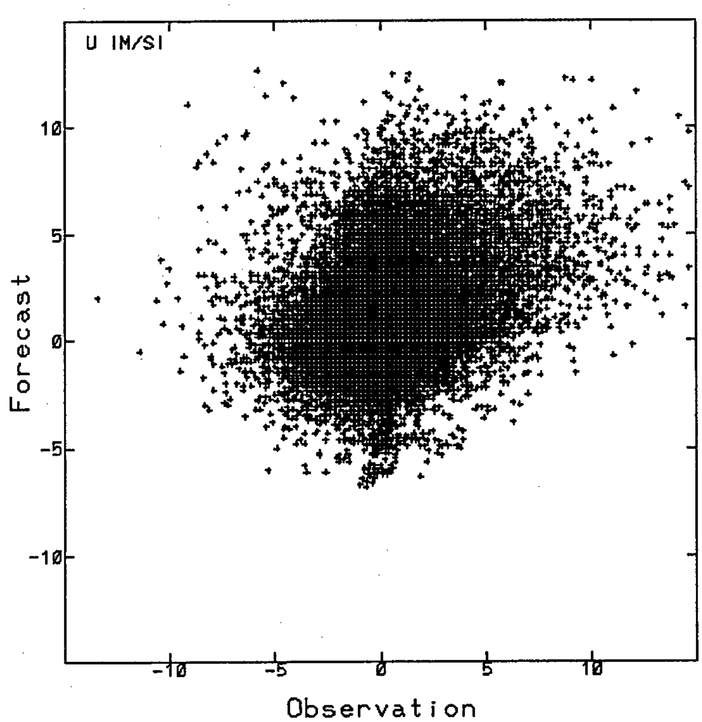

Figure A5. Difference between MM5 forecast data and observation data for wind vector x, component u (domain 3).

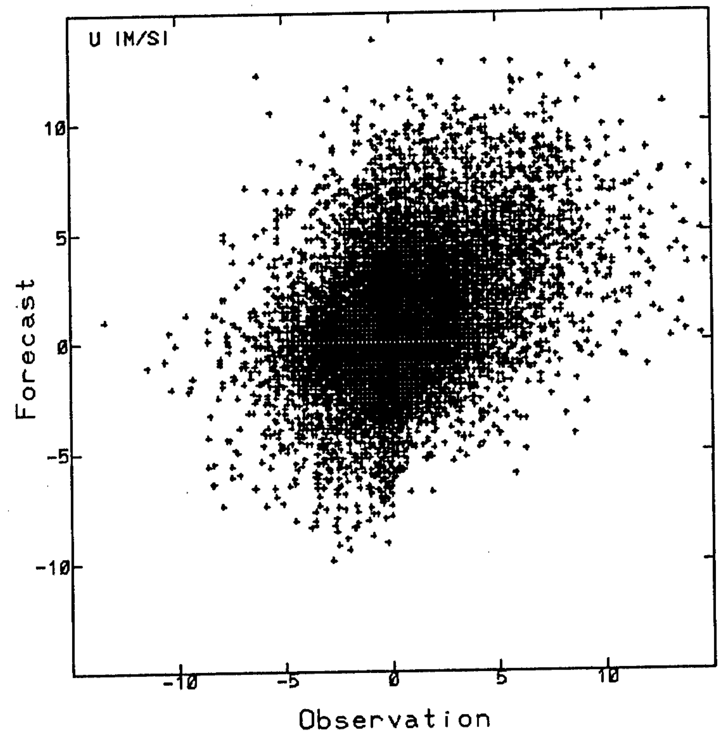

Figure A6. Difference between MM5 forecast data and observation data for wind vector x, component u (domain 4).

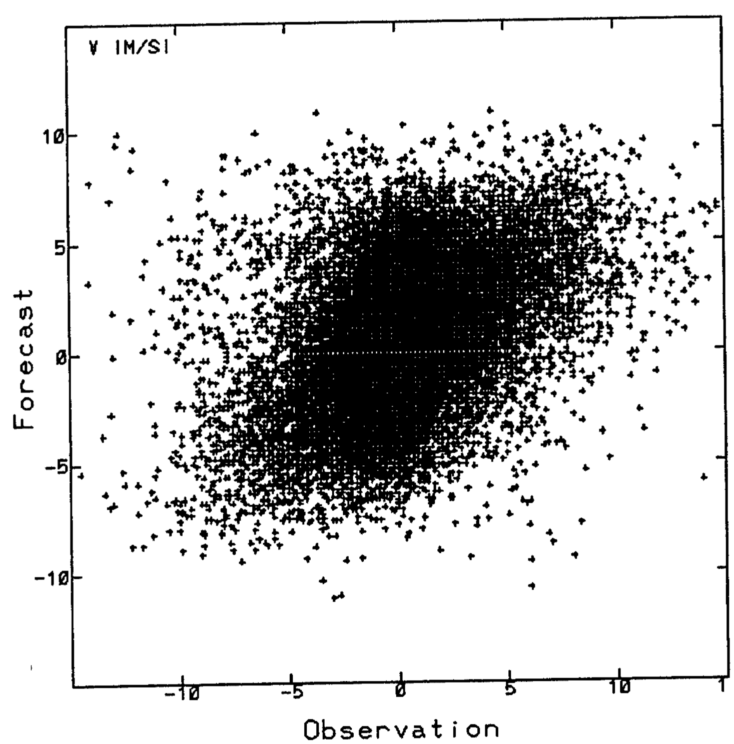

Figure A7. Difference between MM5 forecast data and observation data for wind vector y, component v (domain 3).

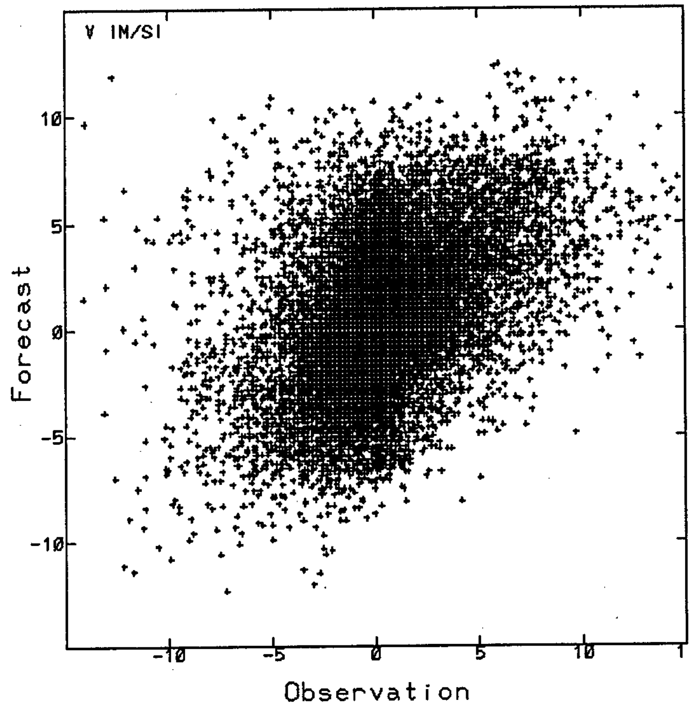

Figure A8. Difference between MM5 forecast data and observation data for wind vector y, component v (domain 3).

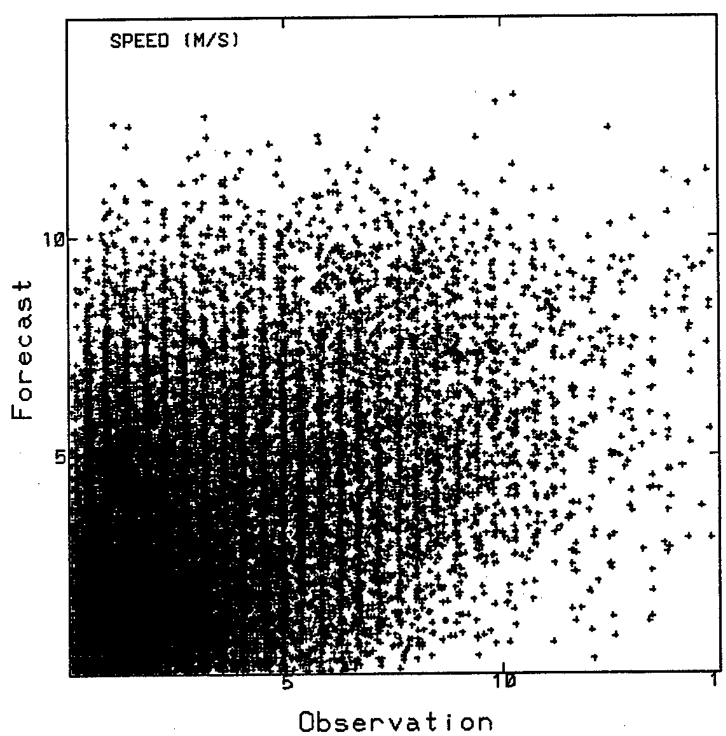

Figure A9. Difference between MM5 forecast data and observation data for wind speed (domain 3).

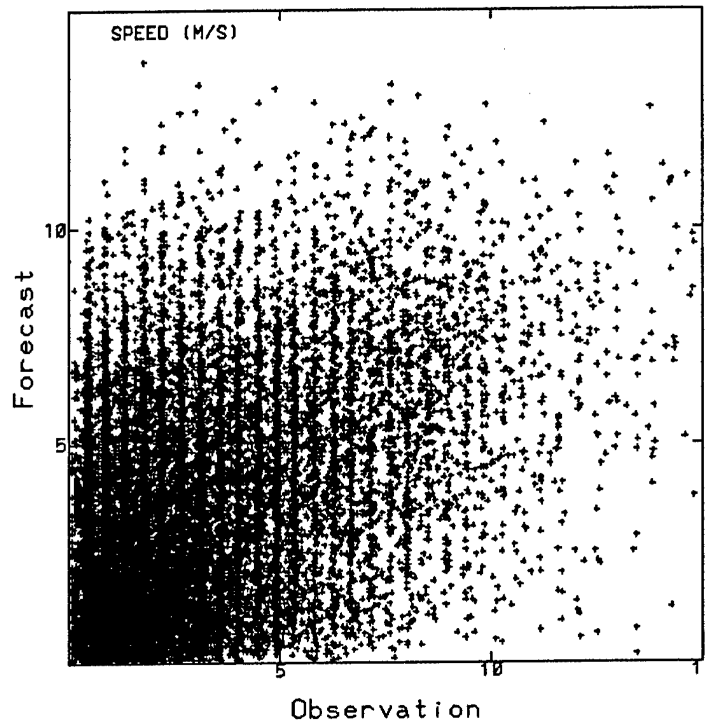

Figure A10. Difference between MM5 forecast data and observation data for wind speed (domain 4).

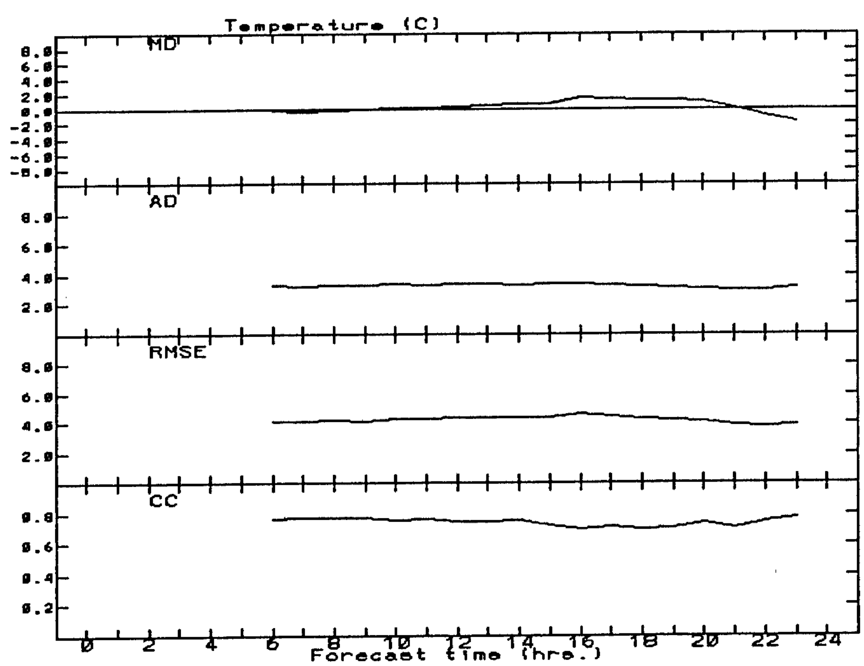

Figure A11. Time series of statistical parameters between MM5 temperature forecast data and surface observation data (domain 3).

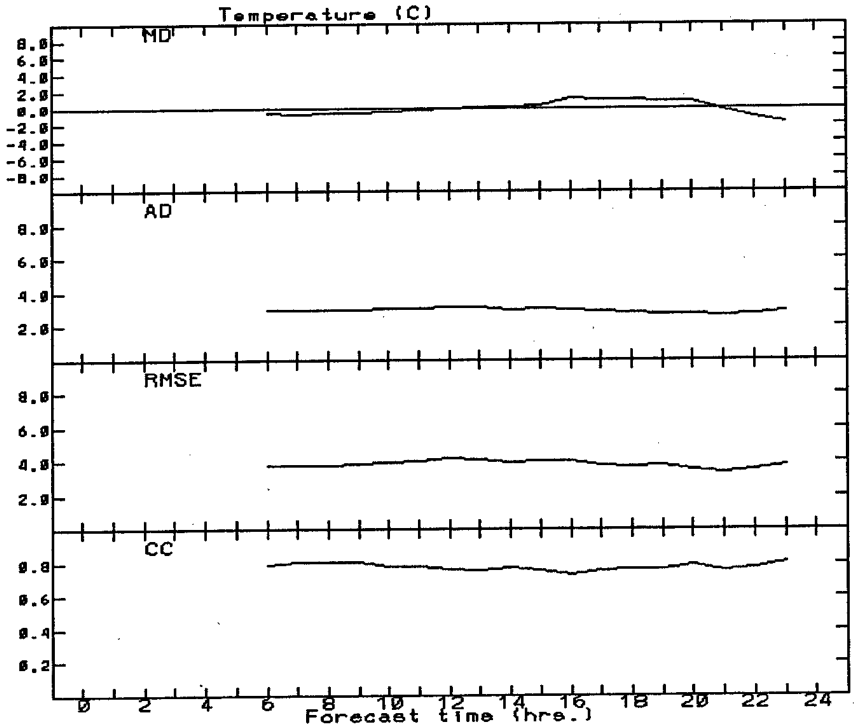

Figure A12. Time series of statistical parameters between MM5 temperature forecast data and surface observation data (domain 4).

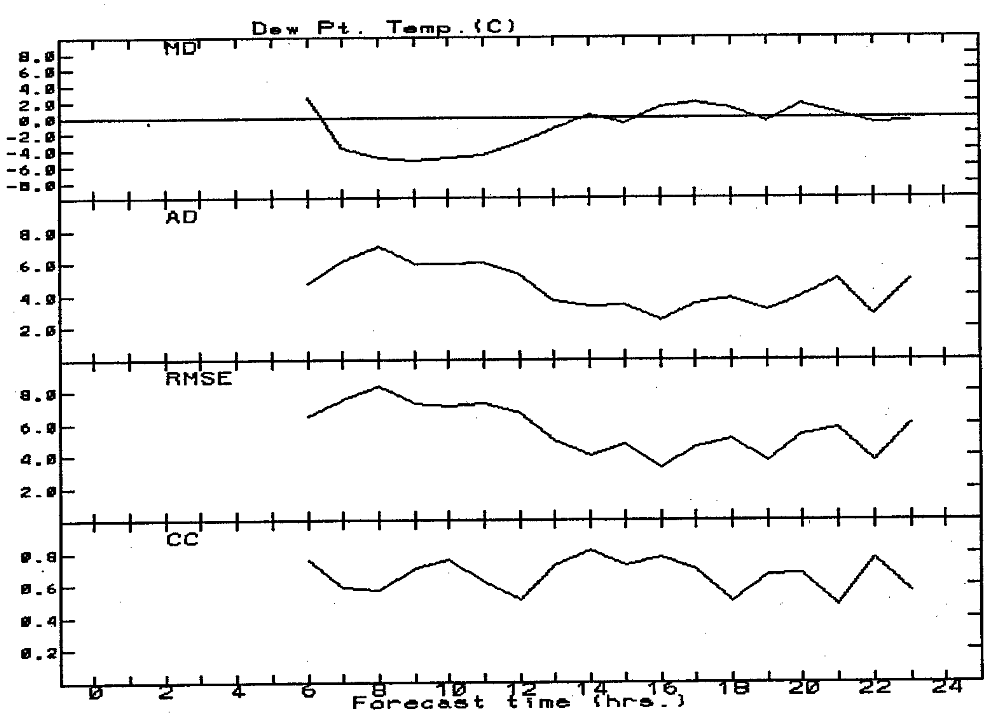

Figure A13. Time series of statistical parameters between MM5 dew point temperature forecast data and surface observation data (domain 3).

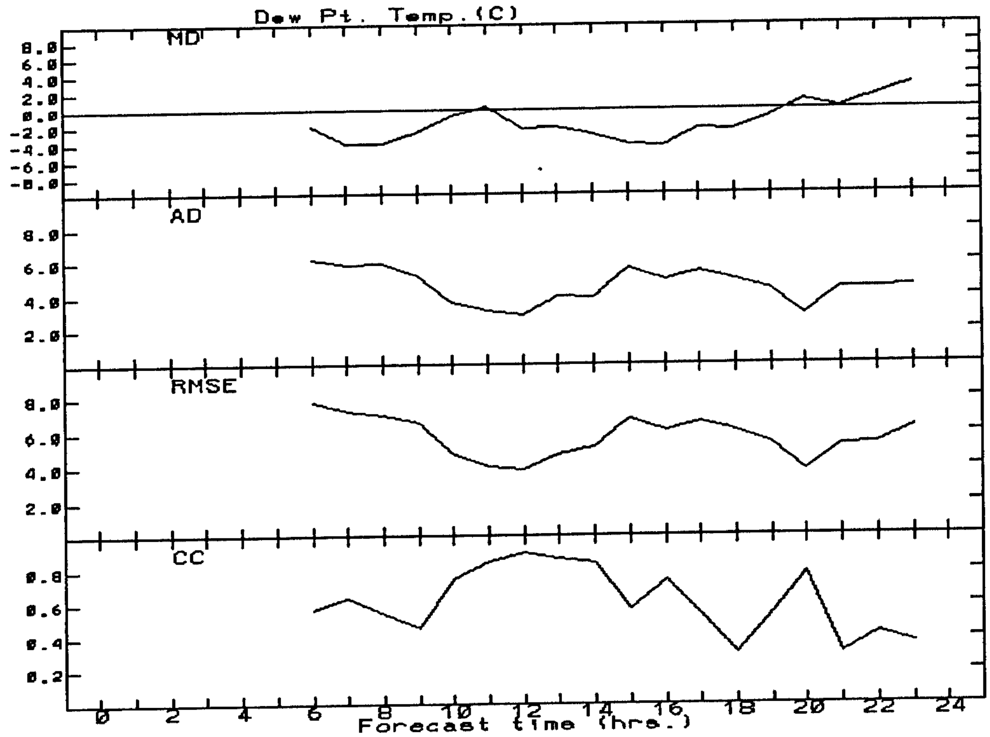

Figure A14. Time series of statistical parameters between MM5 dew point temperature forecast data and surface observation data (domain 4).

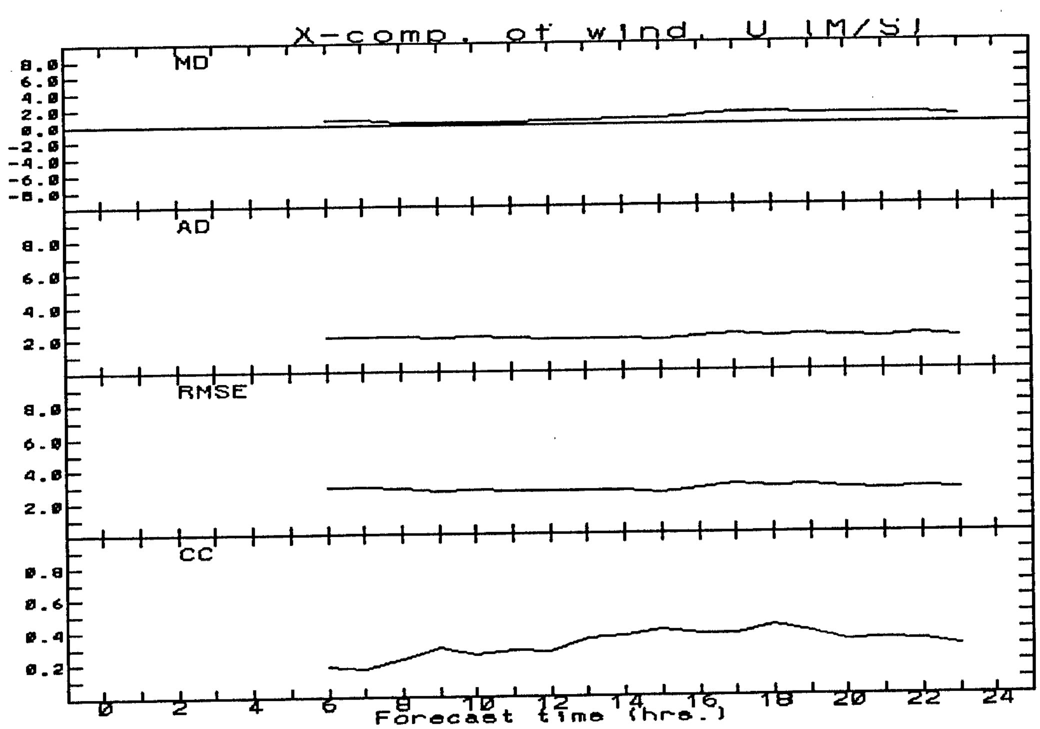

Figure A15. Time series of statistical parameters between MM5 wind vector x, component u forecast data and surface observation data (domain 3).

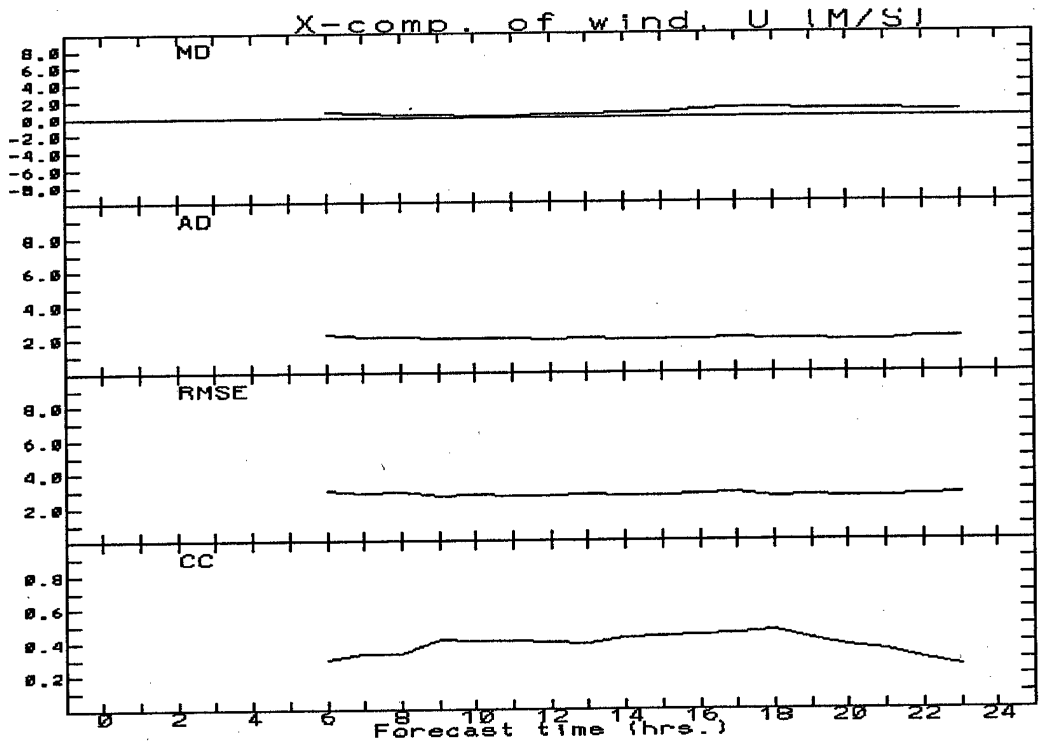

Figure A16. Time series of statistical parameters between MM5 wind vector x, component u forecast data and surface observation data (domain 4).

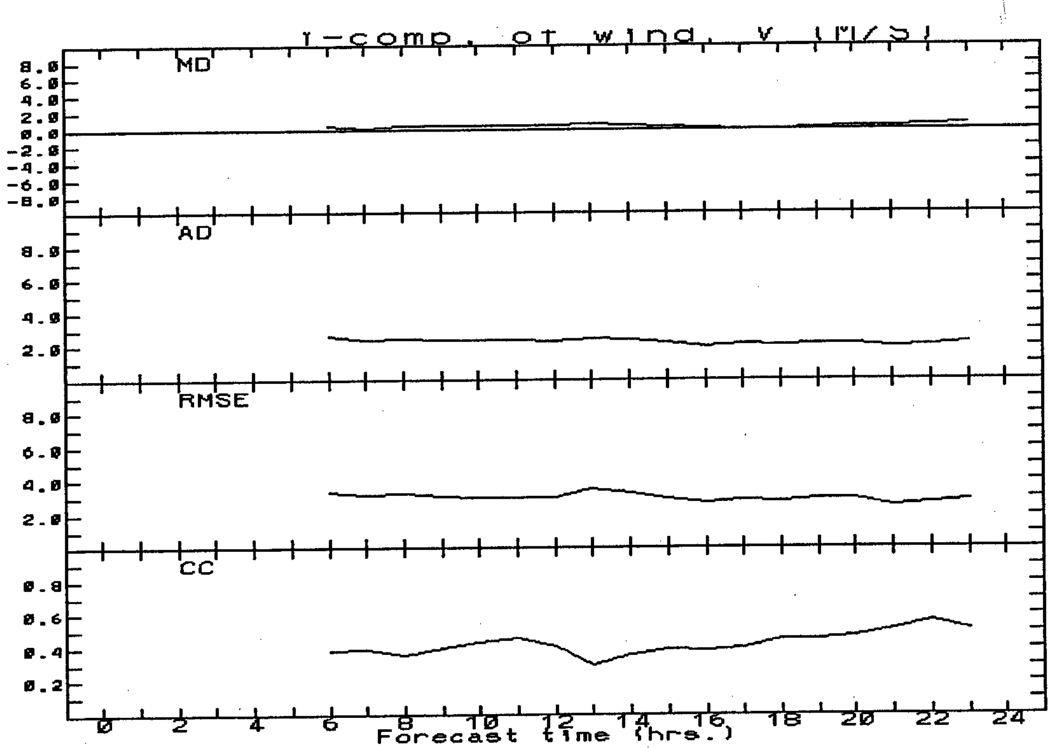

Figure A17. Time series of statistical parameters between MM5 wind vector y, component v forecast data and surface observation data (domain 3).

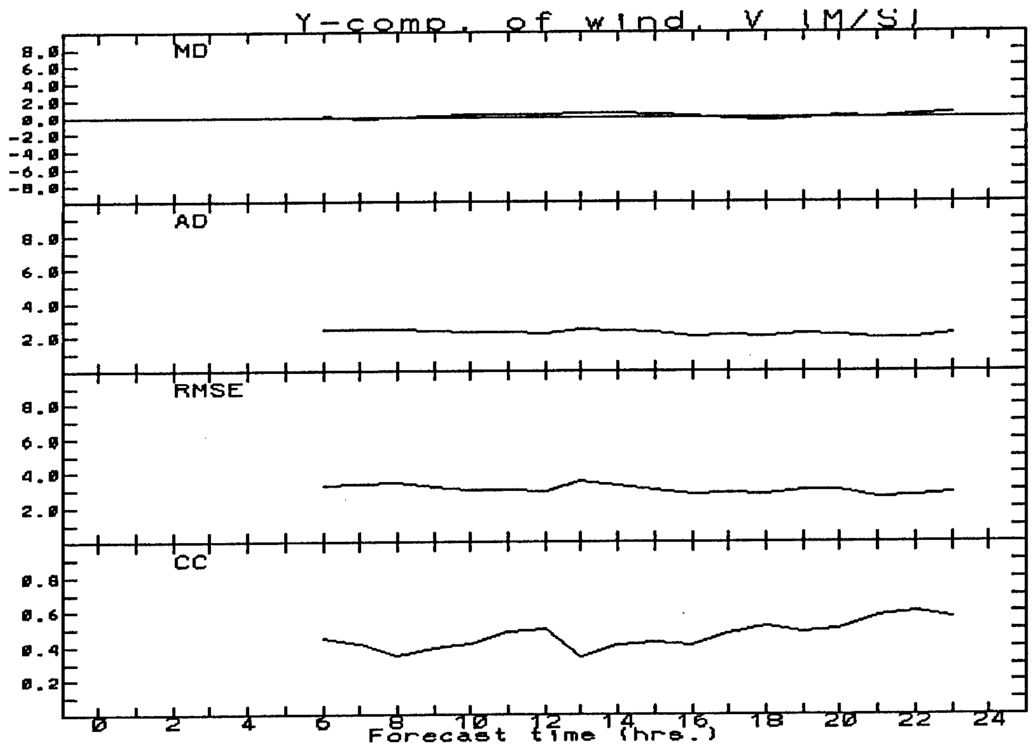

Figure A18. Time series of statistical parameters between MM5 wind vector y, component v forecast data and surface observation data (domain 4).

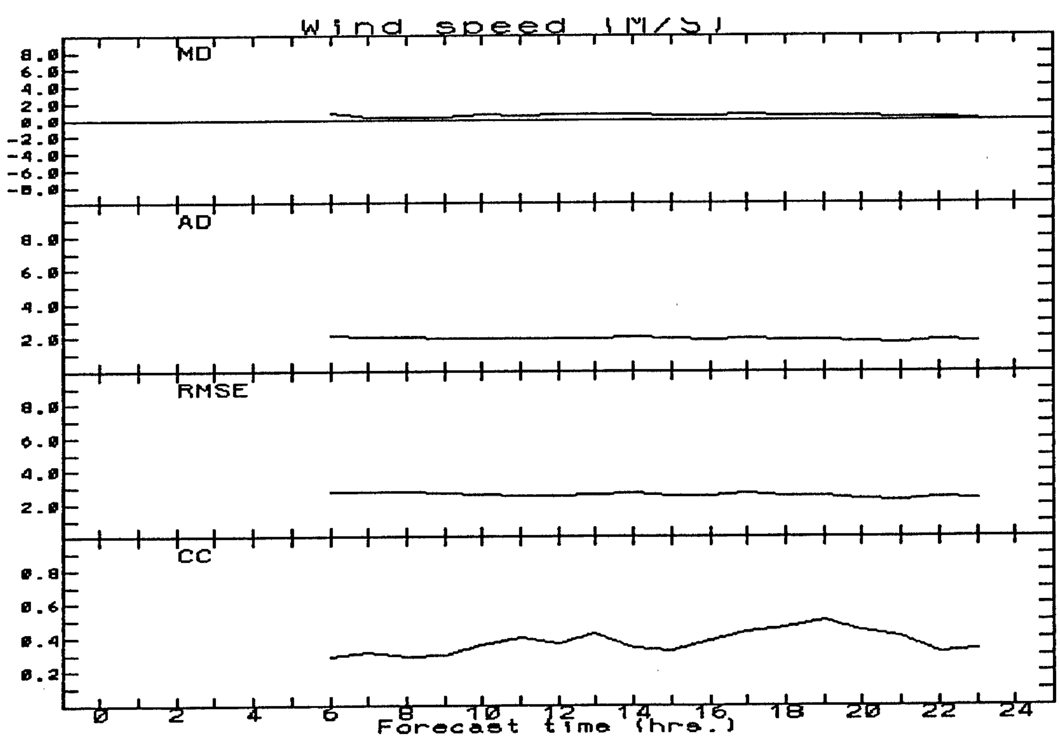

Figure A19. Time series of statistical parameters between MM5 wind speed forecast data and surface observation data (domain 3).

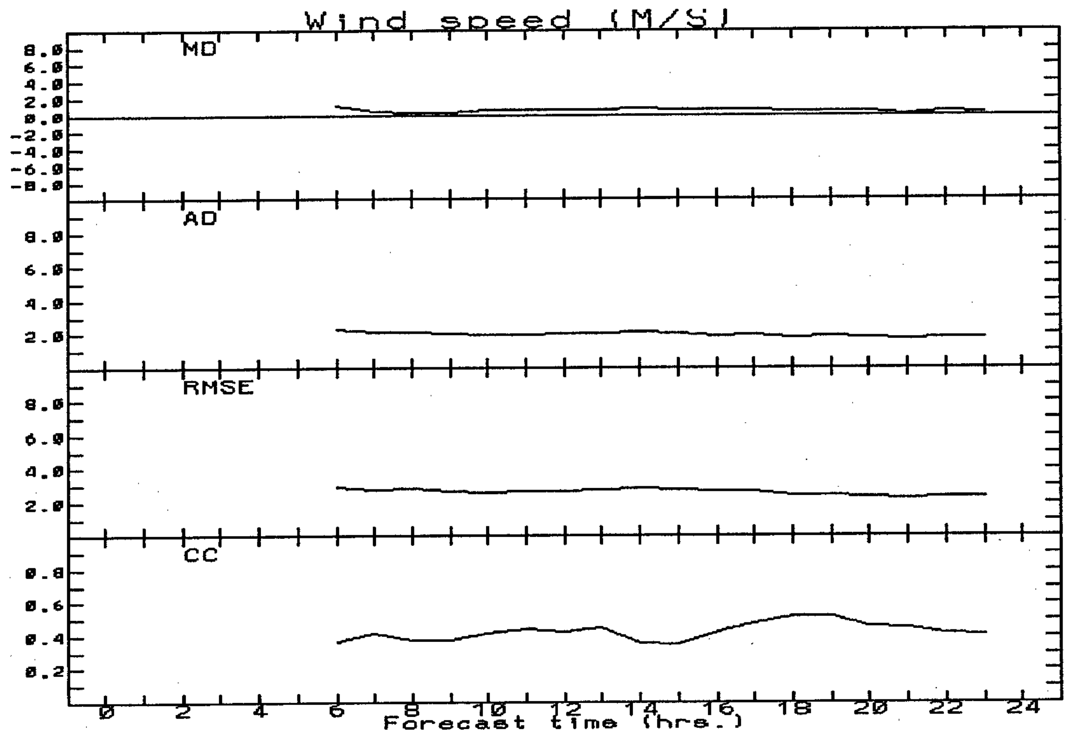

Figure A20. Time series of statistical parameters between MM5 wind speed forecast data and surface observation data (domain 4).

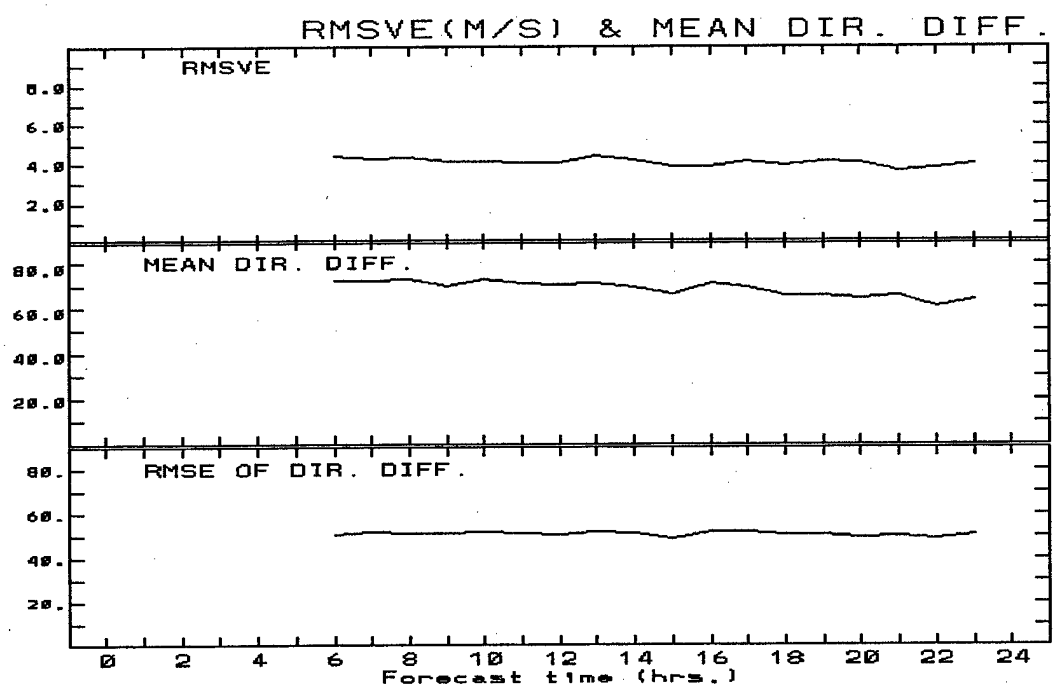

Figure A21. Time series of statistical parameters between MM5 rmsve and mean wind direction forecast data and surface observation data (domain 3).

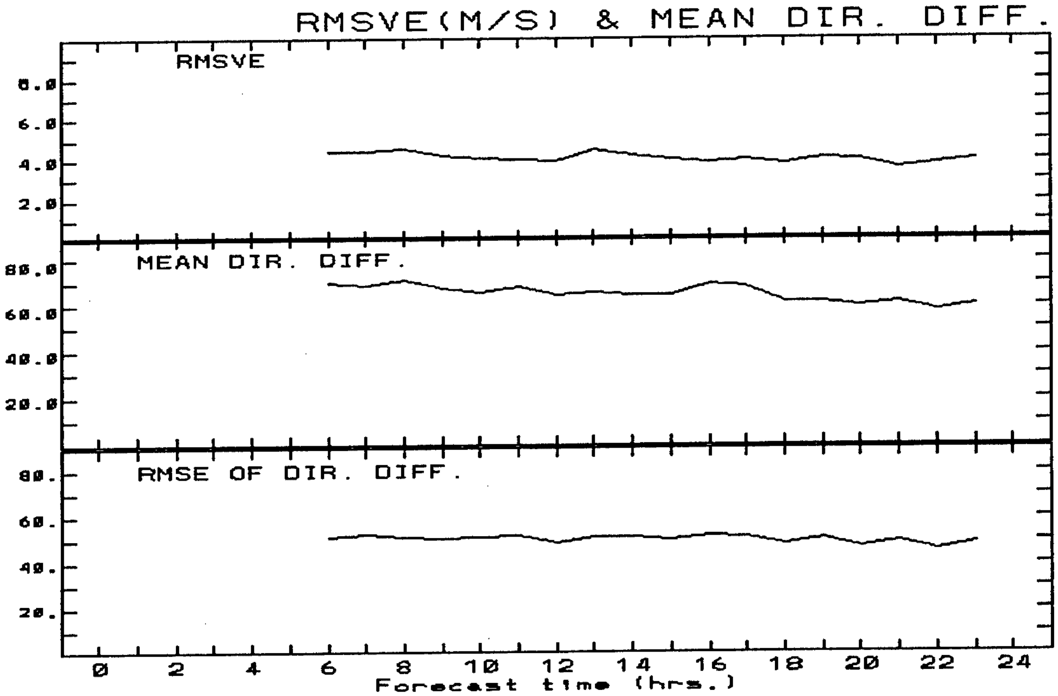

Figure A22. Time series of statistical parameters between MM5 rmsve and mean wind direction forecast data and surface observation data (domain 4).

Appendix B Statistical Diagrams Displaying the Difference Between MM5 Forecast Data and Observation Data for the Period of April-June 2002.

This appendix is part of ARL-TR-2928, Evaluation Study of Mesoscale Models MM5 and BFM Over the Model Domains of Utah Using Surface Meteorological Data by Mesowest.

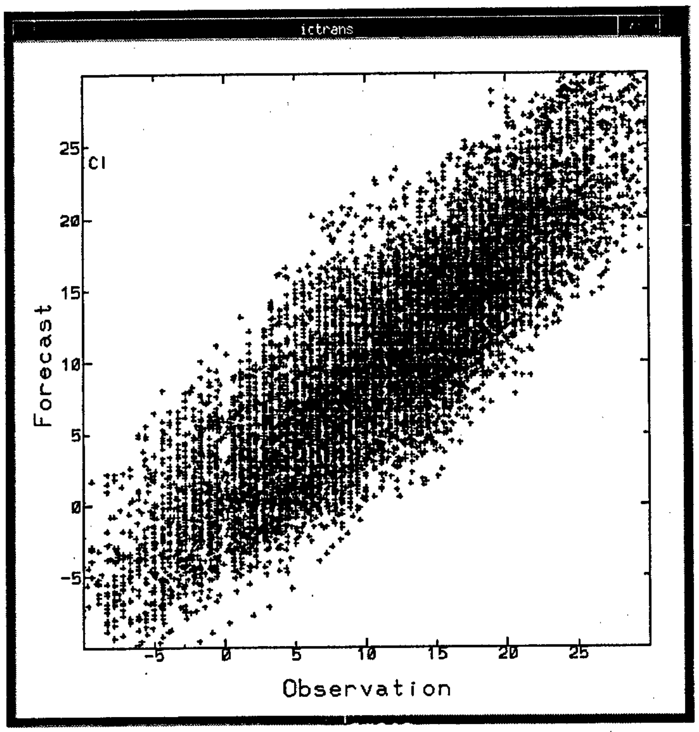

Figure B1. Difference between MM5 forecast data and observation data for temperature (domain 3).

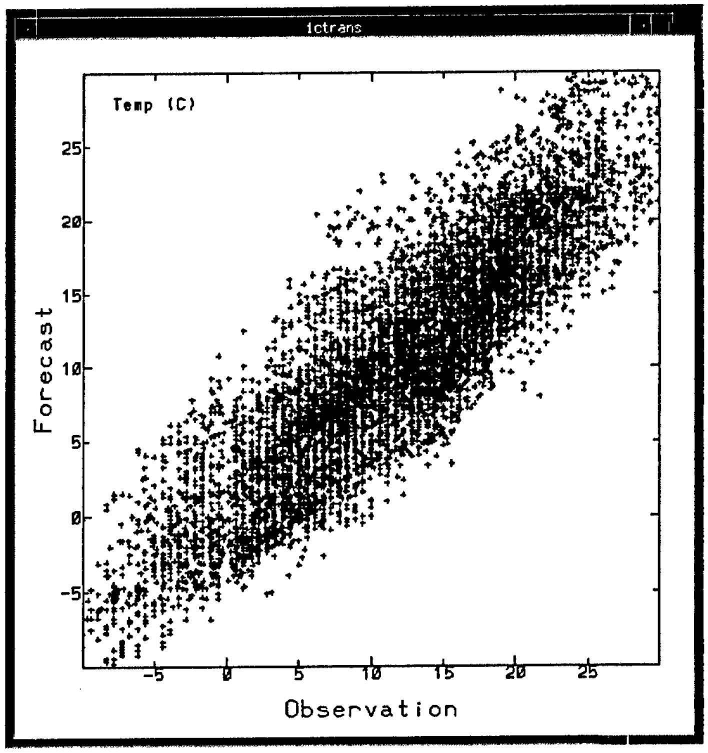

Figure B2. Difference between MM5 forecast data and observation data for temperature (domain 4).

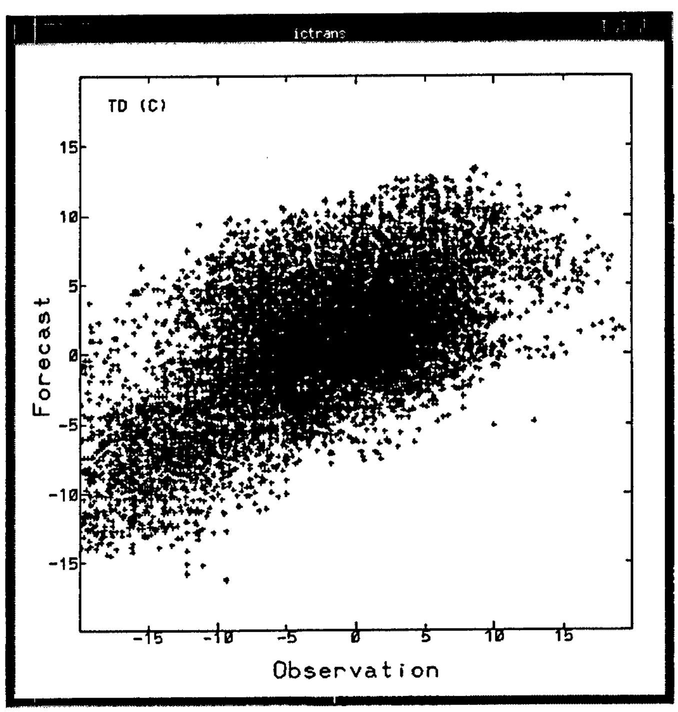

Figure B3. Difference between MM5 forecast data and observation data for temperature (domain 3).

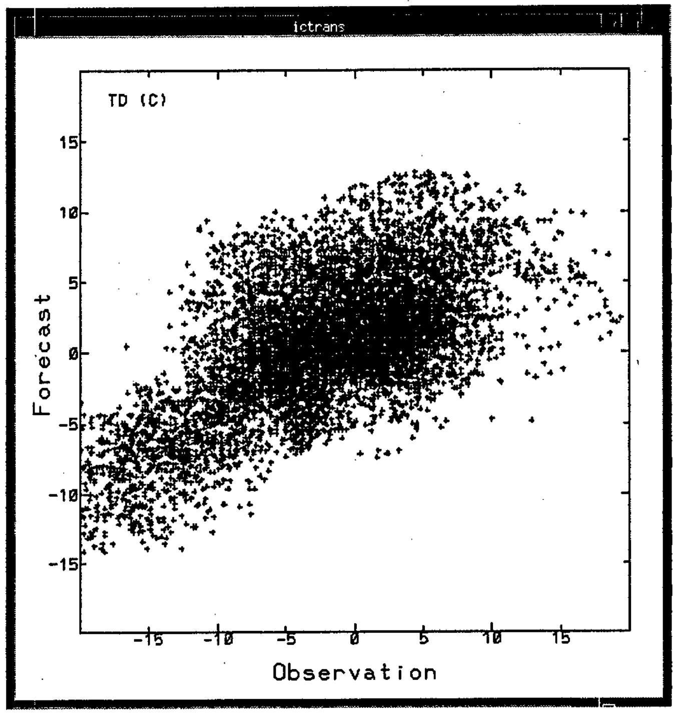

Figure B4. Difference between MM5 forecast data and observation data for temperature (domain 4).

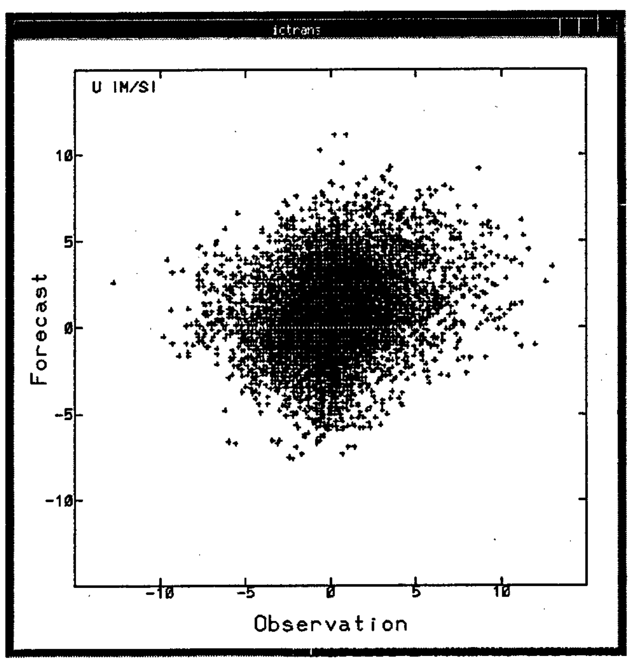

Figure B5. Difference between MM5 forecast data and observation data for wind vector x, component u (domain 3).

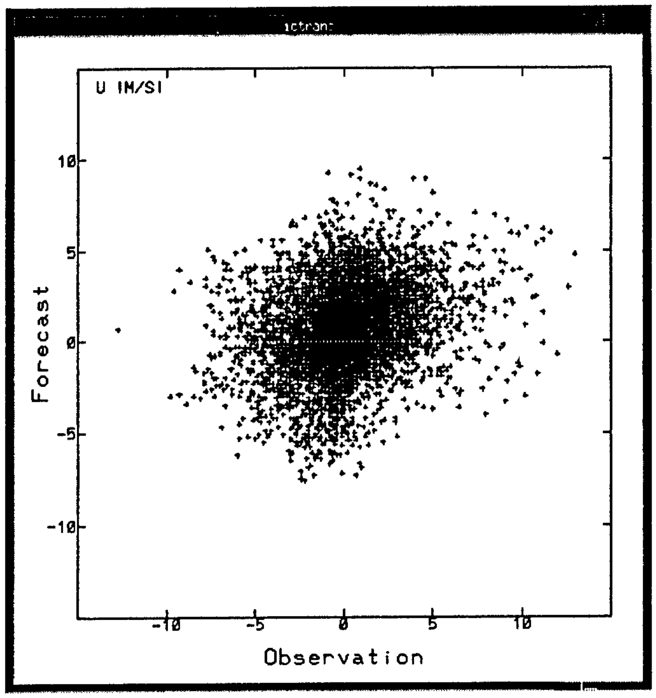

Figure B6. Difference between MM5 forecast data and observation data for wind vector x, component u (domain 4).

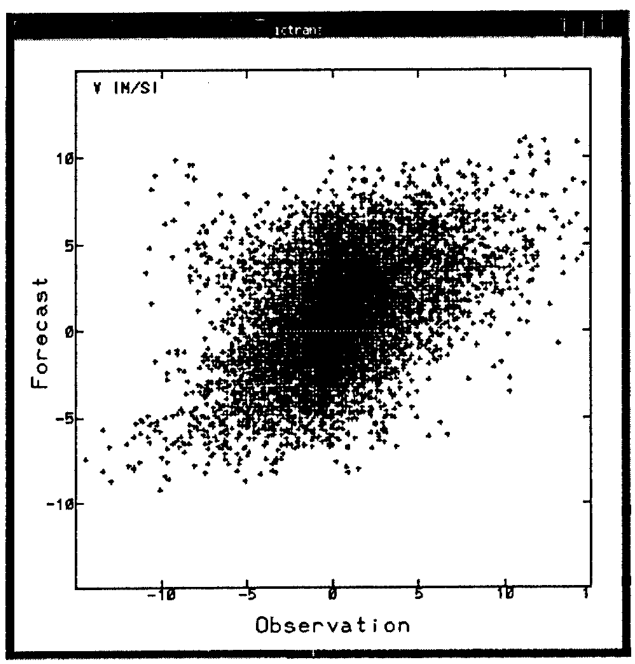

Figure B7. Difference between MM5 forecast data and observation data for wind vector y, component v (domain 3).

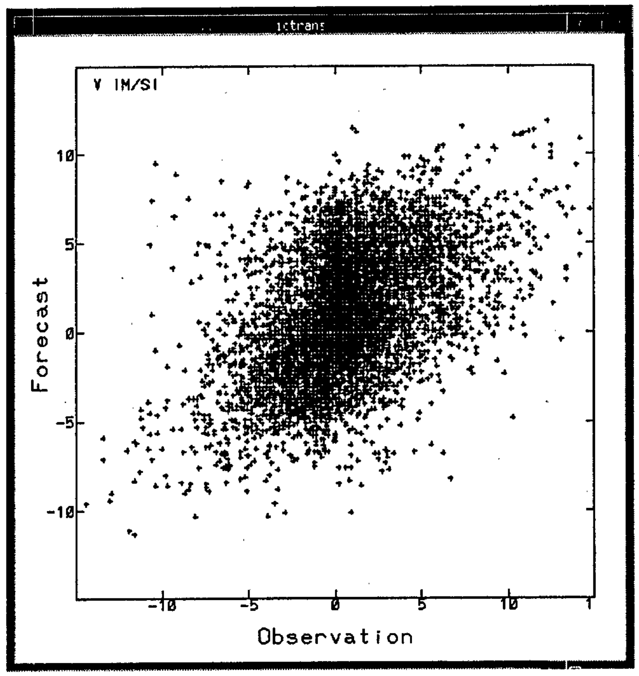

Figure B8. Difference between MM5 forecast data and observation data for wind vector y, component v (domain 4).

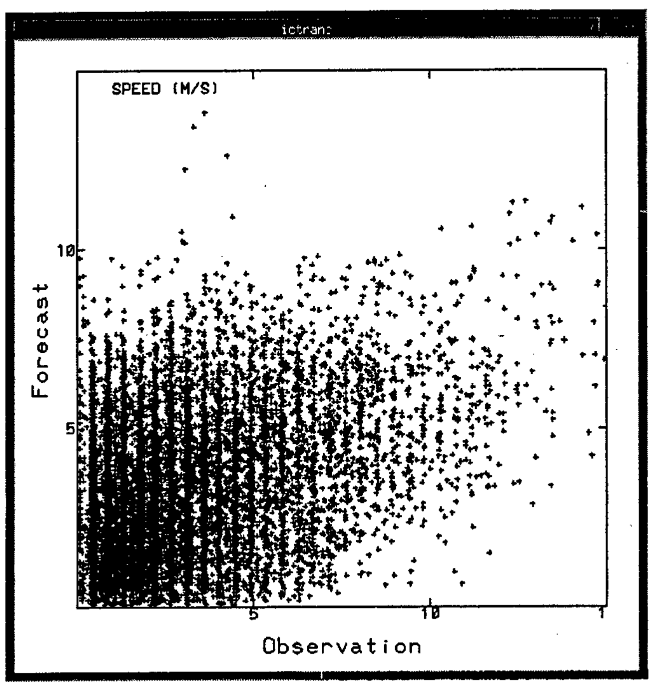

Figure B9. Difference between MM5 forecast data and observation data for wind speed (domain 3).

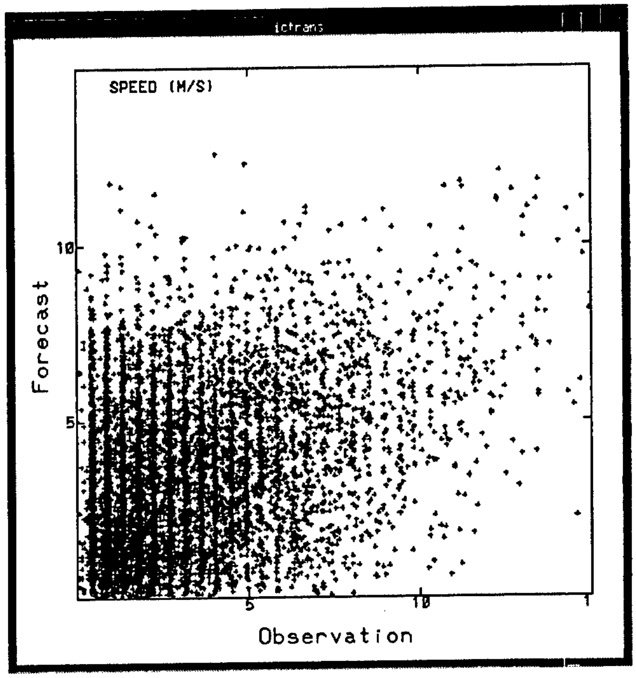

Figure B10. Difference between MM5 forecast data and observation data for wind speed (domain 4).

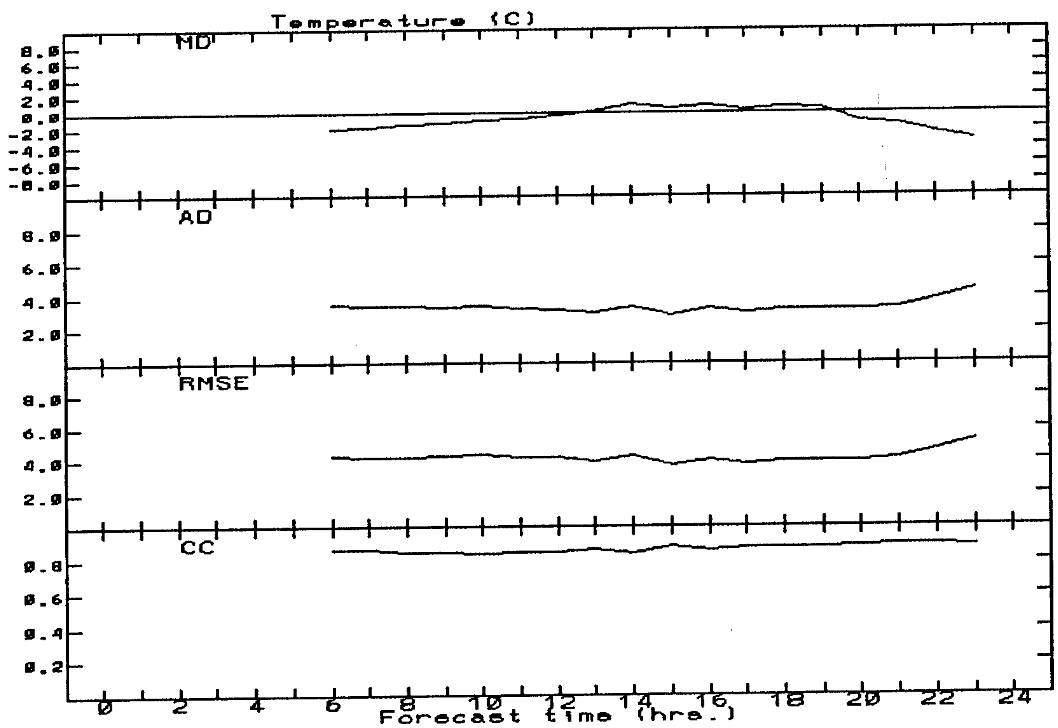

Figure B11. Time series of statistical parameters between MM5 temperature forecast data and surface observation data (domain 3).

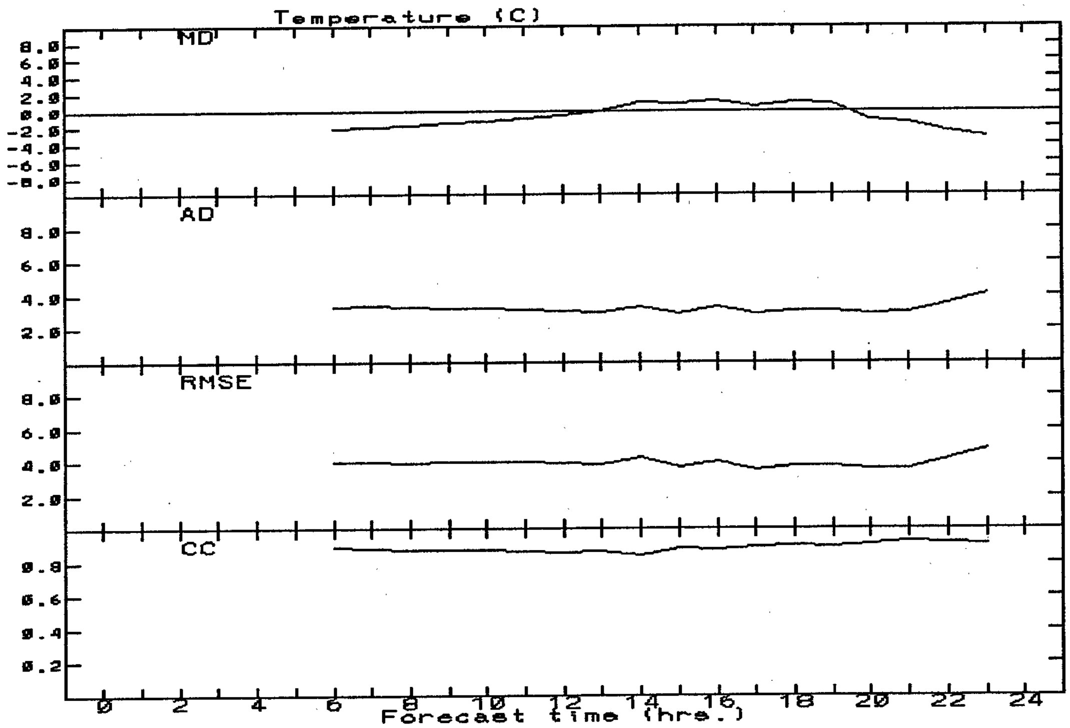

Figure B12. Time series of statistical parameters between MM5 temperature forecast data and surface observation data (domain 4).

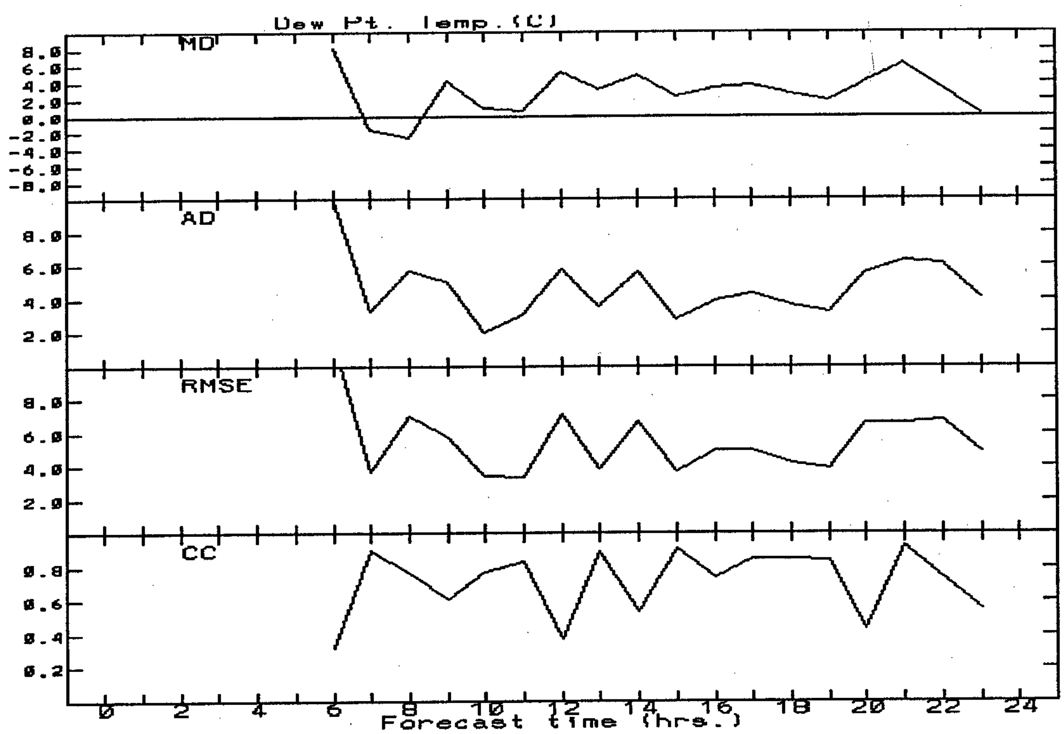

Figure B13. Time series of statistical parameters between MM5 dew point temperature forecast data and surface observation data (domain 3).

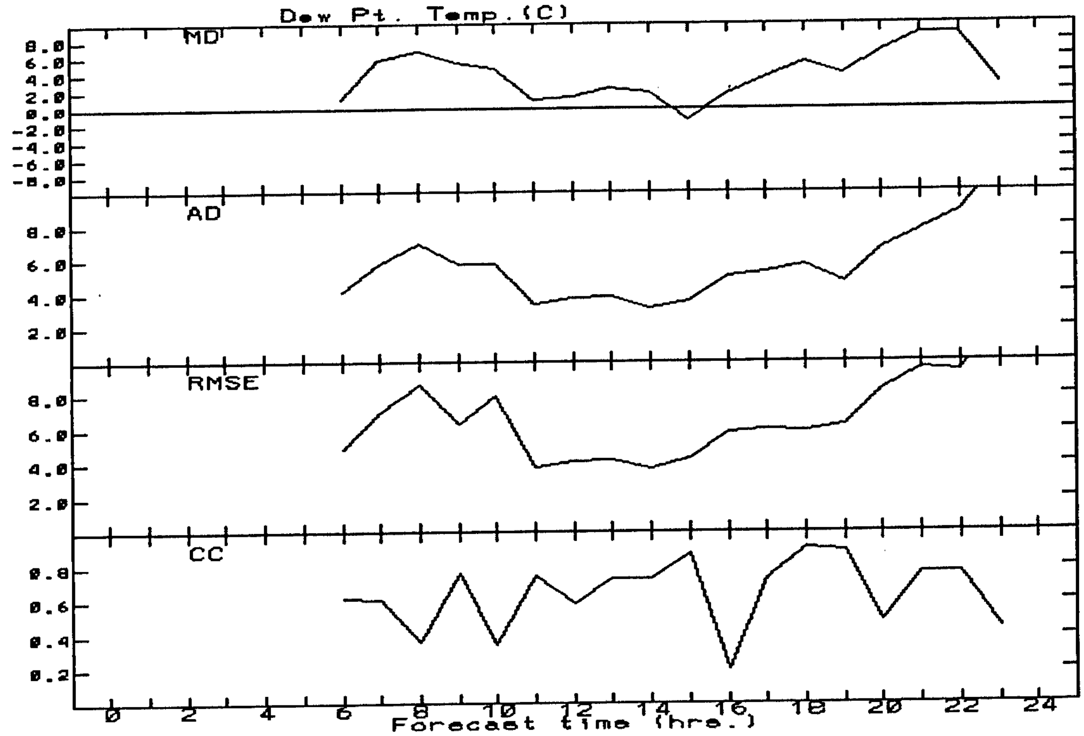

Figure B14. Time series of statistical parameters between MM5 dew point temperature forecast data and surface observation data (domain 4).

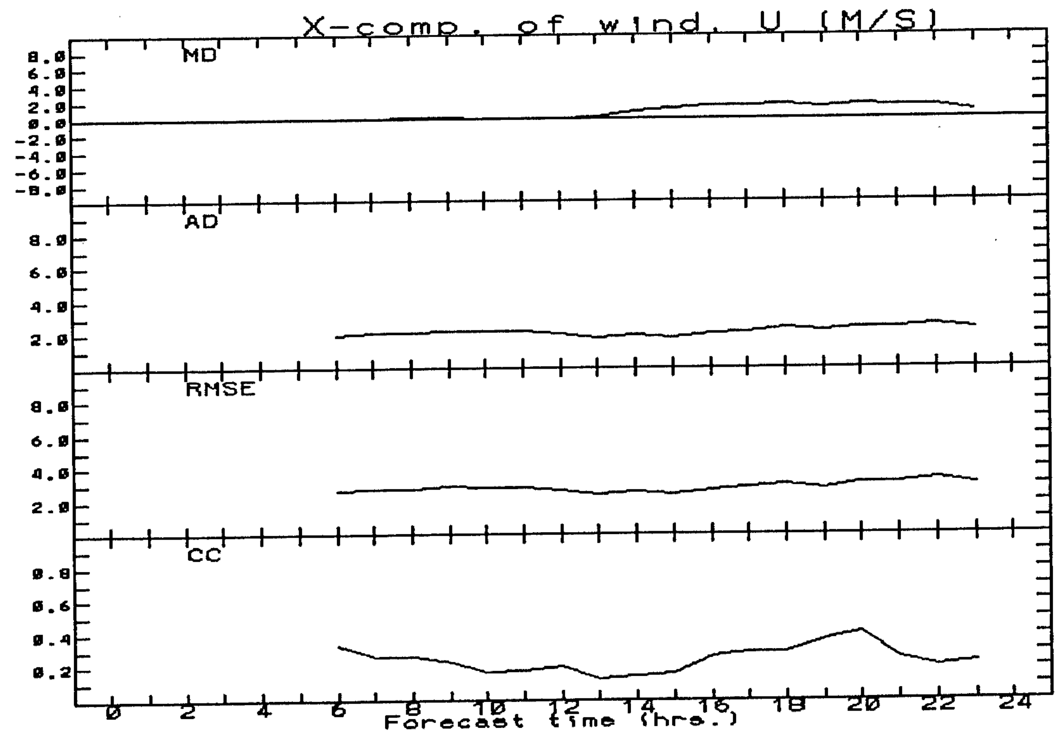

Figure B15. Time series of statistical parameters between MM5 wind vector x, component u forecast data and surface observation data (domain 3).

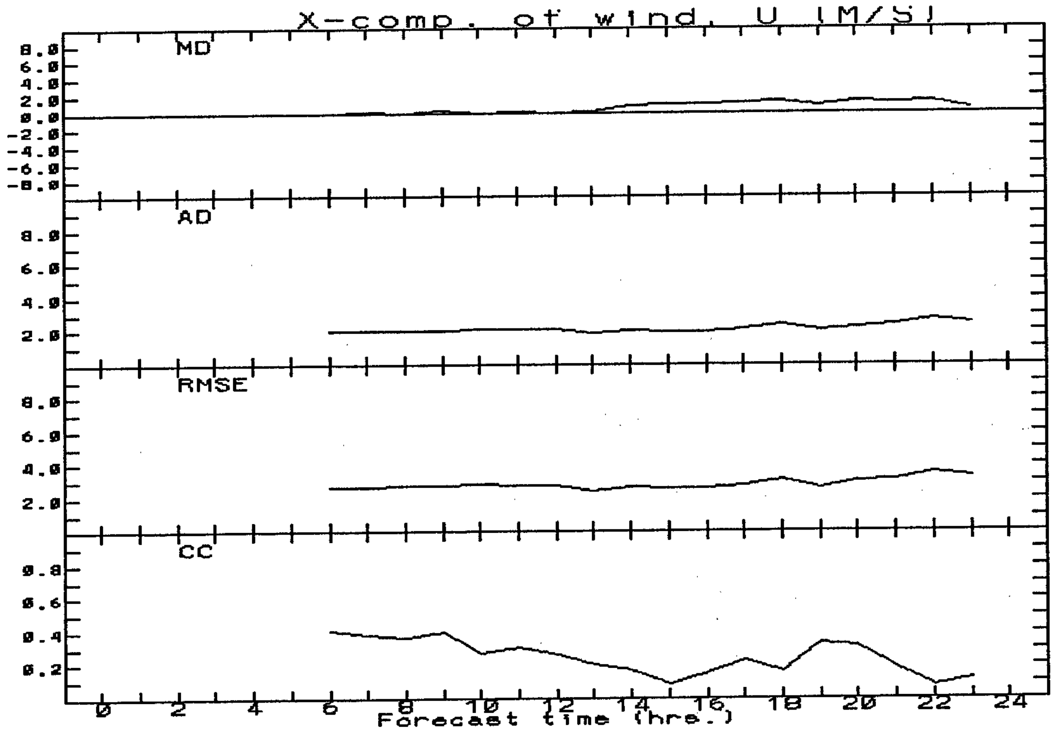

Figure B16. Time series of statistical parameters between MM5 wind vector x, component u forecast data and surface observation data (domain 4).

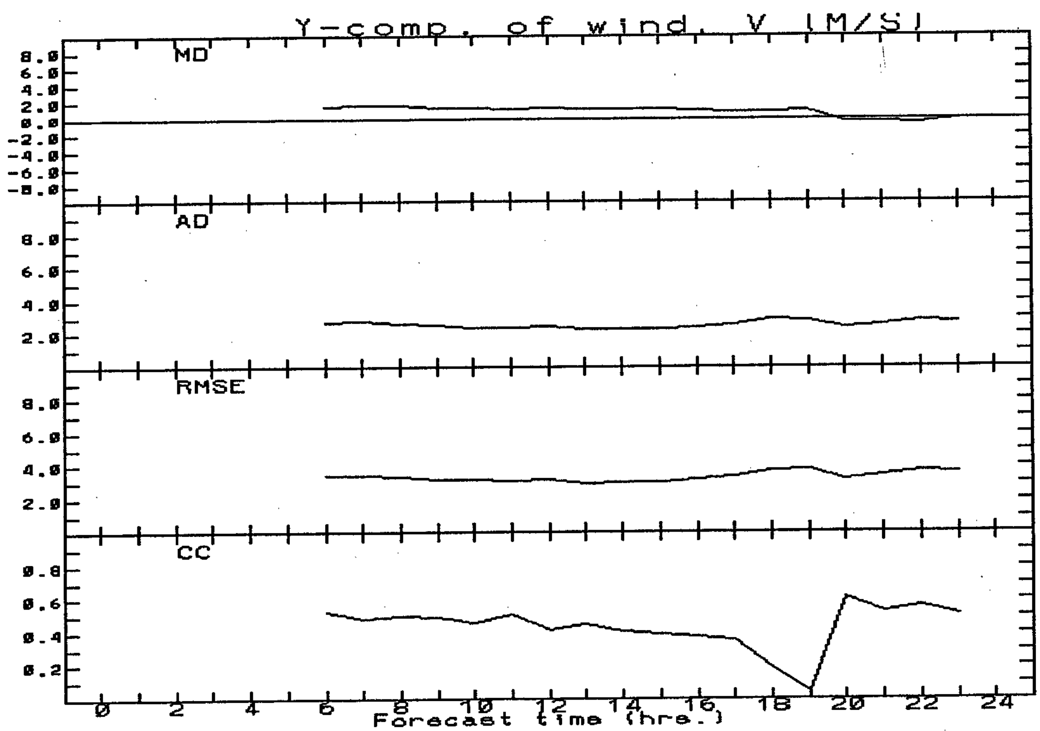

Figure B17. Time series of statistical parameters between MM5 wind vector y, component v forecast data and surface observation data (domain 3).

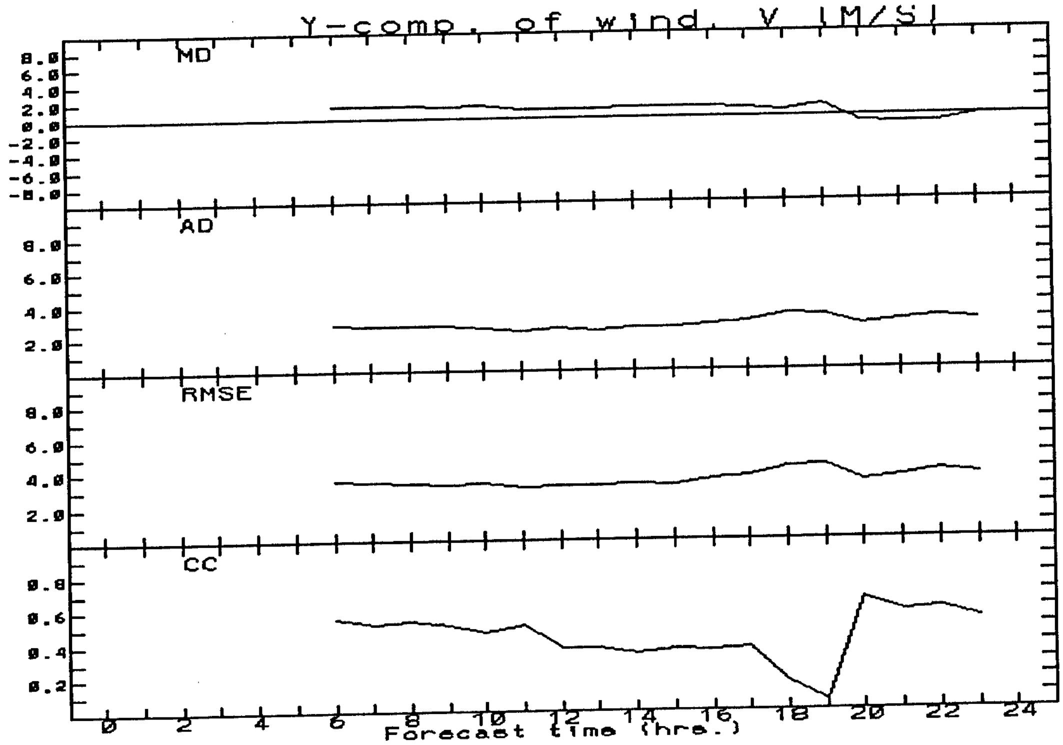

Figure B18. Time series of statistical parameters between MM5 wind vector y, component v forecast data and surface observation data (domain 4).

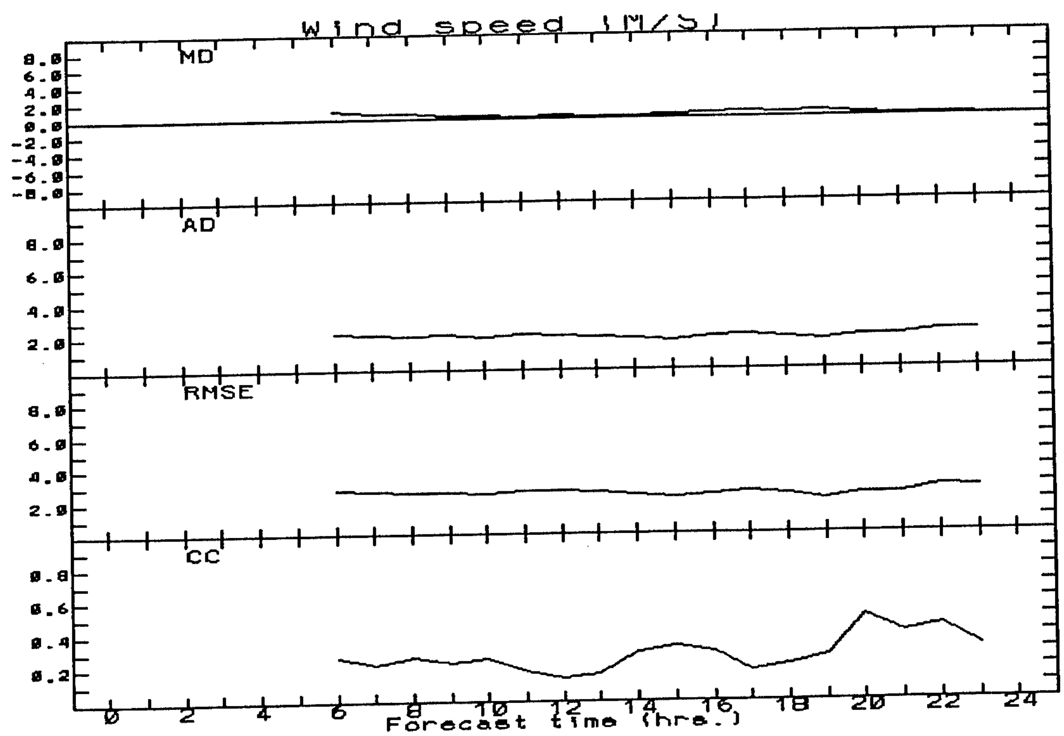

Figure B19. Time series of statistical parameters between MM5 wind speed forecast data and surface observation data (domain 3).

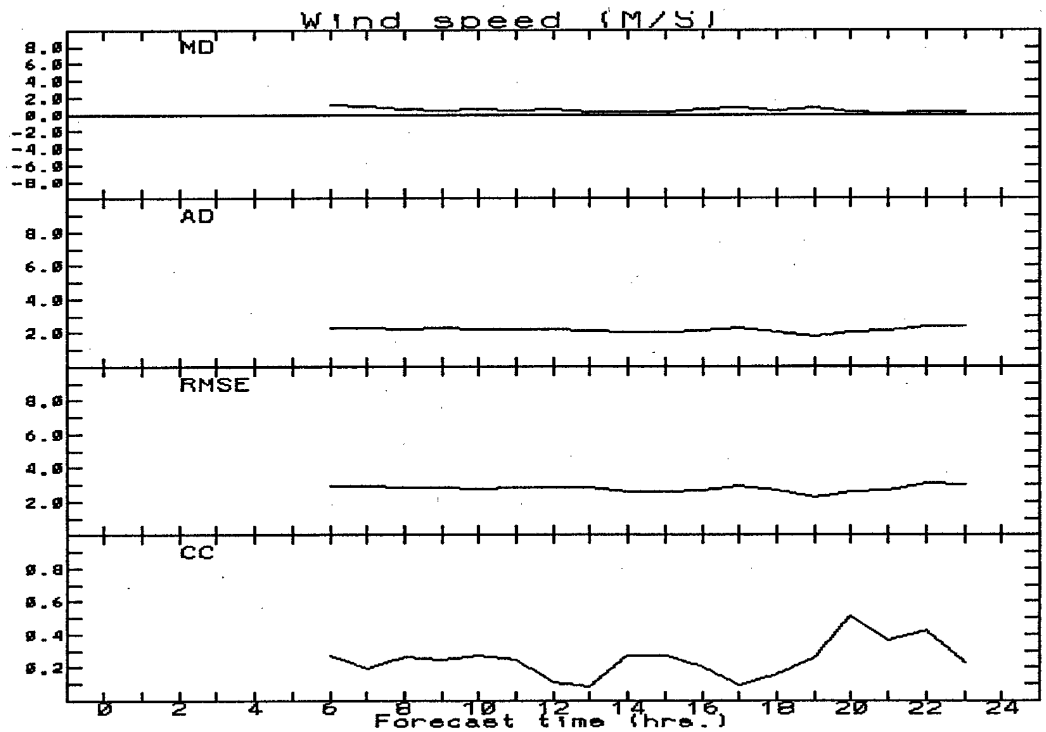

Figure B20. Time series of statistical parameters between MM5 wind speed forecast data and surface observation data (domain 4).

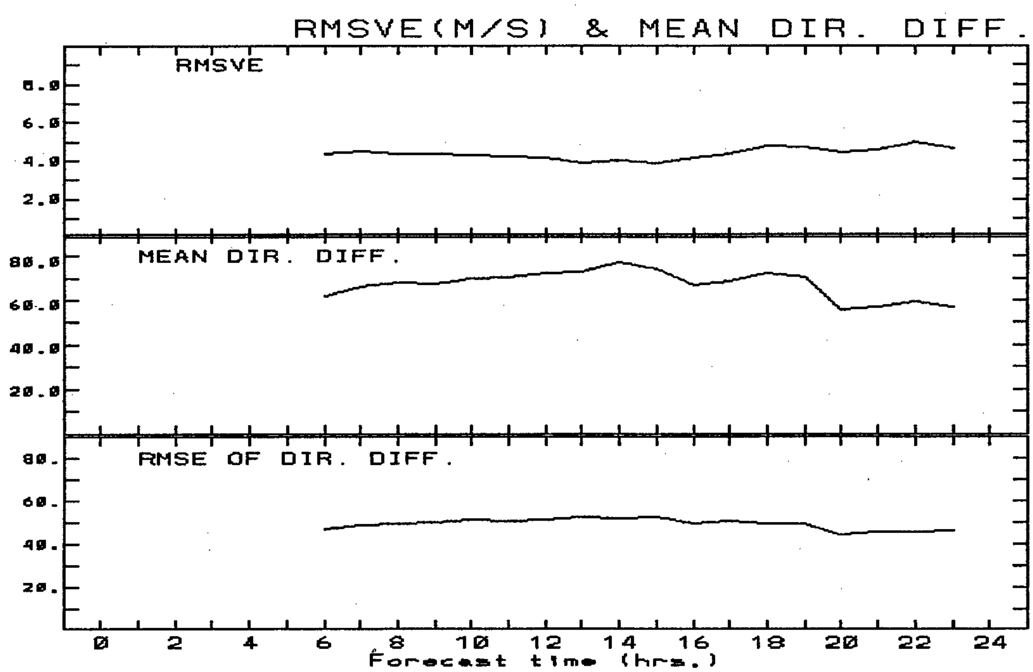

Figure B21. Time series of statistical parameters between MM5 rmsve and mean wind direction forecast data and surface observation data (domain 3).

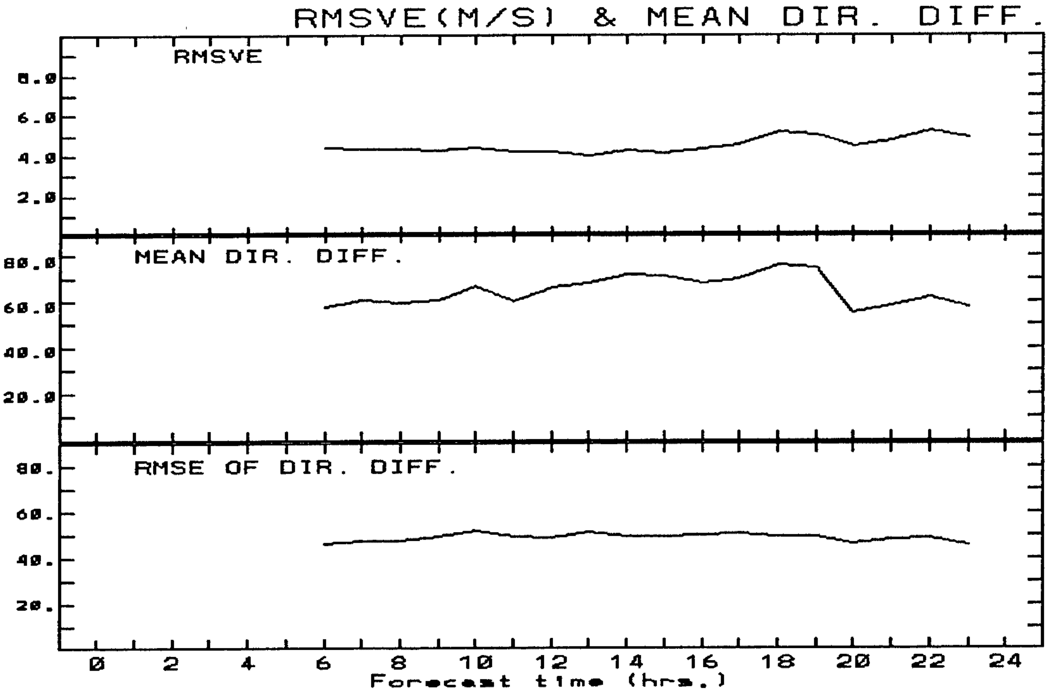

Figure B22. Time series of statistical parameters between MM5 rmsve and mean wind direction forecast data and surface observation data (domain 4).

Appendix C Statistical Diagrams Displaying the Difference Between BFM Forecast Data and Observation Data for the Period of January-March 2002.

This appendix is part of ARL-TR-2928, Evaluation Study of Mesoscale Models MM5 and BFM Over the Model Domains of Utah Using Surface Meteorological Data by Mesowest.

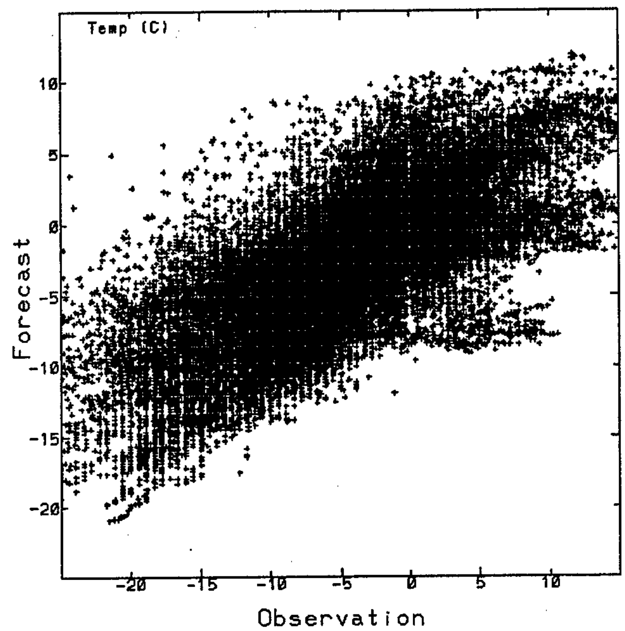

Figure C1. Difference between BFM forecast data and observation data for temperature (5 km grid increment).

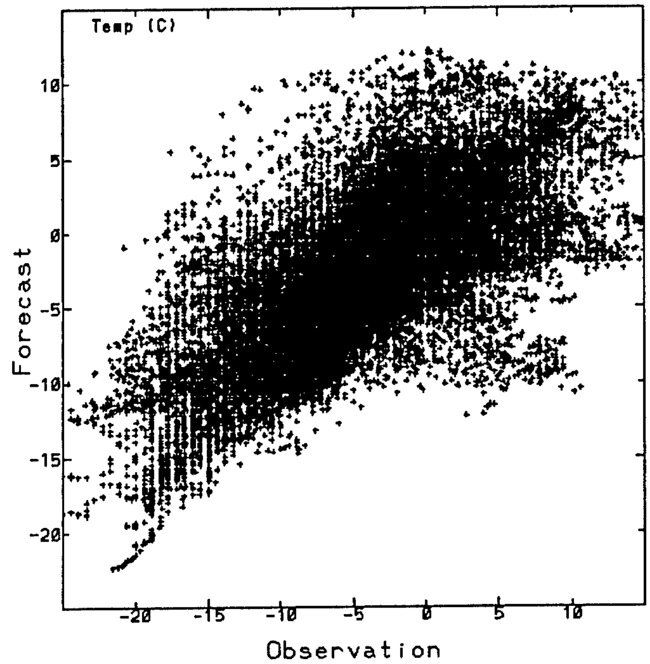

Figure C2. Difference between BFM forecast data and observation data for temperature (2.5 km grid increment).

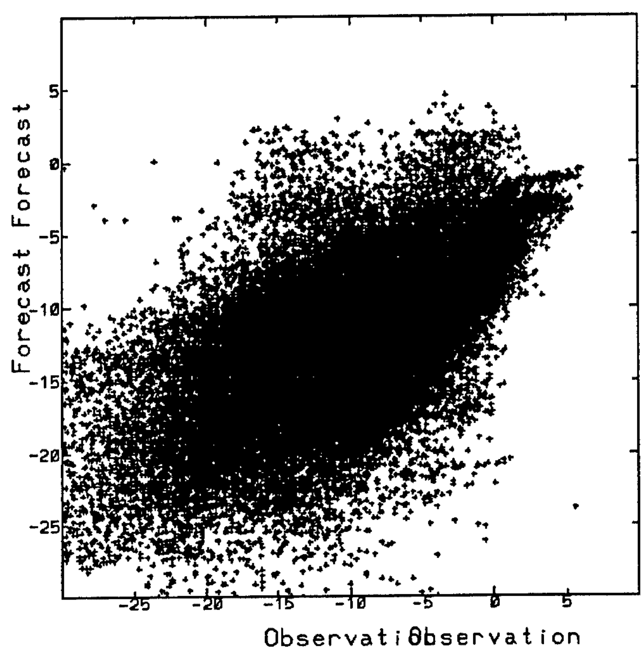

Figure C3. Difference between BFM forecast data and observation data for dew point temperature (5 km grid increment).

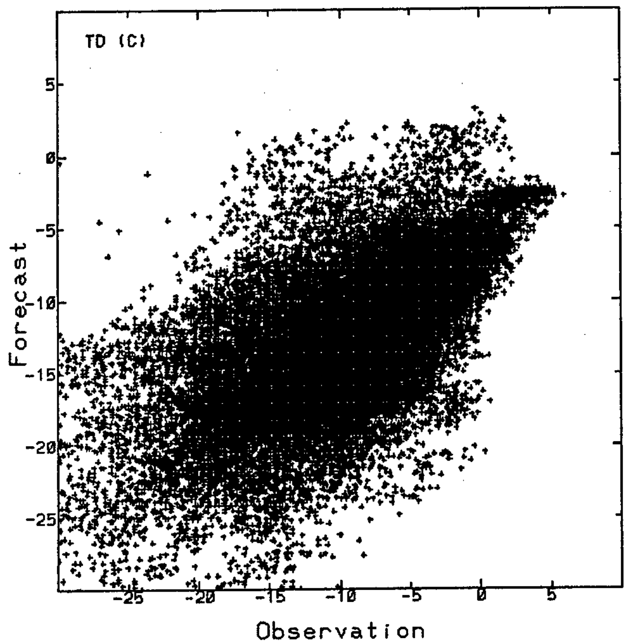

Figure C4. Difference between BFM forecast data and observation data for dew point temperature (2.5 km grid increment).

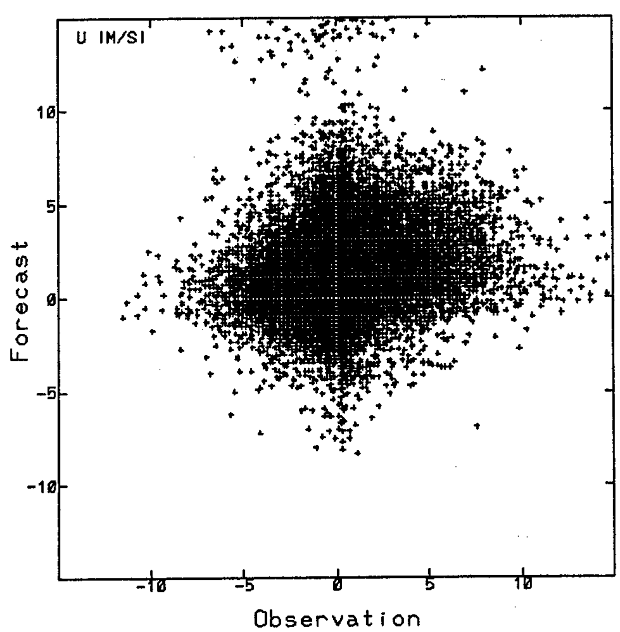

Figure C5. Difference between BFM forecast data and observation data for wind vector x component, u (5 km grid increment).

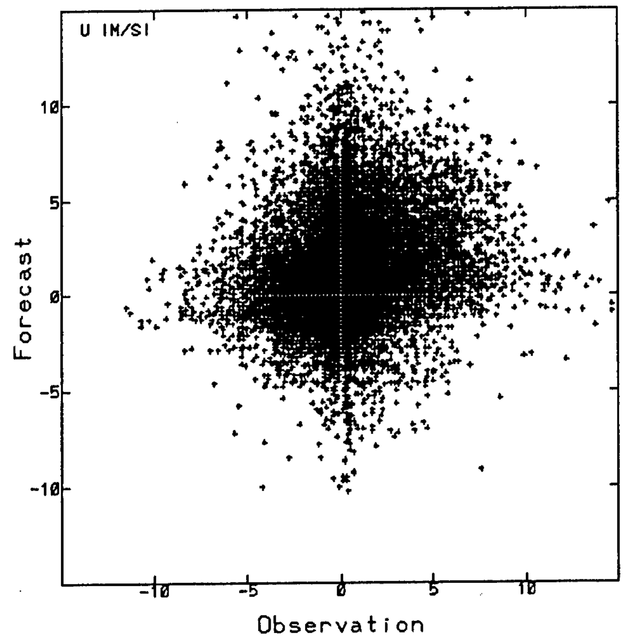

Figure C6. Difference between BFM forecast data and observation data for wind vector x component, u (2.5 km grid increment).

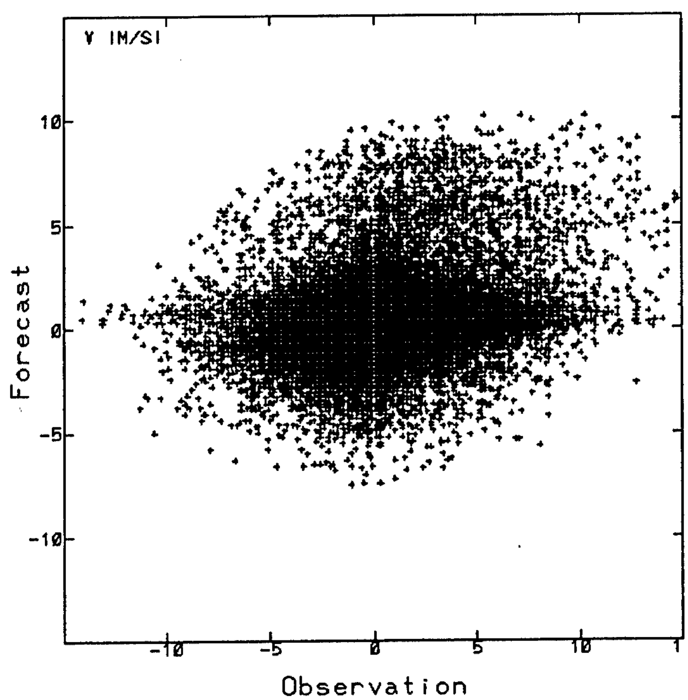

Figure C7. Difference between BFM forecast data and observation data for wind vector y component, v (5 km grid increment).

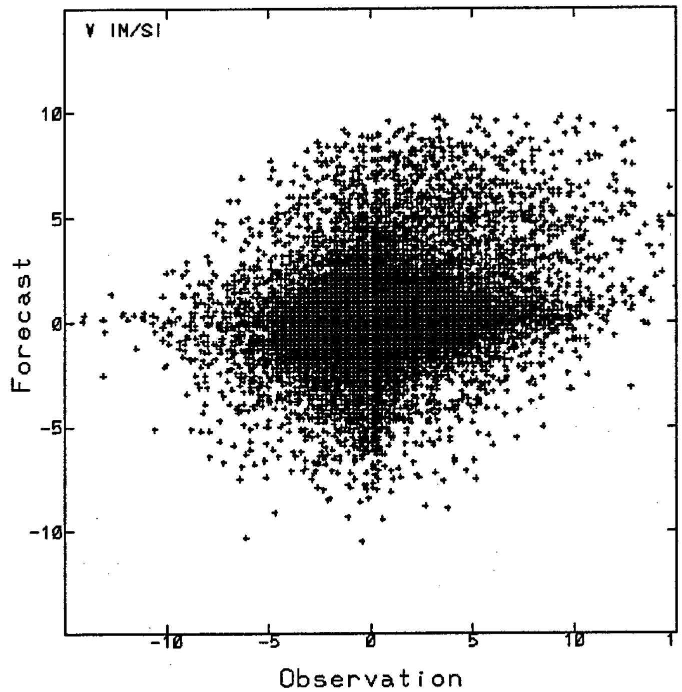

Figure C8. Difference between BFM forecast data and observation data for wind vector y component, v (2.5 km grid increment).

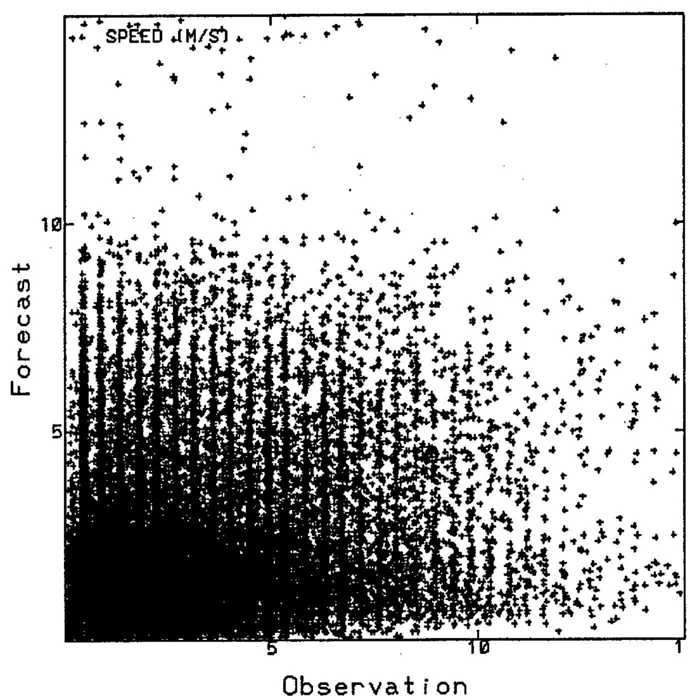

Figure C9. Difference between BFM forecast data and observation data for wind speed (5 km grid increment).

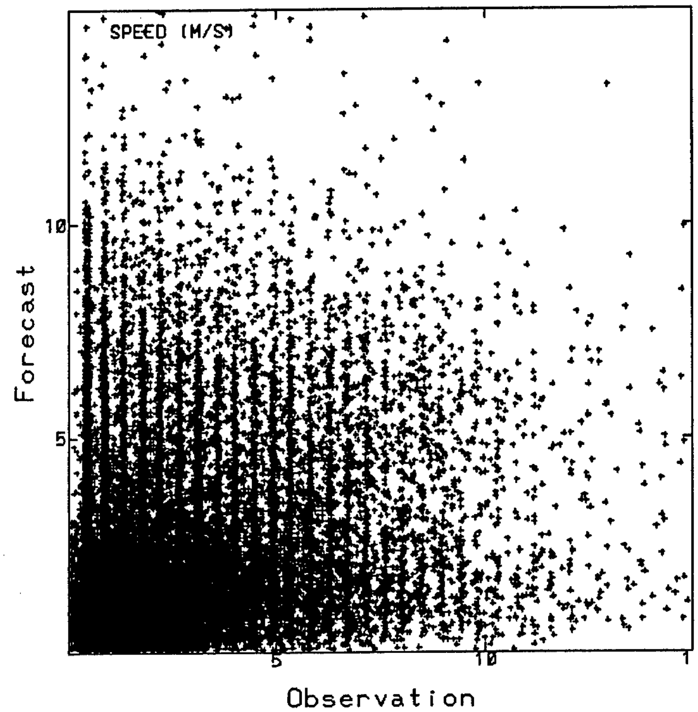

Figure C10. Difference between BFM forecast data and observation data for wind speed (2.5 km grid increment).

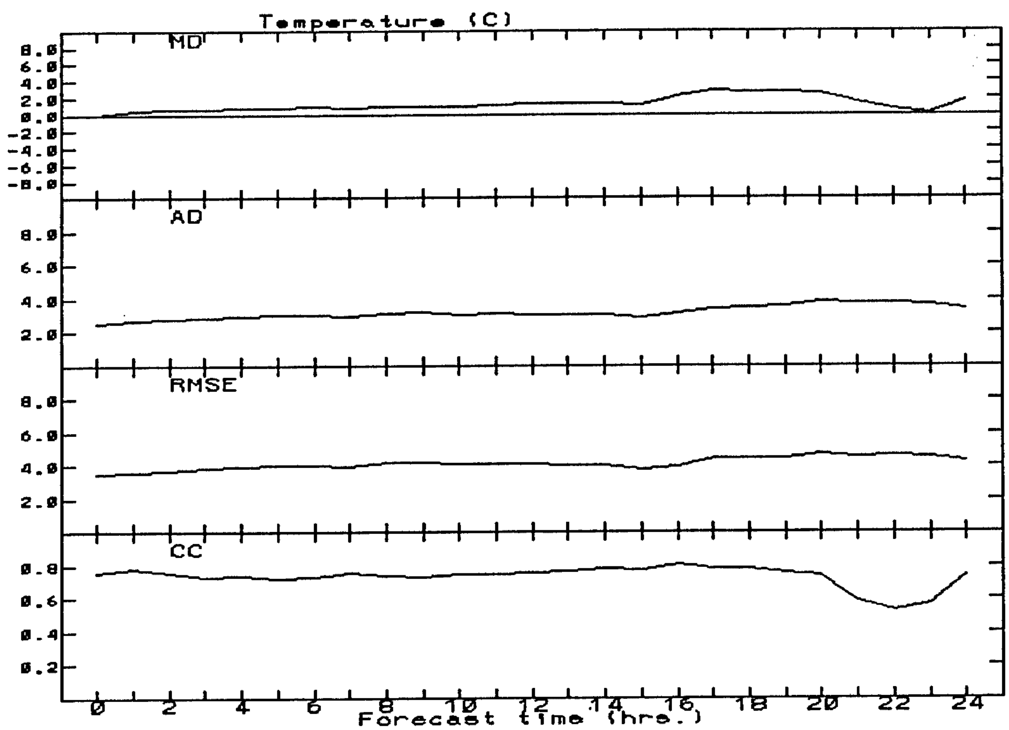

Figure C11. Time series of statistical parameters between BFM temperature forecast data and surface observation data (5 km grid increment).

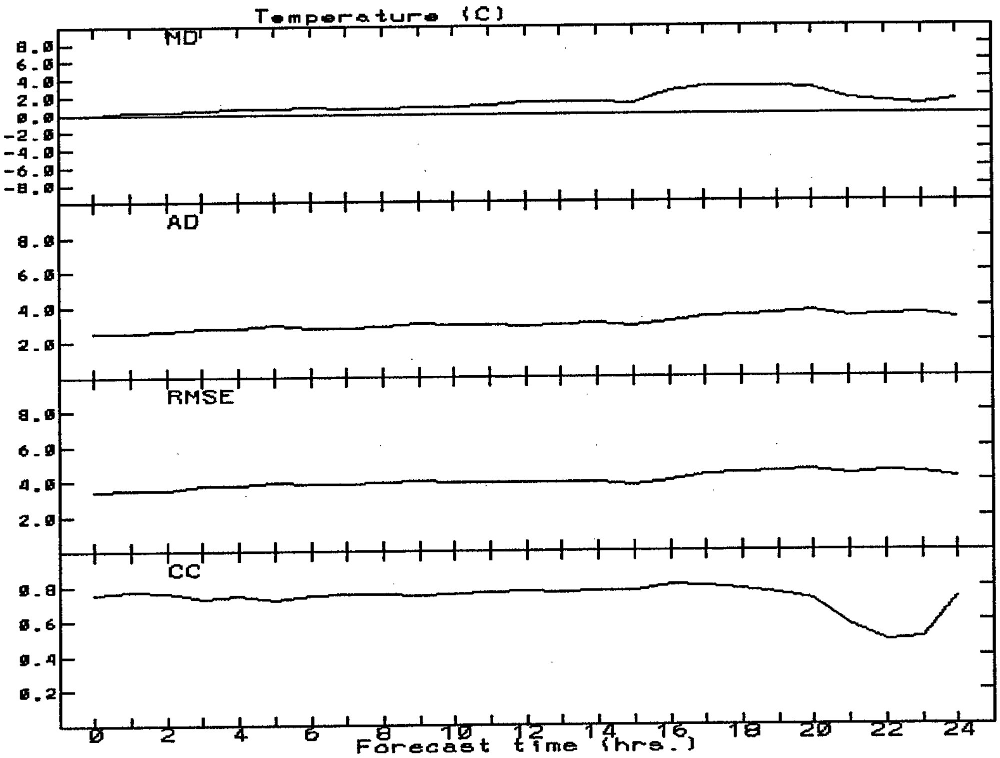

Figure C12. Time series of statistical parameters between BFM temperature forecast data and surface observation data (2.5 grid increment).

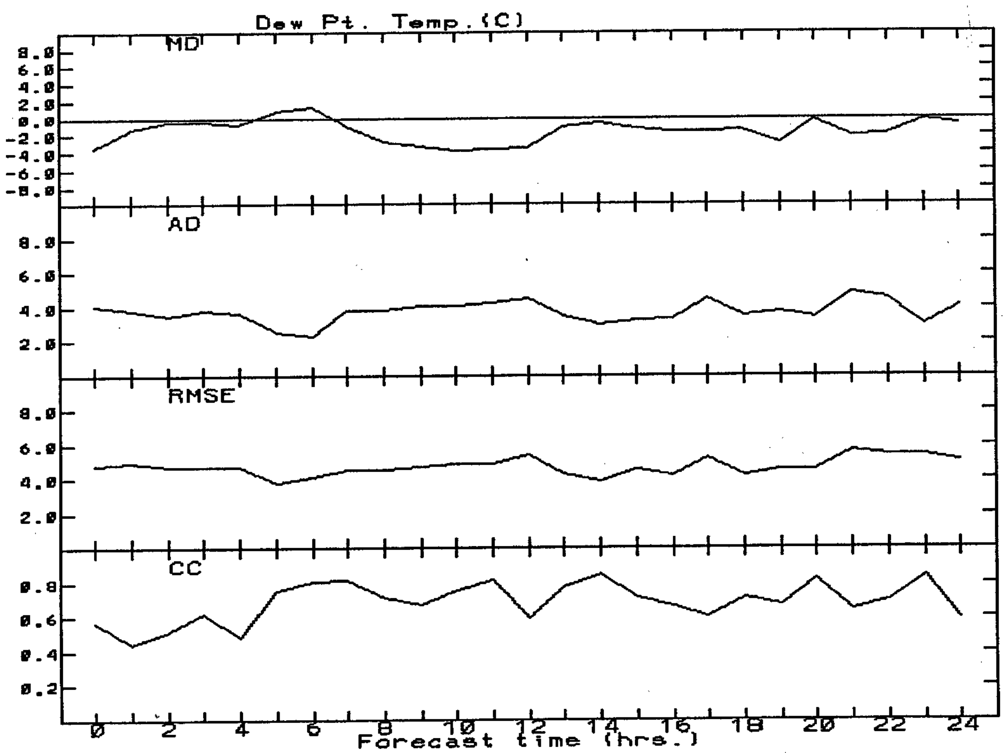

Figure C13. Time series of statistical parameters between BFM dew point temperature forecast data and surface observation data (5 grid increment).

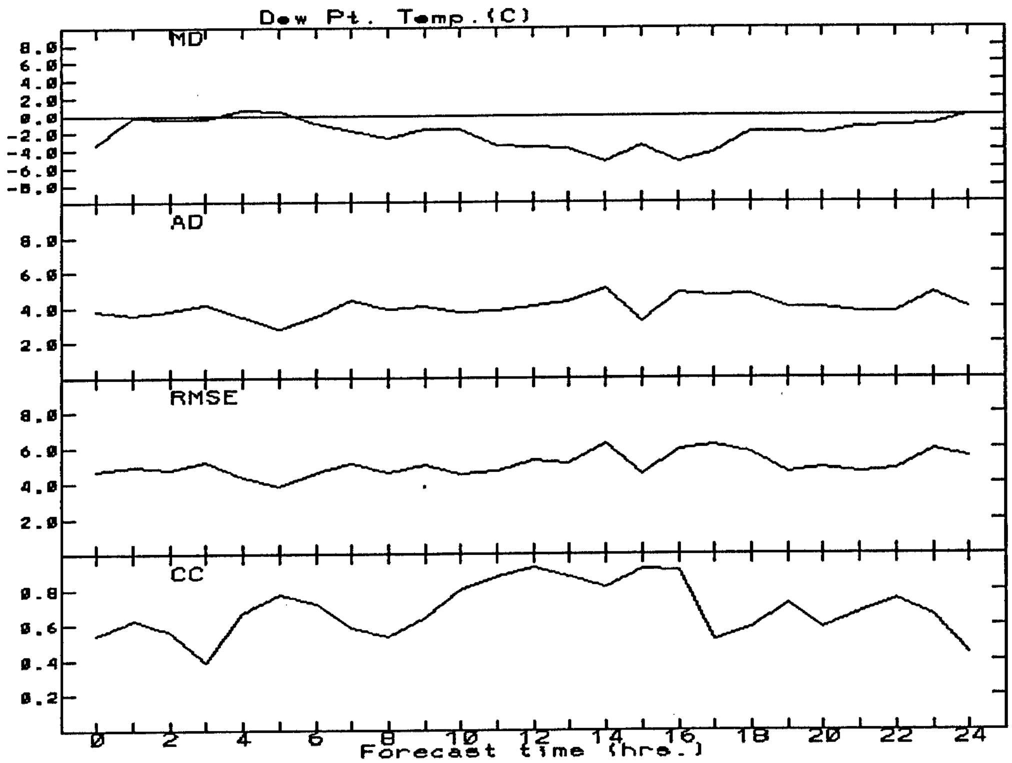

Figure C14. Time series of statistical parameters between BFM dew point temperature forecast data and surface observation data (2.5 grid increment).

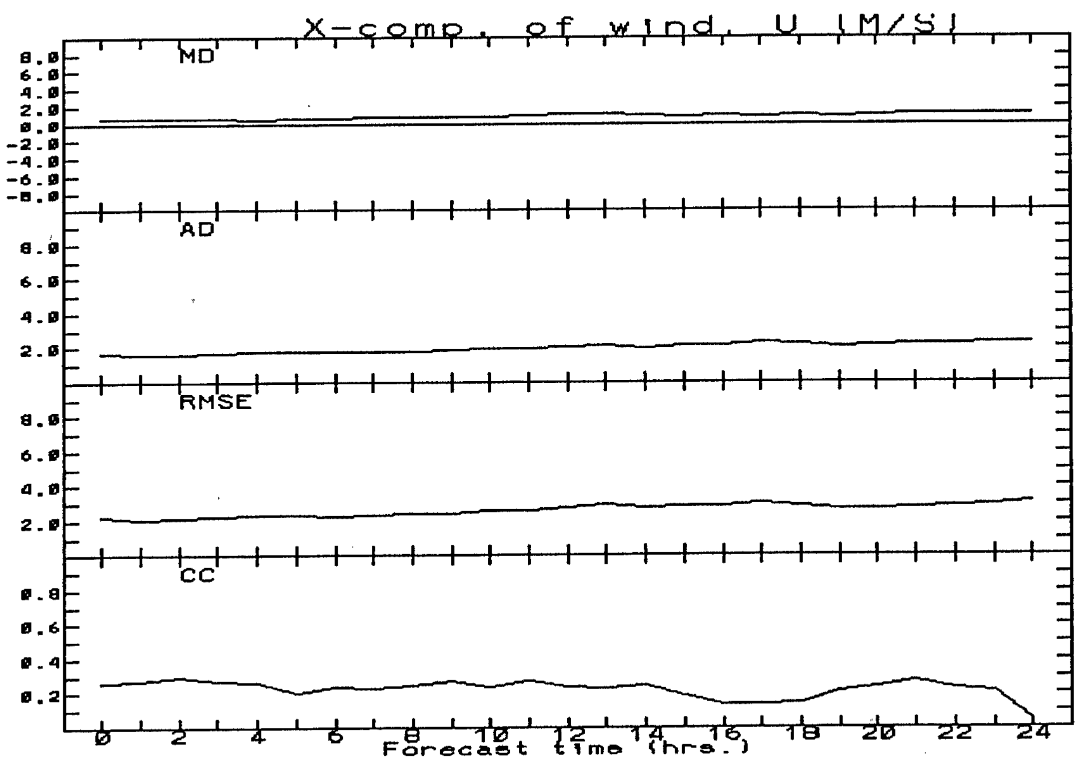

Figure C15. Time series of statistical parameters between BFM wind vector x component u forecast data and surface observation data (5 grid increment).

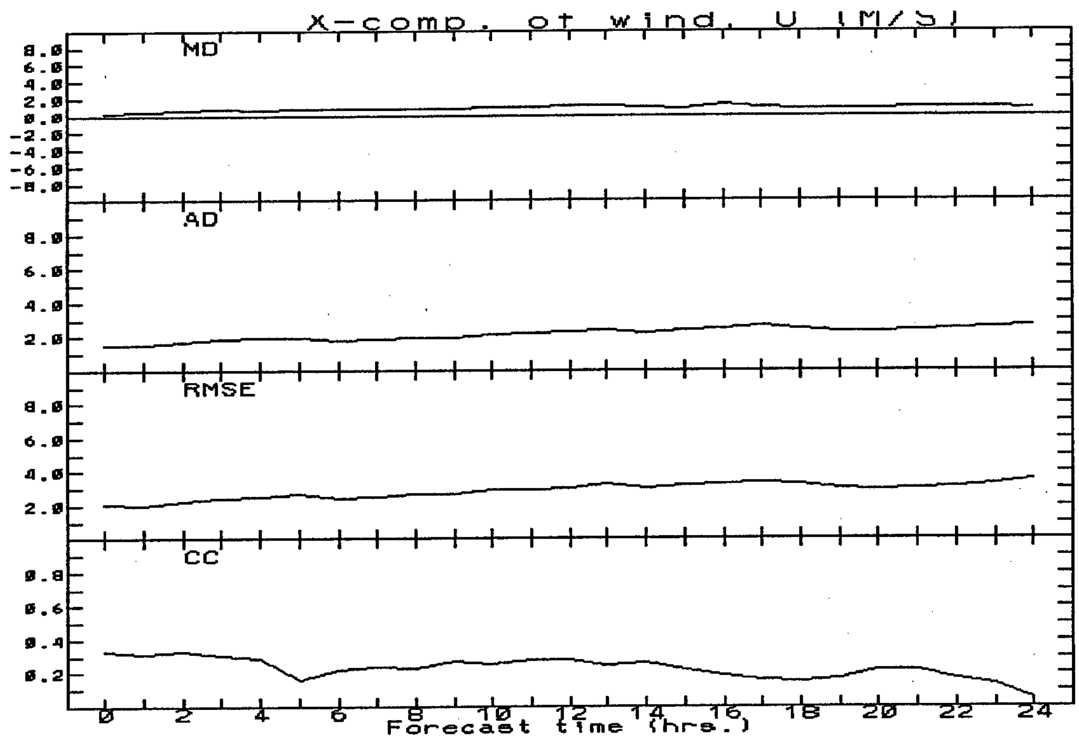

Figure C16. Time series of statistical parameters between BFM wind vector x component u forecast data and surface observation data (2.5 grid increment).

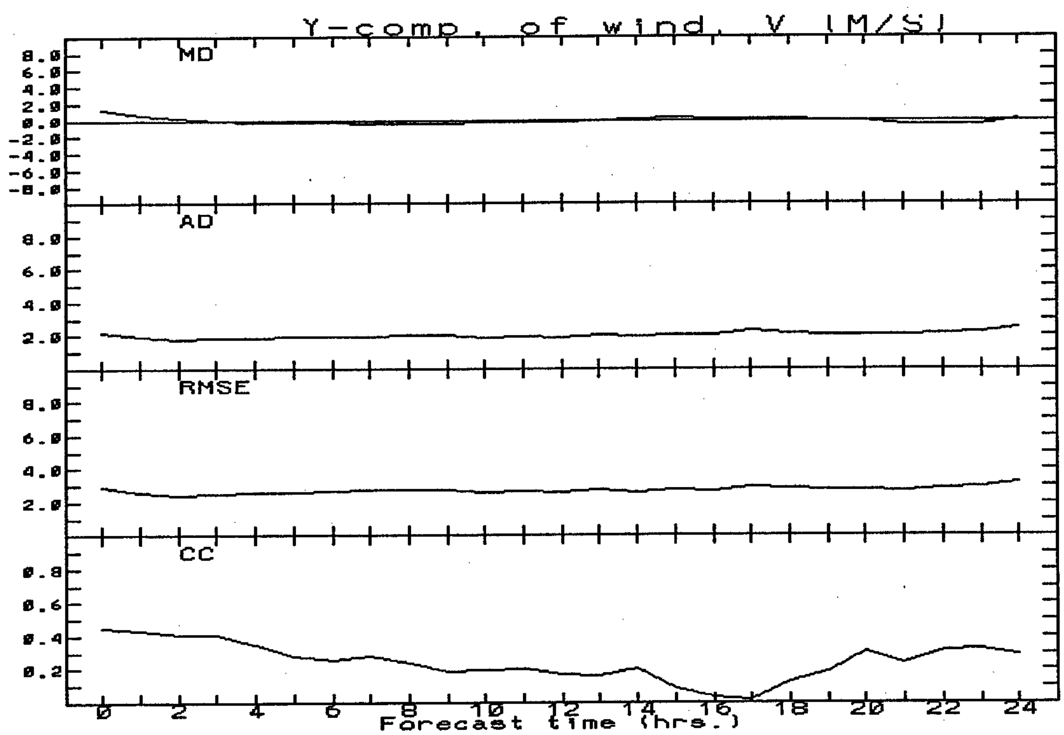

Figure C17. Time series of statistical parameters between BFM wind vector y component v forecast data and surface observation data (5 grid increment).

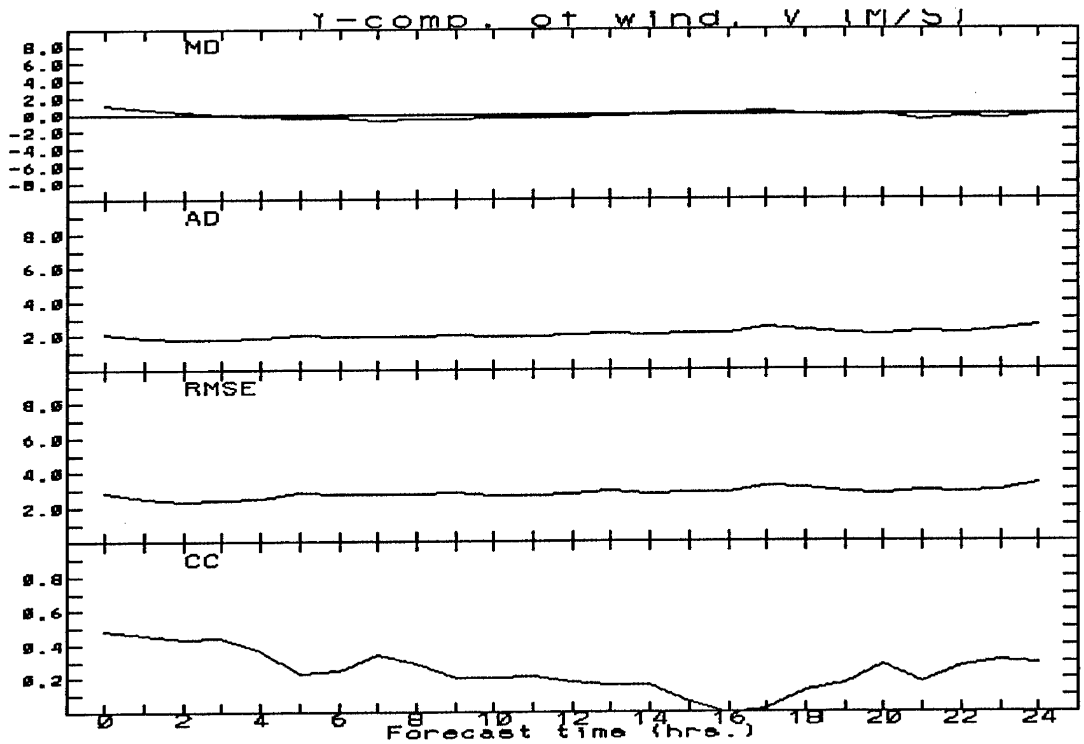

Figure C18. Time series of statistical parameters between BFM wind vector y component v forecast data and surface observation data (2.5 grid increment).

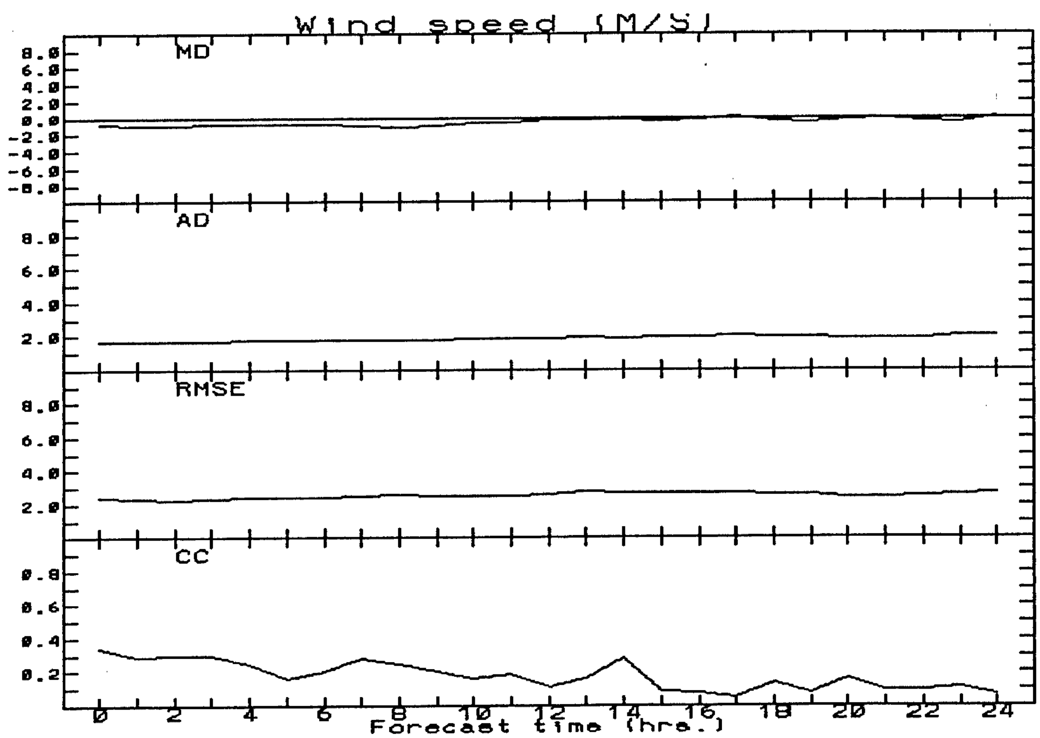

Figure C19. Time series of statistical parameters between BFM wind vector speed forecast data and surface observation data (5 grid increment).

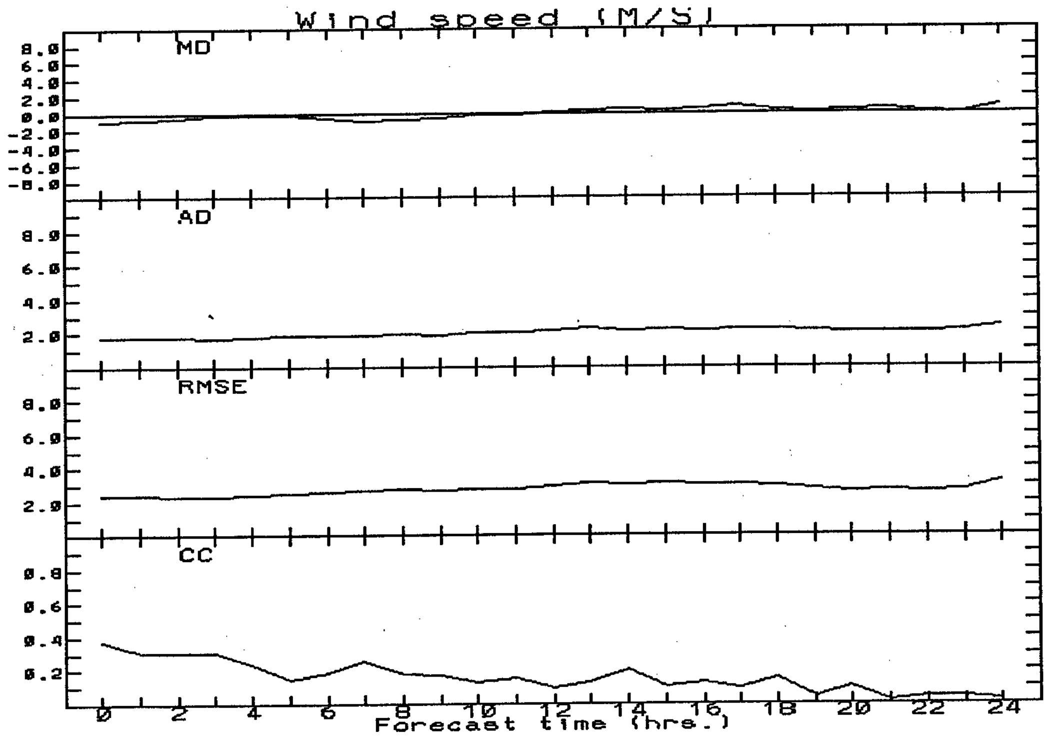

Figure C20. Time series of statistical parameters between BFM wind vector speed forecast data and surface observation data (2.5 grid increment).

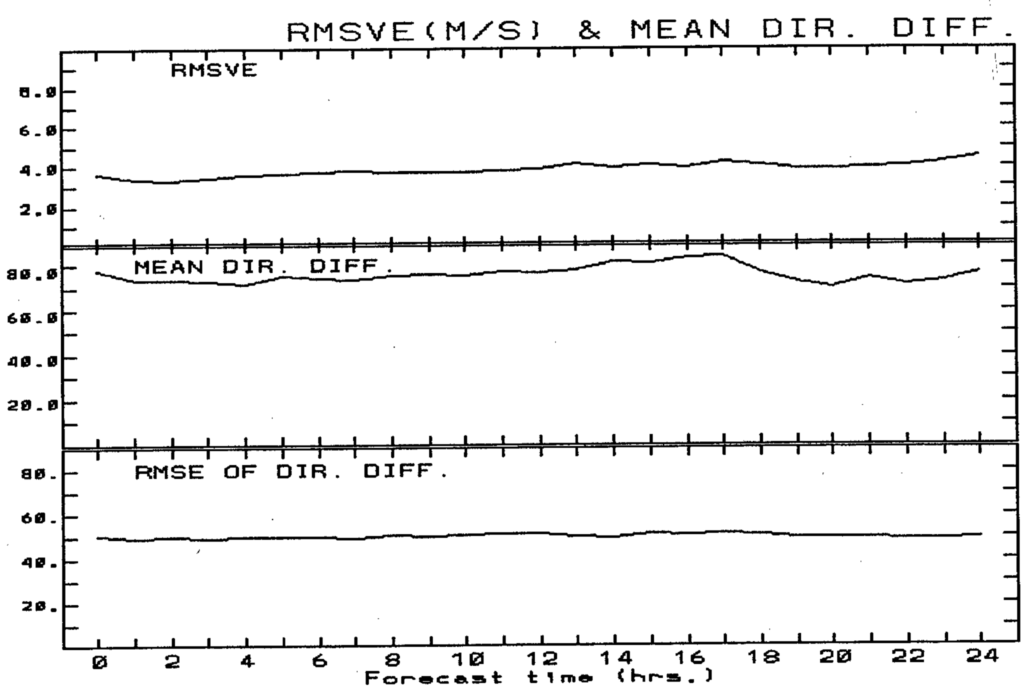

Figure C21. Time series of statistical parameters between BFM rmsve and mean wind direction forecast data and surface observation data (5 grid increment).

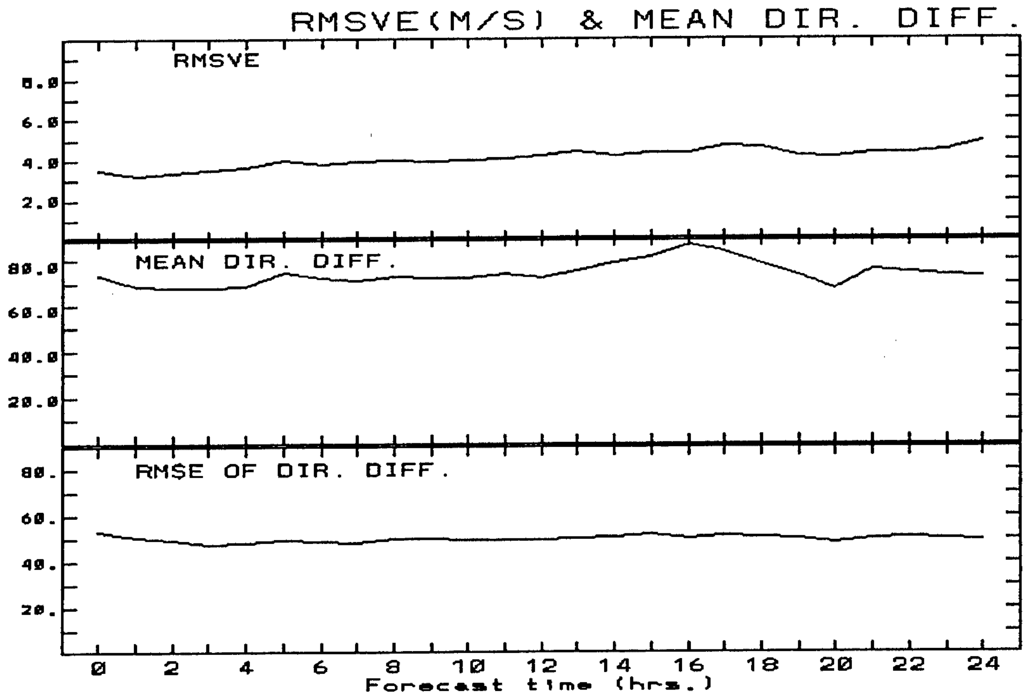

Figure C22. Time series of statistical parameters between BFM rmsve and mean wind direction forecast data and surface observation data (2.5 grid increment).

Appendix D Statistical Diagrams Displaying the Difference Between BFM Forecast Data and Observation Data for the Period of April-June 2002.

This appendix is part of ARL-TR-2928, Evaluation Study of Mesoscale Models MM5 and BFM Over the Model Domains of Utah Using Surface Meteorological Data by Mesowest.

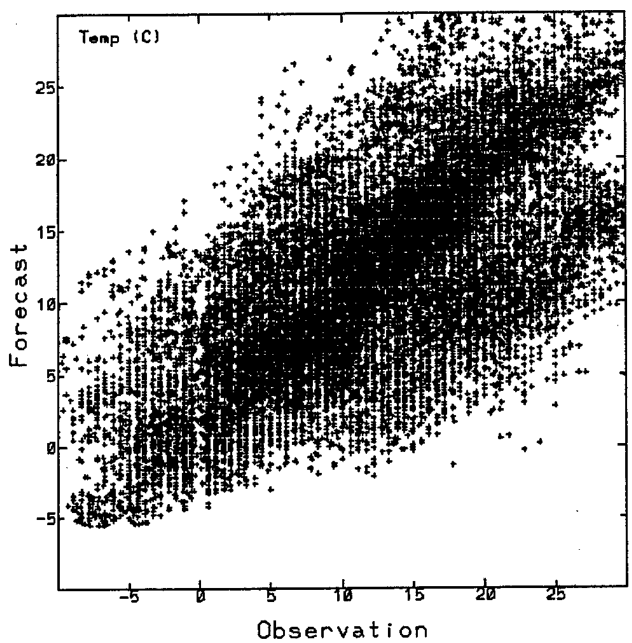

Figure D1. Difference between BFM forecast data and observation data for temperature (5 km grid increment).

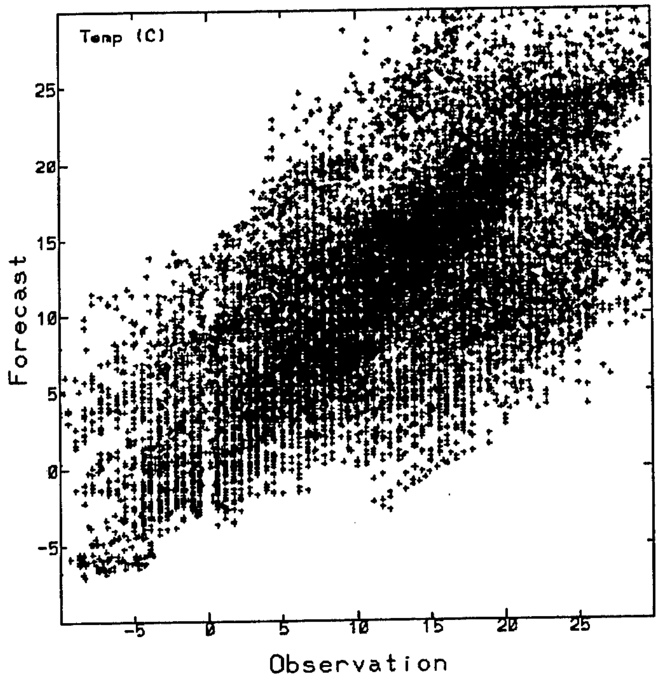

Figure D2. Difference between BFM forecast data and observation data for temperature (2.5 km grid increment).

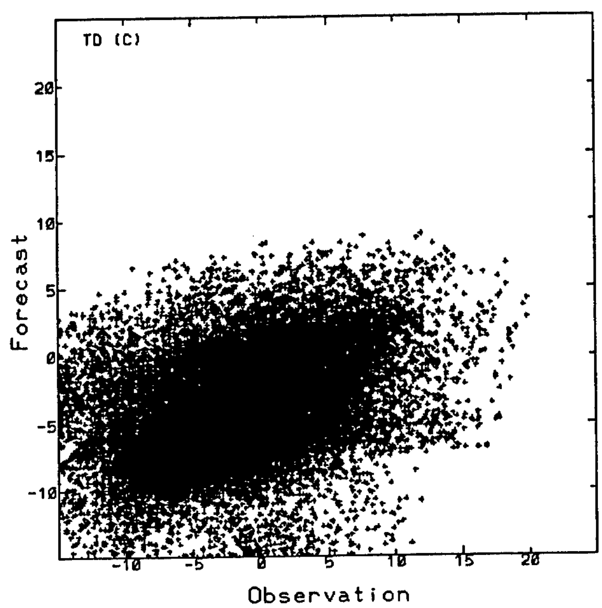

Figure D3. Difference between BFM forecast data and observation data for dew point temperature (5 km grid increment).

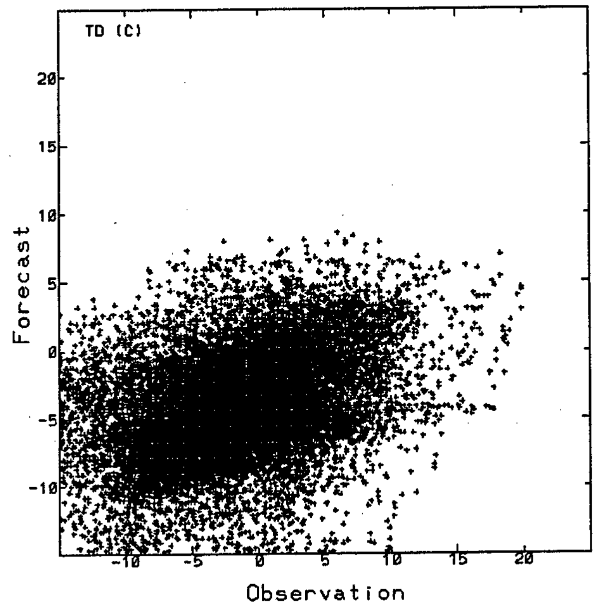

Figure D4. Difference between BFM forecast data and observation data for dew point temperature (2.5 km grid increment).

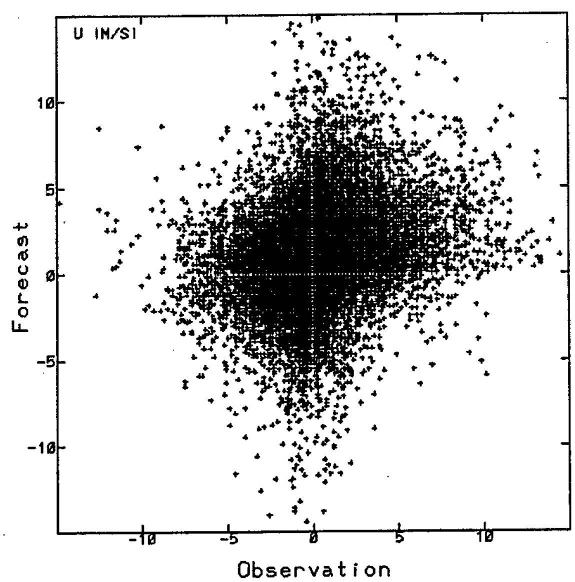

Figure D5. Difference between BFM forecast data and observation data for wind vector x component u (5 km grid increment).

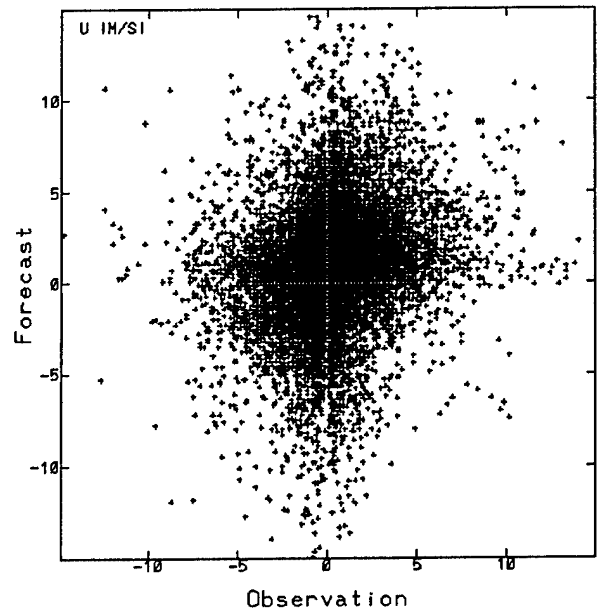

Figure D6. Difference between BFM forecast data and observation data for wind vector x component u (2.5 km grid increment).

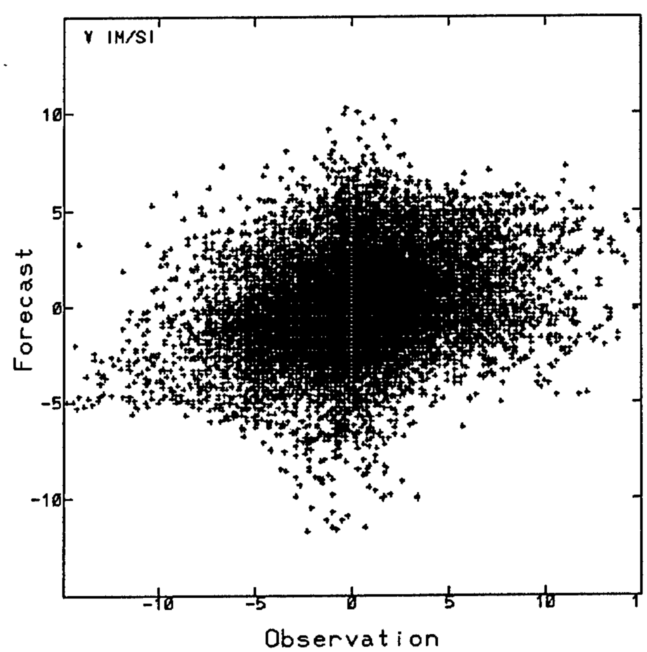

Figure D7. Difference between BFM forecast data and observation data for wind vector y component v (5 km grid increment).

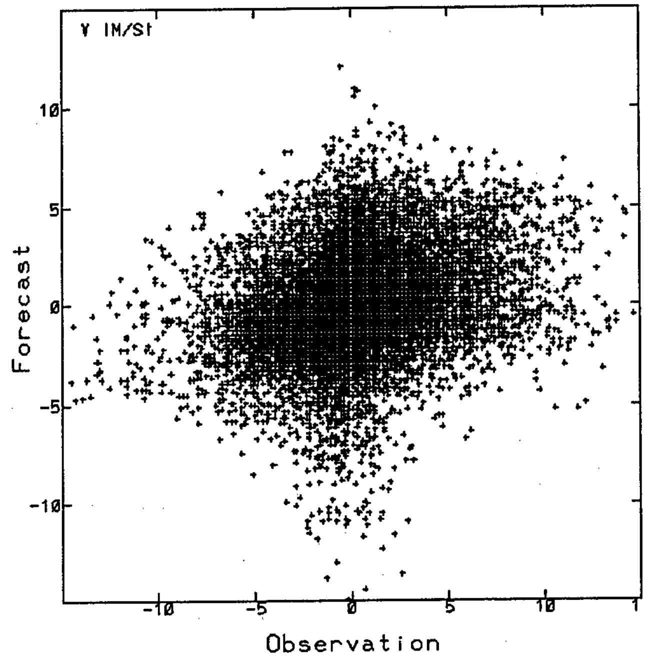

Figure D8. Difference between BFM forecast data and observation data for wind vector y component v (2.5 km grid increment).

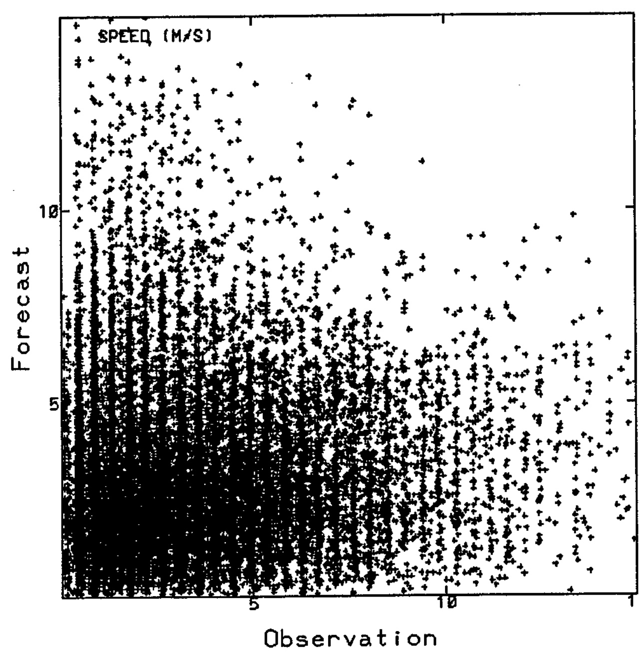

Figure D9. Difference between BFM forecast data and observation data for wind speed (5 km grid increment).

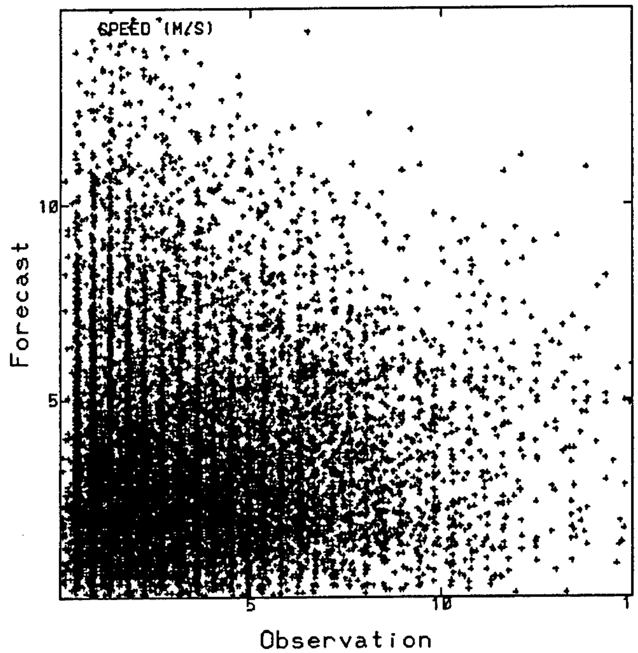

Figure D10. Difference between BFM forecast data and observation data for wind speed (2.5 km grid increment).

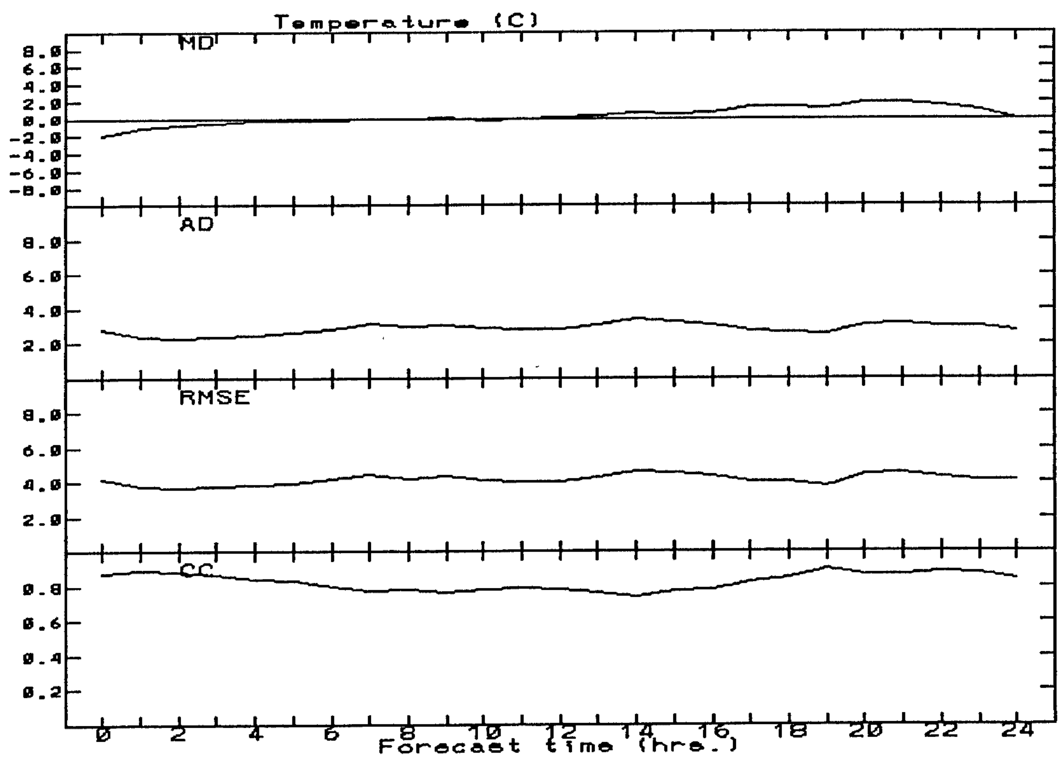

Figure D11. Time series of statistical parameters between BFM temperature forecast data and surface observation data (5 km grid increment).

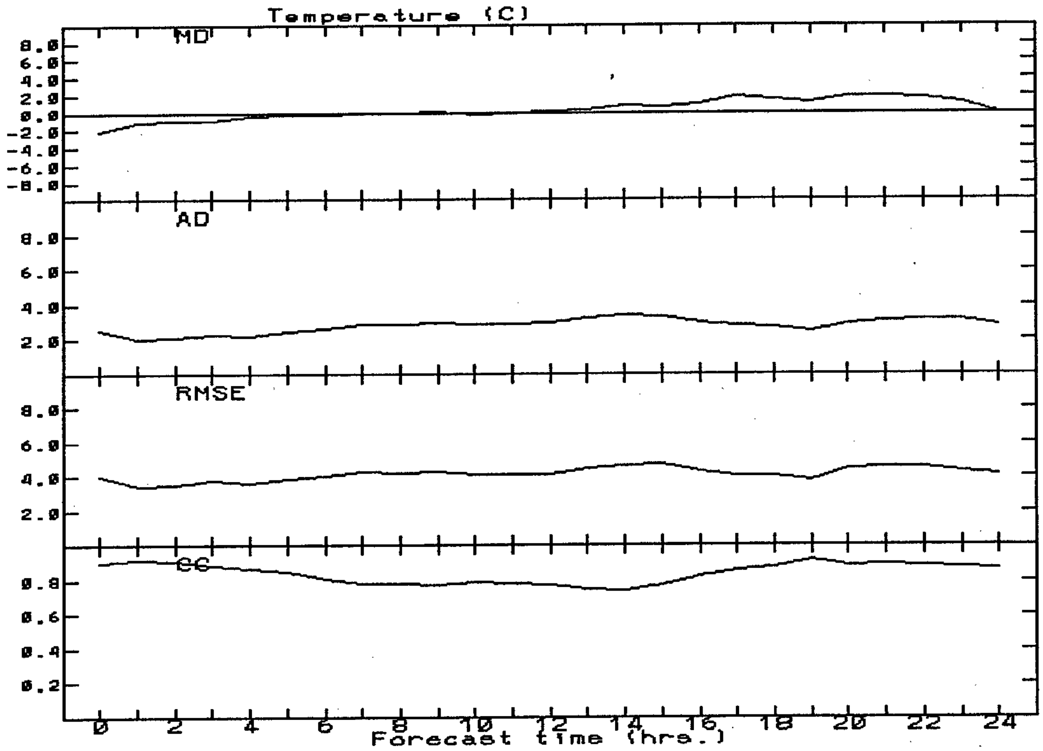

Figure D12. Time series of statistical parameters between BFM temperature forecast data and surface observation data (2.5 km grid increment).

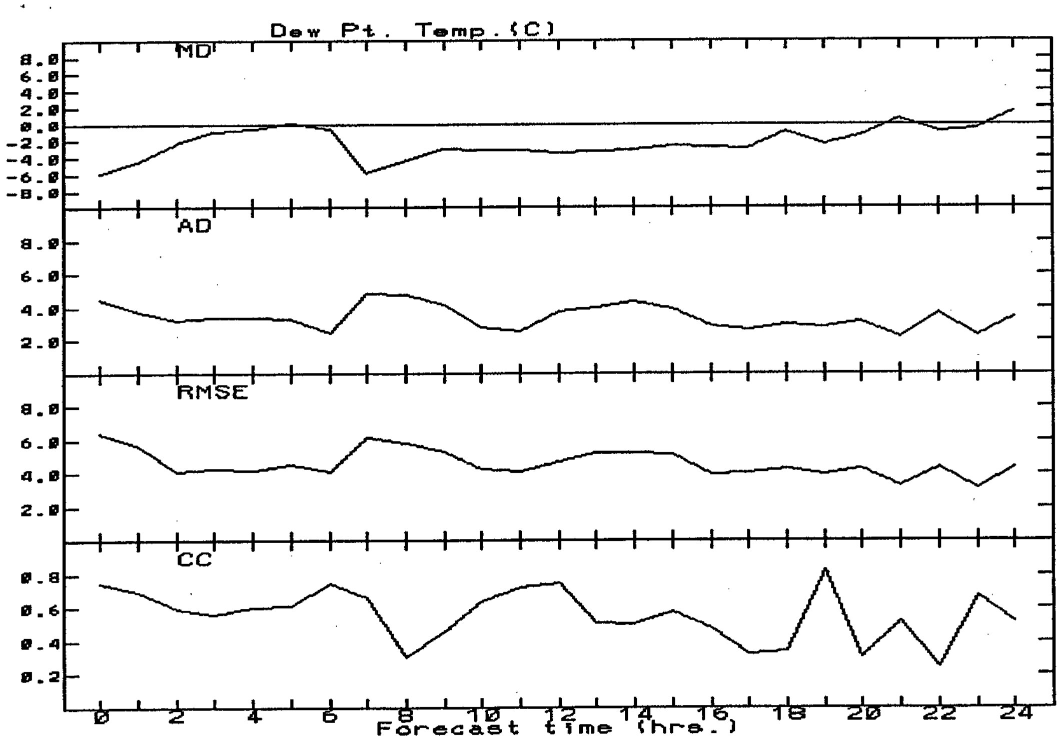

Figure D13. Time series of statistical parameters between BFM dew point temperature forecast data and surface observation data (5 km grid increment).

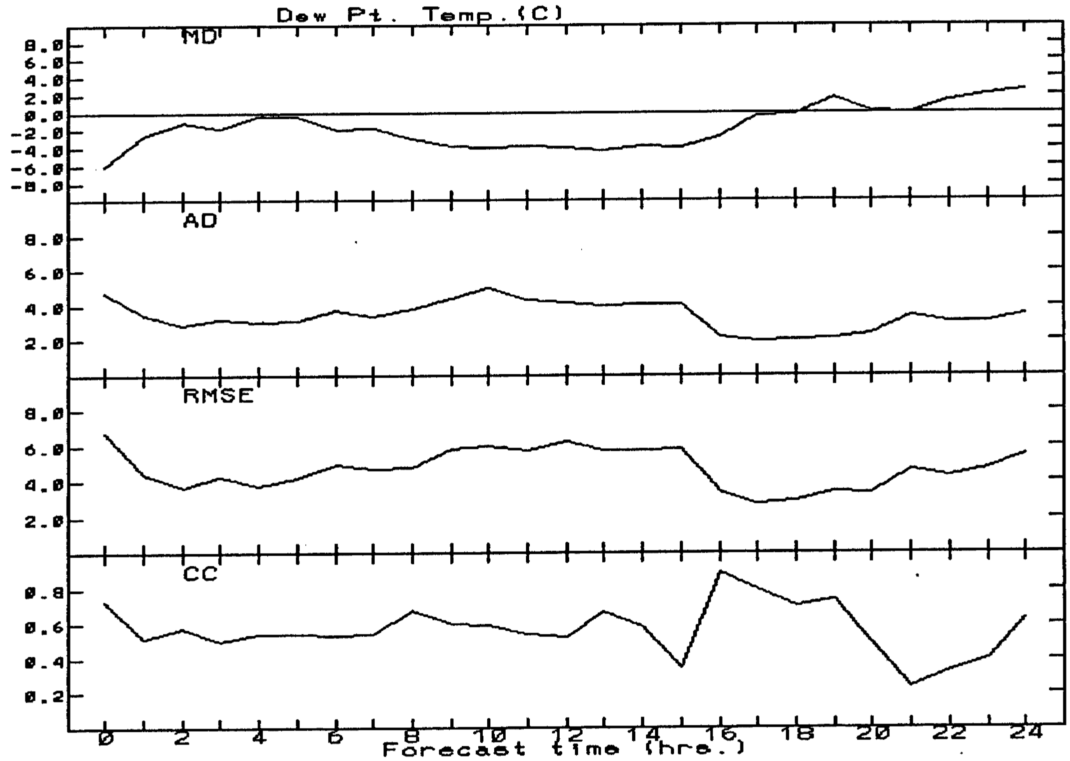

Figure D14. Time series of statistical parameters between BFM dew point temperature forecast data and surface observation data (2.5 km grid increment).

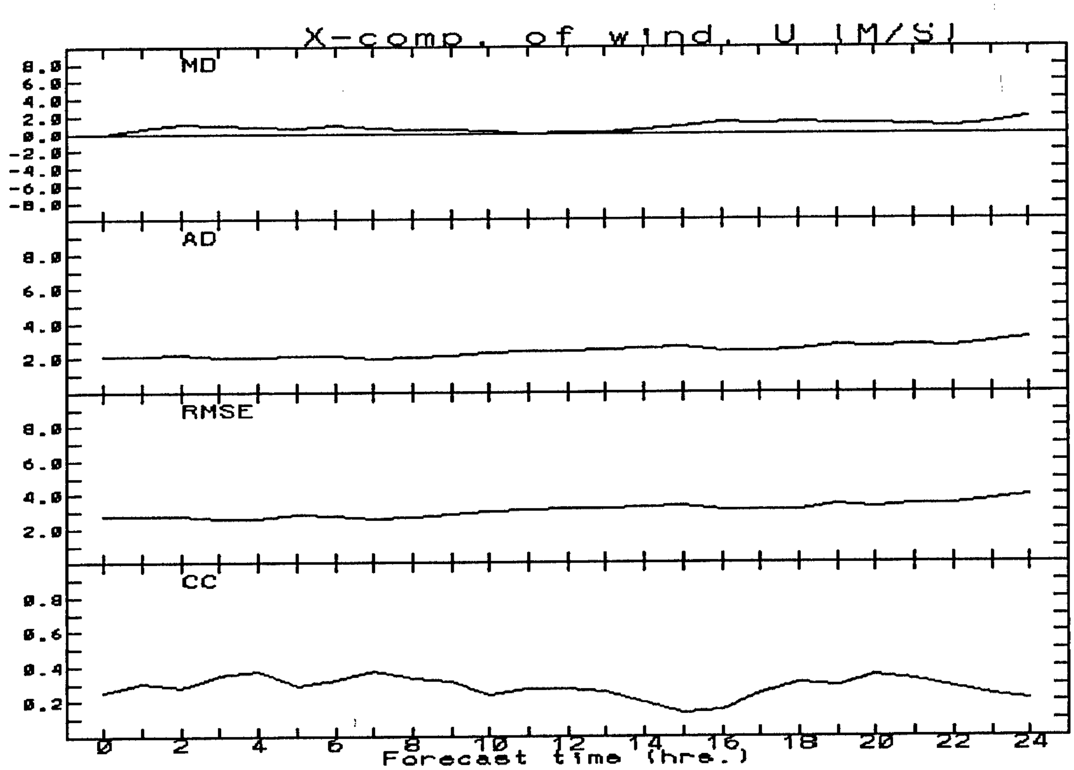

Figure D15. Time series of statistical parameters between BFM wind vector x component u forecast data and surface observation data (5 km grid increment).

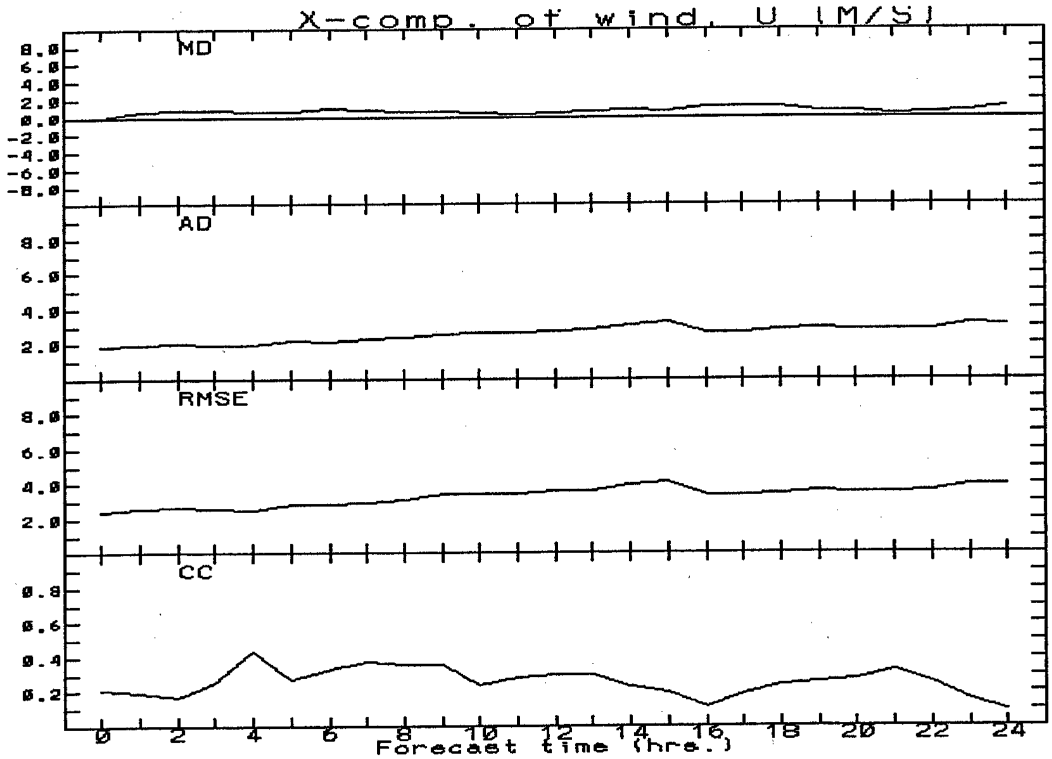

Figure D16. Time series of statistical parameters between BFM wind vector x component u forecast data and surface observation data (2.5 km grid increment).

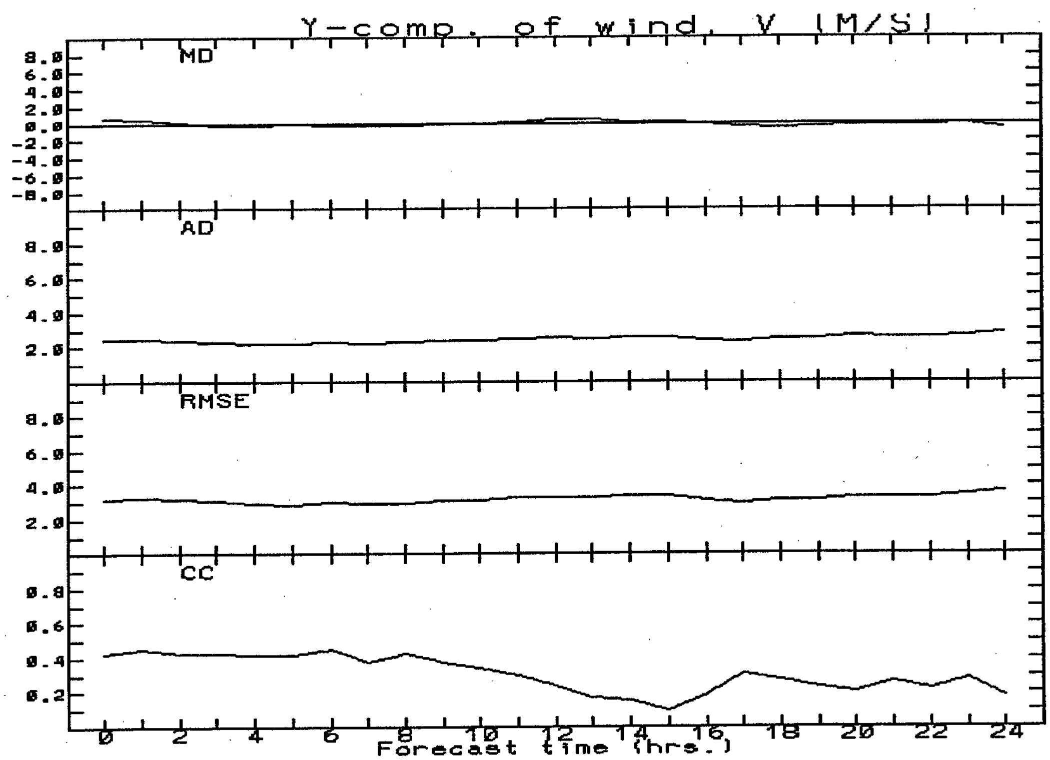

Figure D17. Time series of statistical parameters between BFM wind vector y component v forecast data and surface observation data (5 km grid increment).

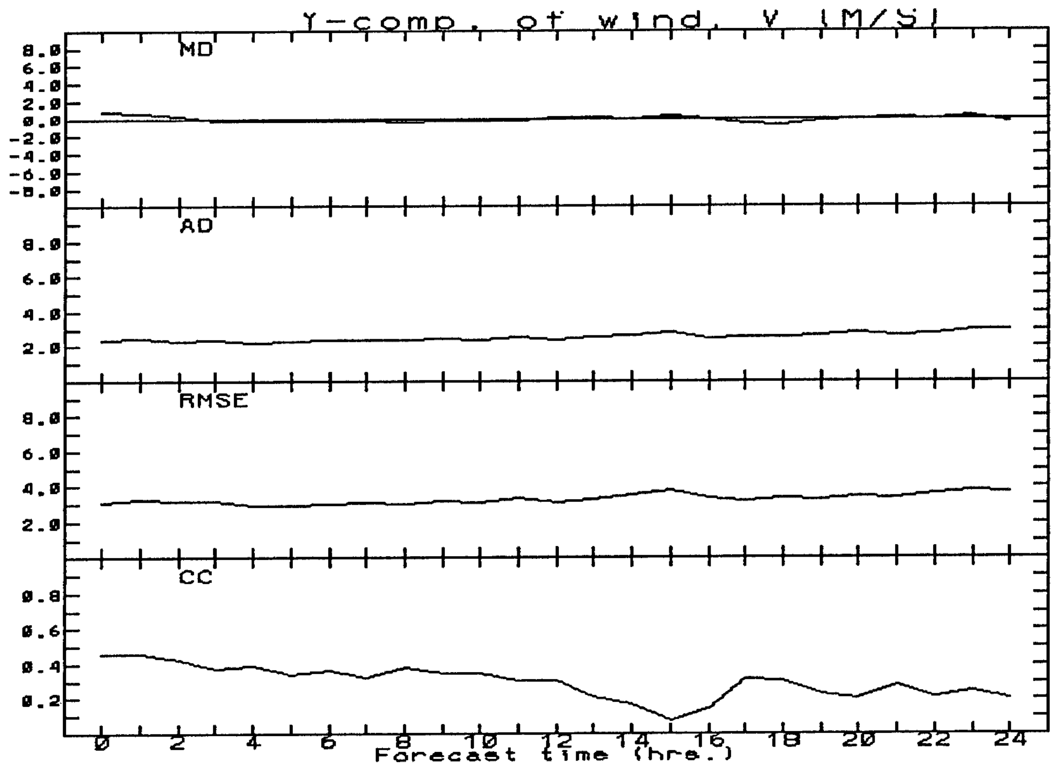

Figure D18. Time series of statistical parameters between BFM wind vector y component v forecast data and surface observation data (2.5 km grid increment).

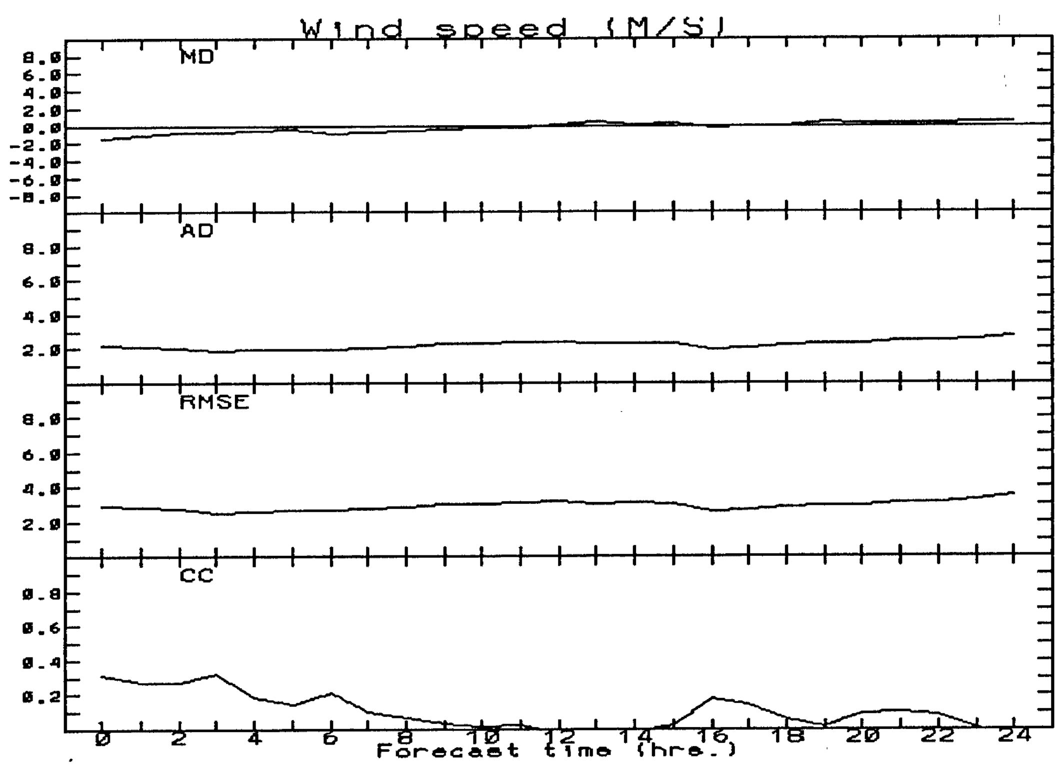

Figure D19. Time series of statistical parameters between BFM wind speed forecast data and surface observation data (5 km grid increment).

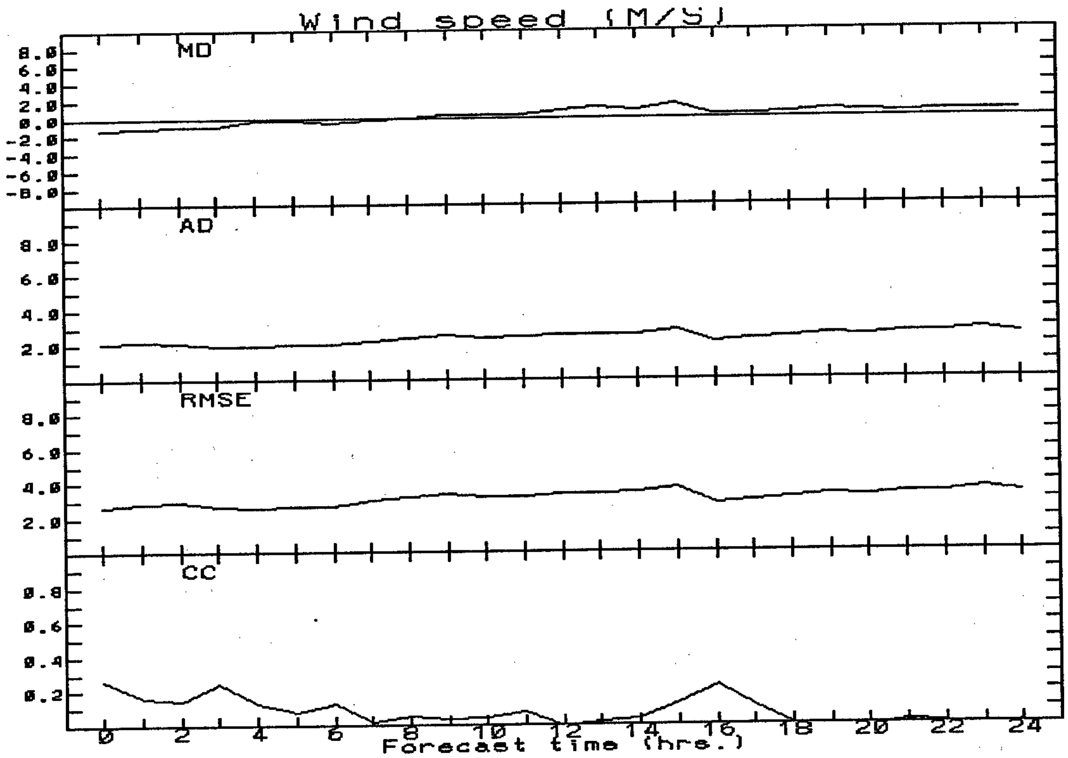

Figure D20. Time series of statistical parameters between BFM wind speed forecast data and surface observation data (2.5 km grid increment).

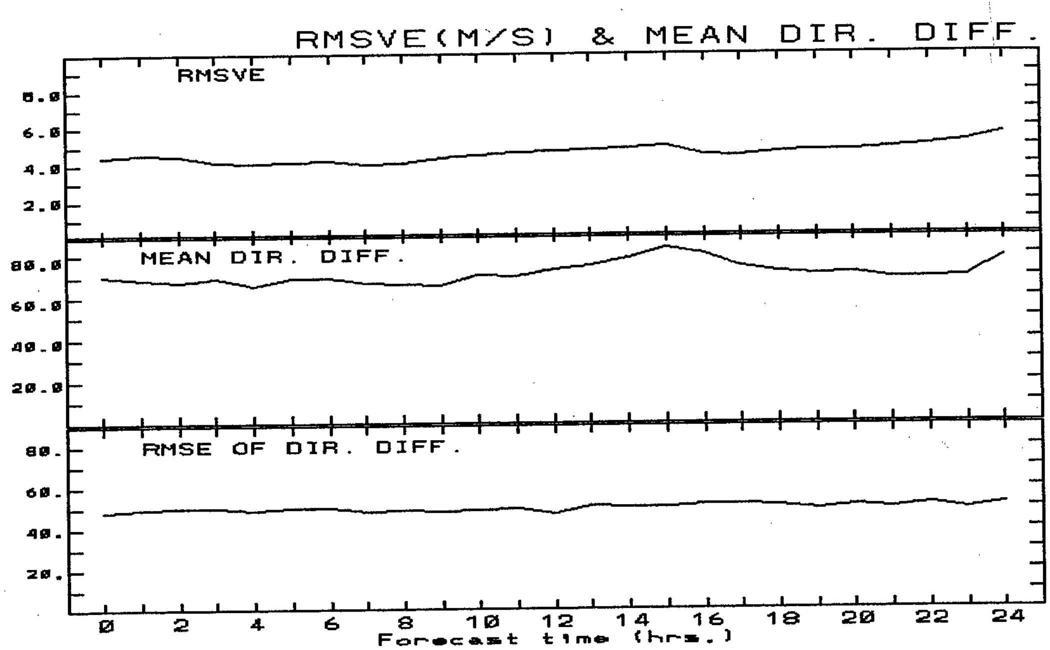

Figure D21. Time series of statistical parameters between BFM rmsve and mean wind direction forecast data and surface observation data (5 km grid increment).

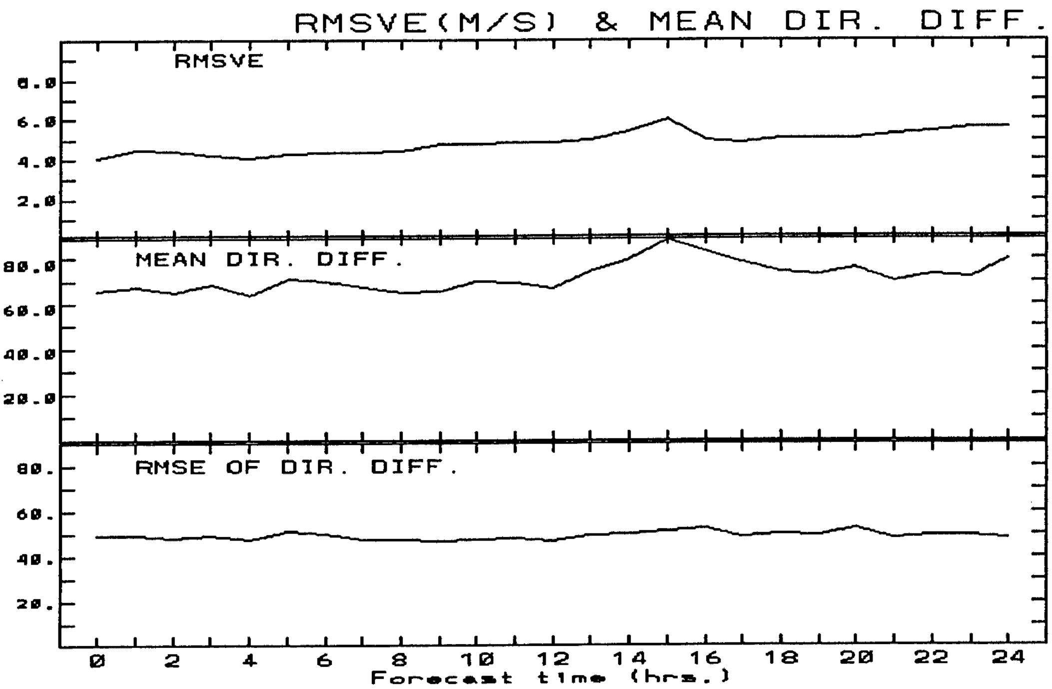

Figure D22. Time series of statistical parameters between BFM rmsve and mean wind direction forecast data and surface observation data (2.5 km grid increment).

Acronyms

AD	absolute difference
ARL	U.S. Army Research Laboratory
BFM	Battlescale Forecast Model
CC	correlation coefficient
HOTMAC	Higher Order Turbulence Model of Atmospheric Circulation
HPC	High Power Computer
IMETS	Integrated Meteorological System
MD	mean difference
MM5	Mesoscale Model version 5
MPI	Message Passage Interface
MRF	Medium Range Forecast
MWDDF	mean wind direction difference
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NOGAPS	Navy Operational Global Atmospheric Prediction System
NORAPS	Navy Operational Regional Atmospheric Prediction System
PBL	Planetary Boundary Layer
RMSE	root mean square error
RMSVE	root mean square vector error
UTC	universal time coordinate
WSMR	White Sands Missile Range

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14. ABSTRACT
The forecast skills of the Penn State/National Center for Atmospheric Research Mesoscale Model version 5 (MM5), and the Battlescale Forecast Model (BFM) were statistically evaluated by comparing the model forecasting data with surface observation data. The study was done for the periods of January-March 2002, and April-June 2002. The MM5 used quadruple-nests of 67.5, 22.5, 7.5, and 2.5 km grid increments, all of which have 51x51 grid points centered near Salt Lake City, UT. The forecast data of domains 3 and 4 were compared with the observation data. The BFM calculations were made separately over two model domains of grid increments of 5 and 2.5 km, both centered at Salt lake City, UT. Findings included: No significant statistical differences in forecast skills between the two MM5 domains, and the two BFM grid increments are similar. Both models produce better results for surface temperature than for dew point temperature, and both models had difficulties in producing good forecast results for wind vectors. The MM5 produced statistically better results. Both models showed better results for April-June than for January-March.

15. SUBJECT TERMS
Mesoscale models, forecast of surface parameters, complex terrain

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