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Different Initialization Data and the Performance by the BFM

by Jeffrey E. Passner

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14. ABSTRACT
The U.S. Army Research Laboratory supports the forecaster by producing weather forecasts on the Integrated Meteorological System (IMETS). On IMETS, a mesoscale model known as the Battlescale Forecast Model (BFM) outputs many weather parameters, including temperature, pressure, dew point, relative humidity, and wind speed. Additionally, many other elements, such as icing, turbulence, clouds, and visibility, are produced in the post-processor. This report investigates how these model outputs are influenced by the initial data that the model incorporates. These influences are studied by evaluating the model's temperature, wind, moisture, and cloud forecasts from 0 to 12 h after model base time. In this study, two different models are used to initialize the BFM: the Pennsylvania State University/ National Center for Atmospheric Research Mesoscale Model Version 5 and the Naval Operational Global Atmospheric Prediction System model. The results are discussed in this report.

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Preface

The Integrated Meteorological System (IMETS) is a weather data system utilized by Air Force weather forecasters in support of Army operations. Prediction and forecast products on IMETS are achieved through the Battlescale Forecast Model (BFM) and the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model Version 5 (MM5), which are used for short-term and long-term forecasts, respectively. The BFM forecast calculations are made using Naval Operational Global Atmospheric Prediction System (NOGAPS) fields, upper-air radiosonde observations, and surface data as initial input. However, in this study, the input data was adjusted so that forecasted grid data from the MM5 was used as BFM initial input instead of data from the NOGAPS. This report describes the processes used to achieve this and the results produced in the temperature, wind, and moisture fields.

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Summary

The U.S. Army Research Laboratory has developed a mesoscale weather model called the Battlescale Forecast Model (BFM). After model initialization, the BFM produces forecast variables for a 24-h period. Since the Army required longer-term prediction, Mesoscale Model Version 5 (MM5) gridded data are received from the U.S. Air Force Weather Agency in order to provide forecast information for up to a 48-h period. The BFM develops its forecast based on initial data fields received from Naval Operational Global Atmospheric Prediction System (NOGAPS) fields data, upper-air sounding data, and surface data. However, to meet other requirements, a second version of the BFM was developed that uses the 15-km output of the MM5 to initialize the BFM and runs the BFM for a 12-h period.

This report describes the theoretical and basic principles of the BFM initialization processes and how they vary based on different initial data. The influences of these initial data are shown by examining the model temperature, wind, moisture, and cloud forecasts from 0 to 12 h after the model base time. Overall, the results show that there is little significant statistical variation in using either initialization scheme. In fact, the only difference found was in the post-processed cloud forecasts, which followed the biases of each model.

1. Introduction

The Integrated Meteorological System (IMETS) is a mobile, operational, automated system that receives, processes, and disseminates weather data utilized by Air Force weather forecasters in support of Army operations. The U.S. Army Research Laboratory (ARL) supports forecasters by producing weather products on IMETS, which in turn enables them to make more specific and precise battlefield weather forecasts. One product that assists in short-term forecasting (≤ 24 h) is an operational mesoscale model, the Battlescale Forecast Model (BFM). For longer-term data, the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model Version 5 (MM5) provides output to cover periods from 6 to 48 h (*1*, *2*).

The BFM uses many forecasting parameters, including temperature, pressure, dew point, relative humidity, and wind speed, as well as various other parameters in the post-processor that are used by Tactical Decisions Aids, such as the Integrated Weather Effects Decisions Aid (*3*).

It is interesting to see how these initial data parameters, in a mesoscale model, influence the model output and the post-processor results. This report examines these influences by evaluating the model temperature, wind, moisture, and cloud forecasts from a 0 to 12-h period after the model base time. The results are discussed in section 6.

2. The BFM

ARL implemented the Higher Order Turbulence Model for Atmospheric Circulation (HOTMAC) as their model for the IMETS platform, in response to the Army's requirement for small-scale weather information, on the order of less than 500 by 500 km. The HOTMAC was selected because it is numerically stable at long time steps, it is globally relocatable, it emphasizes boundary-layer physics, and it is platform independent. Currently, the model is run to 24 h; however, due to military requirements, it was necessary to add the MM5 to the IMETS platform in order to provide forecast grids out to 48 h from the initial forecast time (*4*, *5*).

The BFM contains 16 terrain-following vertical levels, a model top of 7000 m above the highest elevation, a 10-km horizontal resolution, and a log-linear stagger so that there is greater vertical resolution near the surface. The rapid run time for the model can be attributed to a single nest and the absence of moist physics or cumulus parameterization routines. However, because of the implicit approach, time steps on the order of 200 s (at 10-km resolution) are common for typical atmospheric advective speeds and vertical motion fields in the model. Soil temperature on five subsurface levels is solved using the heat conduction equation, while long-wave and short-wave radiation within a single layer for a stratus cloud is calculated using the method of Hanson and Derr. The basic variables that are prognostically forecasted by the model are perturbation potential temperature; the total water substance mixing ratio; wind speed; wind direction; pressure; soil temperature; the turbulence kinetic energy and length scale; and the non-convective precipitation rate (*6*, *7*).

To initialize the BFM, surface data and upper-air observations are input into the model in the area of interest. Additionally, the 36-h, forecasted Naval Operational Global Atmospheric Prediction System (NOGAPS) package, which is issued to ARL by the Air Force Weather Agency (AFWA) via the Air Force Automated Weather Distribution System, is utilized as the long-range data that the BFM is nudged toward. The NOGAPS grid points are spaced 0.5º apart, both in latitude and longitude, on the mandatory pressure surfaces. Lateral and time-dependent boundary conditions (large-scale forcing) are supplied from grid-point data close to the area of interest, taken from NOGAPS output valid at analysis and forecast times of interest.

The BFM-generated outputs for the grid include the *u* and *v* horizontal wind vector components, potential temperature, and the water vapor mixing ratio. These forecast fields are saved at 0, 3, 6, 9, 12, 15, 18, 21, and 24 h from the base time of the model run and placed into a Gridded Meteorological Data Base.

3. BFM Initialization and Objective Analysis

Before initializing the forecast, the user must select an area of interest and center point for the grid, as well as the base time for the model by using a graphical user interface. The BFM then receives surface, upper-air, and numerical model data for objective analysis from the IMETS database. These data come from an expanded area, typically 1600 by 1600 km for a 10-km resolution, although surface data are received only for a smaller (500-by-500 km) model domain.

Typically, BFM forecast calculations can be made using some combination of NOGAPS gridded forecast fields, upper-air radiosonde observations, and surface sensor observations as initial input and time-dependent, lateral boundary condition data. In this study, model runs were done only with a complete set of initial data: NOGAPS or MM5 data, upper-air data, and surface input.

3.1 Initialization Using NOGAPS Model Data

The NOGAPS model produced by the Naval Research Laboratory is a complete global spectral model containing 30 vertical levels to 1 mbar and includes data quality control, tropical cyclone bogusing, data analysis and initialization, and a forecast model. The data analysis is a multivariate statistical technique patterned after the volume method developed by Lorenc for the European Centre for Medium-Range Weather Forecasts (*8*).

The analysis is performed on the Gaussian grid of the global spectral forecast model at the 16 mandatory pressure levels from 1000 to 10 mbar. The NOGAPS is a hybrid system that follows the terrain at low levels and constant pressure surfaces at upper levels. The dynamics formulation uses vorticity and divergence, virtual potential temperature, specific humidity, and terrain pressure as the dynamic variables. The model is central in time with a semi-implicit treatment of gravity-wave propagation (*9*).

The current physics package includes the bulk-Richardson number dependent, vertical mixing scheme; a time-implicit, Louis surface parameterization; gravity wave drag; shallow cumulus mixing of moisture, temperature, and winds; the Emanuel cumulus parameterization; convection and stratiform cloud parameterization; and solar and long-wave radiation (*10-16*).

The NOGAPS forecast calculations are made at the base times of 0000 and 1200 universal time coordinated (UTC) each day, with NOGAPS points spaced at a 0.5° latitudinal distance apart on the mandatory pressure surfaces. The forecast product is available to IMETS as much as 7 h after base time. For example, if the BFM forecast calculation is made at a base time of 1200 UTC, the 1200 UTC NOGAPS data may not be available until about 1900 UTC, thus the previous NOGAPS dataset is used instead (0000 UTC from earlier that day). The NOGAPS data used are the 0, 6, 12, 18, 24, and 36-h forecasts for the BFM runs to 24 h from base time.

The NOGAPS data are post-processed at AFWA to reduce the size of the files such that only the mandatory data are received. An example of the NOGAPS data is displayed in table 1.

Table 1. A sample of NOGAPS data received from AFWA.

Pressure level (mbar)	**Height (mean sea level)**	**Temperature (°K)**	**U Component of Wind (m/sec)**	**V Component of Wind (m/sec)**	**Mixing Ratio (g/kg)**
100.0	16580.1	199.8	1.90	4.00	-2.52
150.0	14155.2	208.9	3.80	18.0	1.67
200.0	12358.0	218.9	2.90	19.9	2.63
250.0	10900.0	228.1	3.0	15.2	2.49
300.0	9657.5	237.6	5.80	8.7	1.82
400.0	7588.2	253.7	12.9	0.10	1.14
500.0	5892.7	265.4	14.0	-2.1	2.27
700.0	3183.9	282.9	9.5	-4.0	5.02
850.0	1534.3	293.8	13.0	-3.2	5.65
925.0	800.1	296.5	7.4	-3.9	7.0
1000.0	111.1	299.3	2.5	-5.0	6.02

As seen in table 1, pressure, geopotential height, temperature, wind, and mixing ratio data are received for each NOGAPS point. These data must be horizontally interpolated from the NOGAPS to the BFM grid points. Eventually, the goal is to run the BFM and produce the following parameters on the BFM's z^* coordinate system:

Θ_v = virtual potential temperature (°K)

Q_v = water vapor mixing ratio (g/kg)

U = east-west component of wind (m/s)

V = north-south component of wind (m/s)

P_{gr} = surface pressure distribution (mbar)

where

z^* = vertical coordinate used in BFM, and defined as

$$z^* = \overline{H}\,\frac{z - z_g}{H - z_g} \qquad (1)$$

where

z = the Cartesian vertical coordinate

z_g = the ground elevation

$\overline{H}$ = the material surface top of the BFM in the z^* coordinate

and

H = the corresponding height in the z coordinate defined by $H = h + z_{gmax}$,

where

z_{gmax} = the maximum value of the terrain elevation in the BFM domain.

To analyze the NOGAPS data, the water vapor mixing ratio is calculated from the dew-point temperature, and U, V, T, Q, and Φ on pressure levels are horizontally interpolated to the BFM horizontal grid points, using the following method:

A first-guess value of the a parameter Ψ at grid point (i,j) is calculated as

$$\Psi(i, j) = \frac{\sum_N \Psi_N \exp\left(-\frac{r_{ij,}N^2}{4k}\right)}{\sum_N \exp\left(-\frac{r_{ij,}N^2}{4k}\right)} \qquad (2)$$

where

Ψ = a parameter

N = the NOGAPS point

Exponential function = the Barnes' weighting function

$r_{ij,}N$ = the normalized distance between a grid point (i,j) and the Nth NOGAPS point

and

k = an empirical parameter to determine the shape of the weighting function.

By using the first-guess values of the four grid points surrounding the Nth NOGAPS point, an interpolated value at this point, Ψ'_N, is bilinearly calculated as

$$t_1 = \Psi(x,y) + (x'-x)*[\Psi(x+1,y)-\Psi(x,y)] \tag{3}$$

$$t_2 = \Psi(x,y+1) + (x'-x)*[\Psi(x+1,y+1)-\Psi(x,y+1)] \tag{4}$$

$$\Psi'_N = t_1 + (y'-y)*[t_2 - t_1] \tag{5}$$

Here,

(x,y) = the southwest grid of four grid points surrounding the Nth NOGAPS point located at (x',y').

The difference between the NOGAPS value and the Ψ_N and Ψ'_N is, $\Delta_N = \Psi_N - \Psi'_N$ is now distributed to the BFM grid points as

$$\Delta(i,j) = \frac{\sum_N \Delta_N \exp\left(-\frac{r^2_{ij,N}}{4\gamma}\right)}{\sum_N \exp\left(\frac{r^2_{ij,N}}{4\gamma}\right)} \tag{6}$$

where

γ = an empirical weight reduction factor (0.2).

A final interpolated value of Ψ at (i,j) is

$$\Psi_f(i,j) = \Psi(i,j) + \Delta(i,j) \tag{7}$$

Once these NOGAPS data have been horizontally interpolated to the BFM grid points, they must be interpolated in the vertical so that parameter Ψ on pressure surfaces is linearly interpolated to z^* levels of the BFM as

$$\Psi(z^*) = \Psi_k + \frac{\Psi_{k+1} - \Psi_k}{\phi_{k+1} - \phi_k}(z_{st} - \phi_k) \tag{8}$$

where

z_{st} = the Cartesian height above sea level of z^*, calculated from eq 1 as

$$z_{st} = z_g + z^* \frac{\overline{H} + z_{gmax} - z_g}{\overline{H}} \tag{9}$$

The radiosonde data is interpolated to BFM grid-point locations using an inverse-distance weighting function, then the data is reinterpolated vertically from the Cartesian surfaces to the model, the terrain-following coordinate surfaces. Prior to the three-dimensional (3-D) objective analysis, a quality control program checks the upper-air data for errors in the geopotential height values, the extreme temperature inversions, the extreme superadiabatic lapse rates, and the wind field. At each sounding location, the wind vector components, potential temperature, and water vapor mixing ratio are vertically interpolated to 30 different levels using a linear interpolation method followed by the horizontal interpolation to the BFM grid using the weighting factor, $1/r^2$, as

$$\Psi(i, j) = \frac{\sum_N \frac{\Psi_N}{r^2_{ij,N}}}{\sum_N \frac{1}{r^2_{ij,N}}} \tag{10}$$

Linear vertical interpolation from z_i to $z_{st,}$ given by eq 9, is performed for each parameter. The final step to initializing the model is to do a composite of the NOGAPS data and the upper-air data. The 3-D fields of all the BFM parameters are obtained from the NOGAPS data on 11 levels, z_i. The upper-air data are interpolated to 30 vertical levels, z_i. The 3-D fields created from the NOGAPS data are now used as background fields. The mean difference between the upper-air data and NOGAPS data is defined as

$$\overline{d} = \frac{\sum_{N=1}^{N} \left(\Psi_{G,N} - \Psi_{U,N} \right)}{N} \tag{11}$$

where

$\overline{d}$ = mean difference.

The value of $\Psi_{G,N}$ is the interpolated value of the Nth upper-air location by using the four surrounding grid points and $\Psi_{U,N}$ Nth upper-air data. A bilinear interpolation method is then used to calculate $\Psi_{G,N}$.

By replacing Ψ_G (i,j), by

$$\Psi^*{}_G(i,j) = \Psi_G(i,j) + \bar{d} \tag{12}$$

the mean error is removed, but the values of $\Psi^*{}_{M,N}$ interpolated from $\Psi^*{}_G$ (i,j) for the Nth upper air location are not generally equal to $\Psi_{U,N}$.

The difference

$$d^*{}_N = \Psi_{U,N} - \Psi^*{}_{G,N} \tag{13}$$

is not zero, but the mean d^* is

$$\bar{d}^* = \frac{\sum_{N=1}^{N} d^*_N}{N} = 0 \tag{14}$$

The final step is to distribute d^* to the entire field using a weighting function of $1/r^2$, thus getting an adjusted value for each parameter. This procedure is applied to all vertical levels, z_i, for all the parameters, and vertical linear interpolation from z_i to z^* are performed. Linear interpolation from z_i levels to z_{st} are performed for all parameters and dew-point fields are converted to water vapor.

3.2 Initialization Using the MM5 Data

The MM5 is a limited-area, non-hydrostatic, terrain-following, sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation.

Terrestrial and isobaric meteorological data are horizontally interpolated from a latitude-longitude mesh to a variable high-resolution domain on a Mercator, Lambert Conformal, or polar stereographic projection. Since the interpolation does not provide mesoscale detail, these interpolated data may be enhanced with observations from the standard network of surface and rawinsonde stations, using either a Cressman or multiquadric scheme. In the MM5, there is also a program that performs the vertical interpolation from pressure levels to sigma coordinates. The sigma surfaces near the ground closely follow the terrain, while the higher-level sigma surfaces tend to approximate isobaric surfaces. Additionally, the MM5 has a flexible, multiple nesting capability; advanced physical parameterization; a 3-D data assimilation system via nudging; and the ability to be run on various platforms (*17*).

Version 3 of the MM5 was used for this study; it is from AFWA and has a resolution of 15-km mesh data on 41 vertical levels. ARL receives these MM5 data in a gridded binary form for the continental United States twice daily, initialized at 0600 UTC and 1800 UTC, respectively. Due to computational and processing constraints, there is a 6-h stagger between the initialization valid time of the 15-km mesh and the first forecast output, thus the first MM5 forecast is a 6-h forecast. The frequency of the model output is every 3 h for a time period of 48 h.

To generate complete data at the standard observation heights of 10 magl and 2 magl, ARL uses similarity theory to extrapolate to these lower levels from the lowest MM5 sigma level. In this fashion, ARL can produce temperature, dew-point, and wind data at levels 2 magl and 10 magl, in addition to the 41 MM5 sigma levels of data.

The parameterizations selected by AFWA with this version of the MM5 are as follows:

- Grell cumulus parameterization: Designed for grid sizes of 10 to 30 km, this parameterization accounts for sub-gridscale convection and compensating subsidence.
- MRF planetary boundary-layer model: This model parameterizes the mixture of heat, moisture, and momentum in the boundary layer.
- Reisner mixed phase explicit moisture microphysics: Cloud and rainwater fields and ice processes are predicted explicitly. No graupel or riming processes are calculated.
- Dudhia cloud radiation: This parameter provides solar and infrared fluxes at the ground and atmospheric tendencies resulting from the radiative processes.
- MM5 five-layer soil model: Temperature is predicted in 1, 2, 4, 8, 16-cm layers with a fixed substrate below, using vertical diffusion equations.

The 15-km MM5 data used to initialize the BFM looks the same as the NOGAPS data, with the exception of the addition of the heights in meters along with the heights above mean sea level for each vertical level for each of the 43 levels. An example of just a few of the levels is shown in table 2.

Table 2. A sample of MM5 data used to initialize the BFM.

Pressure (mbar)	HT (m)	HT MSL (m)	Temperature (°K)	U component (knots)	V component (knots)	Mixing Ratio (g/kg)
981.4	2.0	246.0	311.4	18.8	-2.1	2.4
980.5	10.0	254.0	310.7	18.8	-3.0	3.4
979.3	20.0	264.1	310.1	18.8	-3.5	4.0
975.9	52.2	296.2	309.5	18.4	-3.8	4.4
970.7	100.7	344.7	308.9	18.1	-4.0	4.7
963.4	169.8	413.8	308.2	17.7	-4.1	5.0

NOTE: HT = height and HT MSL = height above mean sea level.

4. Statistical Evaluation of Mesoscale Models

The three main products used in this study to evaluate model or post-processed derived output are mean absolute difference (AD), root mean square error (RMSE), and correlation coefficient (CC). The equations for these are

$$AD = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} \left| x_{o,i,j} - x_{p,i,j} \right|}{m * n} \tag{15}$$

where

x = meteorological variable

o = observation

p = prediction of variable

i = ith surface station

j = jth forecast day

n = number of stations

m = total number of forecast days.

Small values of AD are related to good agreements between observation and forecast.

$$RMSE = \sqrt{\frac{\sum_{j=1}^{m} \sum_{i=1}^{n} (x_{o,i,j} - x_{p,i,j})^2}{m * n}} \qquad (16)$$

The values of RMSE are proportional to those of the AD. The CC is displayed in eq 17. The CC measures the strength of the relationship between two variables. When CC>0, it indicates a positive linear relationship. A value of 1.00 indicates a "perfect" correlation between the observed and predicted values of a meteorological forecast.

$$CC = \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} x_{o,i,j} * x_{p,i,j}}{\sqrt{\sum_{j=1}^{m} \sum_{i=1}^{n} x^2_{o,i,j} * \sum_{j=1}^{m} \sum_{i=1}^{n} x^2_{p,i,j}}} \qquad (17)$$

---

5. Evaluation of the Different BFM Initialization Methods

There were 53 model runs done in this study in a variety of locations in the United States; however, there was an emphasis on typical wintertime weather cases during the cold seasons of 2002-2003 and 2003-2004. There were many grid locations used in this study, although about 40 percent of all model runs were conducted on the New York grid due to the complex weather patterns and cloud forecasts during the cold season. The main focus in this research effort was to investigate the temperature, dew-point, wind, and cloud output of the BFM. To validate these data, hourly surface observations were used at a variety of locations on the grid. Since the BFM-MM5 only has a 12-h model run time, the statistics for this study were calculated at 0 h, 3 h, 6 h, and 12 h after base time. In these discussions BFM-NOGAPS will refer to the BFM version run with NOGAPS data as initial data and BFM-MM5 will refer to the version of the model using the MM5 data as input.

The results in table 3 are very similar to the results using the BFM-NOGAPS that Passner presented in an earlier study, which showed a CC of 0.96 at 0 h, 0.94 at 6 h, and 0.95 at 12 h after base time (*18*).

While the statistical work of Henmi in many evaluations of the BFM shows different results and biases, it should be noted that Henmi did much of his evaluation using a BFM with 1° NOGAPS data rather than 0.5° data (which was used in this study). While it is uncertain how much of an influence the input data differences are responsible for, it is unfair to compare them directly. Additionally, Henmi tested the BFM at limited locations rather than combining many grids into one study (*19*).

Table 3. Surface temperature error for the BFM-NOGAPS and the BFM-MM5.

Model Hour	**Samples**	**AD**	**RMSE**	**CC**
BFM-NOGAPS				
00-h	188	2.31	3.13	0.94
03-h	189	1.89	2.47	0.97
06-h	190	2.29	2.96	0.96
12-h	180	2.57	3.26	0.96
BFM-MM5				
00-h	189	2.19	2.84	0.95
03-h	189	2.39	3.14	0.95
06-h	190	2.72	3.42	0.95
12-h	180	3.27	4.24	0.93

One of the intriguing trends in table 3 is that the BFM-NOGAPS shows better skill than the BFM-MM5 starting with the 3-h time and continuing through the 12-h forecast. In theory, these results might be unexpected since the MM5 runs are conducted on a 15-km grid; however, earlier investigation of the MM5 shows larger errors in early time frames (≤ 12-h forecasts) than in later ones (>12 h). Passner's 2003 study indicated the MM5 has a CC of 0.85 at 6 h, compared to 0.95 at 12 h and 0.97 at 36 h. These errors in the early forecast periods may have contributed to the larger errors in the BFM-MM5 (*18*).

The dew-point skills follow the same overall trends, as seen in table 4. These data illustrate the same pattern as seen in table 3, except for at the 0-h time, when the BFM-MM5 data demonstrates a higher CC, although the RMSE and AD remain comparable. Beginning with the 3-h forecast, the BFM-NOGAPS exhibits higher skill in all categories. In the 2003 study of MM5 forecast data, Passner showed that the MM5 had a higher AD and lower CC at 6 h after base time, but showed an improvement in skill at 12 h and beyond. In table 4, this trend is not observed, instead the BFM-MM5 shows an increase in error through the 12-h forecast period. Additionally, the same pattern is demonstrated using the BFM-NOGAPS (*18*).

Table 4. Surface dew-point error for the BFM-NOGAPS and the BFM-MM5.

Model Hour	**Samples**	**AD**	**RMSE**	**CC**
BFM-NOGAPS				
00-h	185	1.16	1.95	0.95
03-h	185	2.02	2.76	0.96
06-h	186	2.04	2.78	0.96
12-h	176	2.72	3.55	0.90
BFM-MM5				
00-h	189	1.28	1.93	0.98
03-h	189	2.35	3.27	0.94
06-h	190	2.71	3.65	0.92
12-h	180	3.50	4.55	0.88

The wind speed and wind direction were also studied for each BFM. Table 5 shows the AD, RMSE, and CC for wind direction.

The results in table 5 are inconclusive through the 12-h forecast period. The most noticeable difference in model performance is at the initial time, where the BFM-NOGAPS has a higher CC, but conversely has a higher AD and RMSE. In other studies by Henmi (such as the one utilizing the Ft. Irwin, CA, grid in 1998), Henmi found a CC of approximately 0.50 for the wind direction; however, again in that study, he used 1° NOGAPS data rather than the 0.5° NOGAPS data used in this study (*20*).

Table 5. Surface wind-direction errors for BFM-NOGAPS and the BFM-MM5.

Model Hour	Samples	AD	RMSE	CC
BFM-NOGAPS				
00-h	161	34.8	56.5	0.73
03-h	168	43.6	67.5	0.57
06-h	167	40.1	63.4	0.47
12-h	165	44.3	63.0	0.62
BFM-MM5				
00-h	158	24.9	46.6	0.64
03-h	164	41.3	68.2	0.65
06-h	163	39.9	60.8	0.60
12-h	163	44.7	64.4	0.58

In table 6, the results for the wind speed errors are shown for each method of the BFM.

Table 6. Surface wind-speed errors for the BFM-NOGAPS and the BFM-MM5.

Model Hour	Samples	AD	RMSE	CC
BFM-NOGAPS				
00-h	177	2.7	3.4	0.74
03-h	177	4.1	5.3	0.62
06-h	178	3.9	4.8	0.70
12-h	169	3.9	5.0	0.52
BFM-MM5				
00-h	185	2.4	3.4	0.76
03-h	185	4.2	5.2	0.54
06-h	186	3.2	4.0	0.73
12-h	177	4.2	5.3	0.41

The results in table 6 indicate nearly identical errors for each model-initialization method and this agrees with results in Passner's 2003 BFM study (not published), which yielded a CC of 0.76 at 0 h and 0.42 at 12 h after model initiation. Henmi's 2000 study at White Sands Missile Range indicated a CC of 0.53 for the BFM, which is somewhat lower than the results of this current study; however, his model evaluation occurred in the windy months of April and May and thus were most likely subjected to higher error and lower CC (*19*).

While all the parameters discussed in tables 3-6 are direct model output of the BFM, it is also necessary to explore how the post-processed variables are influenced by initial model data. The post-processed variables are meteorological parameters that can not be derived until all basic model information is available after the completion of the model forecast hour. It is often advantageous to derive variables after the model run, since they are not dependent upon time derivatives and add additional run time for the model. Some of the parameters derived using this technique include clear-air turbulence, icing, thunderstorm probability, clouds, and fog. Since it is impossible to show the output of all the elements derived by the post-processor, only the short-term cloud forecasts are discussed in this report. The cloud forecasts are based on the model-derived relative humidity, time of day, and season.

To evaluate the cloud amounts and heights, the cloud forecasts were compared to Meteorological Aviation Routine Weather Reports, which are coded weather observations from selected airports across the world. For a forecast to be "correct," the height of the observed cloud had to be within the following specifications:

- 1000 ft of the forecasted cloud height below 5000 ft above ground level (AGL)
- 1500 ft between 5000 to 10000 ft AGL
- 2000 ft above 10000 ft AGL

Since the error was not considered significant, scattered clouds were not considered as "wrong" forecasts in instances when there was no ceiling forecasted. However, if a ceiling was forecasted and only scattered clouds were observed, the forecast was considered wrong. When a broken layer was forecasted and an overcast layer was observed, the forecast was still considered correct, as was a forecast for overcast conditions where broken clouds were reported. Once an overcast layer was reported, it was impossible to verify any layers above that layer. In this study, the clouds were verified only at the hour of the observation. Table 7 shows the results of the BFM-NOGAPS and BFM–MM5 in this study, along with an explanation of the error.

Table 7. Accuracy of cloud forecasts using the BFM-NOGAPS and the BFM-MM5.

Model Hour	Samples	Percent Right	Percent Wrong	Missed Ceiling	Forecasted Ceiling	Forecasted Ceiling Too Low	Forecasted Ceiling Too High
BFM-NOGAPS							
00-h	179	61	39	28	10	17	15
03-h	175	58	42	31	25	11	6
06-h	177	56	44	31	15	20	12
12-h	176	56	44	22	30	21	5
Total	707	58	42	112	80	69	38
BFM-MM5							
00-h	189	59	41	21	21	23	15
03-h	184	53	47	20	33	27	7
06-h	191	57	43	16	36	25	6
12-h	187	51	49	11	41	34	6
Total	751	55	45	68	131	99	34

In table 7, there is no significant difference in the accuracy of the post-processed cloud forecasts; both BFM methods show only a slight decrease in skill over the course of the 12-h forecast. In a study done in 1998-1999, the BFM-NOGAPS followed these trends yielding forecasts that were 72 percent correct at 0 h, 58 percent correct at 3 h, 56 percent correct at 6 h, and 64 percent correct at 12 h. It is uncertain as to why the earlier study had a higher percentage of correct forecasts at 0 h and 12 h, although it may be attributed to the 1998-1999 sample being a combination of 0000- and 1200-UTC forecasts, while the current study involves only 1200-UTC forecasts. Additionally, the data shown in table 7 uses a larger sample size than was used the previous study (*18*).

One similarity to earlier studies of the BFM-NOGAPS is the cloud errors trend. The BFM-NOGAPS "missed" a ceiling about 37 percent of the time in the wrong forecasts—in other words, a ceiling was observed but had not been forecasted. In 27 percent of the wrong cases, the BFM-NOGAPS forecasted a ceiling, although none was observed. In 23 percent of the wrong samples, the post-processor forecasted a ceiling, but the actual ceiling was observed lower than the forecast predicted, and in 13 percent of the cases, the observed ceiling was higher than what had been forecasted. These findings agree with the 1998-1999 study; however, the BFM in this study missed fewer ceilings than the BFM in the previous study. Again, it should be noted the earlier study contained models run at both 1200 and 0000 UTC, as well as covered a smaller sample size, so some of the difference may be due to this combination.

The most prominent difference in this study is the cloud-forecast errors generated using the BFM-MM5, as displayed in table 7. There is a greater error in forecasting a ceiling and having none observed, than in missing a ceiling forecast (forecasting no ceiling where a ceiling is observed). In 39 percent of the wrong forecasts, a ceiling was forecasted but did not occur, while in 20 percent of the wrong cases, no ceiling was forecasted, but one was actually observed. There was a slight trend in forecasting a ceiling too low in the BFM-MM5 (30 percent of wrong forecasts) as compared the BFM-NOGAPS (23 percent of the wrong forecasts). Additionally, these trends became more pronounced through the 12-h forecast cycle. There was no bias in the forecast error at 0 h; however, at 12 h, 45 percent of the error was due to forecasting a ceiling and observed none, whereas 82 percent of the error was from forecasting a ceiling too low or forecasting a ceiling and having none observed. The BFM-MM5 rarely misses a ceiling by forecasting it too high.

6. Conclusions and Discussion

Two different methods to initialize the BFM were used: one using the 11-level, 0.5 ° NOGAPS data and one using the 43-level, 15-km MM5 data delivered by AFWA. The main conclusion in this report is that neither of the two dissimilar models used as initial data (NOGAPS versus MM5) provided much statistical differences to the skills of the BFM, though in many of the parameters, the results were slightly improved using NOGAPS data as opposed to MM5 data, which had a smaller grid resolution and a higher vertical resolution.

In this work, the only significant revisions of the BFM for the MM5 data were in interpolating to height levels rather than pressure levels, and in making the nudging uniform since there was no significant scale difference between the 10- and 15-km grids. Otherwise, there were no adjustments made in the BFM for the two data sources.

However, while there were no significant differences in the BFM performance between the two initialization sources, it is interesting to note that BFM-MM5 did demonstrate a slightly higher CC for temperature and dew-point data and a better AD for wind direction and wind speed data at the initial time (0 h). By the 3-h forecast period, the BFM-NOGAPS displayed better skill in the temperature and dew-point fields, but showed no differences in the wind fields. Thus, if there is any advantage to using the BFM-MM5, it appears to be most useful at the initial time, which might infer that a smaller grid resolution (15 km) and a higher vertical resolution might be most useful in the short term for the BFM. As expected, overall model performance decreased with time for the temperature and dew-point fields, although the model's wind fields degraded most significantly at the 6-h forecast mark. It is uncertain why the BFM would show the highest error at 6 h, but it may be due to the maximum influence of radiation (typically at 1800 UTC in this study).

In their work over the Pacific Northwest, Mass et al. (*21*), noted that MM5 model performance was significantly improved when changing from a 36-km grid to a 12-km grid, but there was not as much improvement from a 12-km grid to a 4-km grid. This raised the question as to how much model improvement could be expected by changing the initial data from 0.5° to 15 km, as was done here. Based on these results of this study, not much is gained by doing so with the BFM.

Additionally, there are other issues in this study that should be examined. The results were based on surface observations only, and while there was no noticeable difference in skill between the methods, the upper-air levels have not been investigated. By increasing vertical resolution, there might have been great improvement in the upper levels, which was not found in this study since only surface data were verified. It is possible that there may have been poor analysis of initial MM5 data, since a detailed evaluation was never studied. Another possible influence might have been the number of cloudy-weather cases in this study; if too many cloudy-weather cases were part of this study, as seems likely, there would not have been enough emphasis placed on the radiation scheme and nudging. And finally, there might have been too many synoptically driven cases, which again would deemphasize the influence of the mesoscale models (*22*).

Still, a study of models using different initialization schemes is an interesting one. It does appear that in the case of the BFM, not much is gained by using MM5 data over NOGAPS data to initialize the model. It is uncertain if this trend would be seen with other models or how different models would integrate different large-scale data.

References

1. Passner, J.E. Expert Systems and Empirical Rules for Army Operations on IMETS. *Proceedings of the 13th Conference on Weather Analysis and Forecasting*, Vienna, VA, 1993, 608–611.

2. Dudhia, J. A Non-Hydrostatic Version of the Penn State/NCAR Mesoscale Model: Validation Tests and Simulation of an Atlantic Cyclone and Cold Front. *Mon. Weather Rev.* **1993**, *121*, 1493–1513.

3. Sauter, D.P. The Integrated Weather Effects Decision Aid (IWEDA): Status and Future Plans. *Proceedings of the 1996 Battlespace Atmospheric Conference*, Naval Command, Control, and Ocean Surveillance Center, San Diego, CA, 75–81, 1996.

4. Pielke, R.A. *Mesoscale Meteorological Modeling*; Academic Press: New York, NY, 1984.

5. Yamada, T.; Bunker, S. A Numerical Model Study of Nocturnal Drainage Flows with Strong Wind and Temperature Gradients. *J. of Applied Met.* **1989**, *28*, 545–554.

6. Henmi T.; Dumais, R.E. Jr. *Description of the Battlescale Forecast Model*; ARL-TR-569; U.S. Army Research Laboratory: White Sands Missile Range, NM, 1998.

7. Hansen, H.P.; Derr, V.E. Parameterization of Radiative Flux Profiles with in Layer Clouds. *J. of Applied Met.* **1987**, *26*, 1511–1521.

8. Lorenc, A. A Global Three-Dimensional Multivariate Statistical Scheme. *Mon. Weather Rev.* **1981**, *109*, 701–721.

9. Hogan, T.F.; Rosmond, T.E. The Description of the Navy Operational Global Atmospheric Prediction System's Spectral Forecast Model. *Mon. Weather Rev.* **1991**, *119*, 1786–1815.

10 Louis, J.F.; Tiedtke, M.; Geleyn, J.F. A Short History of the Operational PBL Parameterization at ECMWF. *ECMWF Workshop on Planetary Boundary Parameterization*, November 1981, 59–79.

11. Louis, J.F. A Parametric Model of Vertical Eddy Fluxes in the Atmosphere. *Boundary Layer Met.* **1979**, *17*, 187–202.

12. Palmer, T.N.; Shutts, G.J.; Swinbank, R. Alleviation of a Systematic Westerly Bias in General Circulation and Numerical Weather Prediction Models Through an Orographic Gravity Wave Drag Parameterization. *Quart. J. Roy. Met. Soc.* **1986**, *112*, 1001–1039.

13. Tiedtke, M. The Sensitivity of the Time-Scale Flow to Cumulus Convection in the ECMWF Model. *Workshop on Large-Scale Numerical Models*, 1983, 297–316.

14. Emanuel, K.A.; Zivkovic-Rothman, M. Development and Evaluation of a Convection Scheme for Use in Climate Models. *J. Atmos. Sci.* **1999**, *56*, 1766–1782.

15. Teixeira, J; Hogan, T. Boundary Layer Clouds in a Global Atmospheric Model. *J. of Climate* **2002**, *15*, 1261–1276.

16. Harshvardhan, R; Davies, R.; Randall, D.; Corsetti, T. A Fast Radiation Parameterization for Atmospheric Circulation Models. *J. Geophys. Res.* **1987**, *92*, 1009–1016.

17. Grell, G.A.; Dudhia, J.; Stauffer, D.R. *A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)*; NCAR Tech. Note NCAR/TN-398+STR; 1995.

18. Passner, J.E. *Post-Processing for the Battlescale Forecast Model and Mesoscale Model Version 5*; ARL-TR-2988; U.S. Army Research Laboratory: White Sands Missile Range, NM, 2003.

19. Henmi T. *Comparison and Evaluation of Operational Mesoscale MM5 and BFM Over WSMR*; ARL-TR-1476; U.S. Army Research Laboratory: White Sands Missile Range, NM, 2000.

20. Henmi T.; Dumais, R.E., Jr. *The Battlescale Forecast Model (BFM) During the TFXXI at Fort Irwin, CA: Statistical Evaluation of 24-h Forecast Fields and Model Improvement*; ARL-TR-1685; U.S. Army Research Laboratory: White Sands Missile Range, NM, 1998.

21. Mass C.F.; Owens, D.; Westrick, K.; Cole, B. Does Increasing Horizontal Resolution Produce More Skillful Forecasts. *Bull Amer. Met. Society* **2002**, *83*, 407–430.

22. Dumais, R.E., Jr. Private communication. (2004).

List of Acronyms

3-D	three-dimensional
AD	mean absolute difference
AFWA	Air Force Weather Agency
AGL	above ground level
ARL	U.S. Army Research Laboratory
BFM	Battlescale Forecast Model
CC	correlation coefficient
HOTMAC	Higher Order Turbulence Model for Atmospheric Circulations
IMETS	Integrated Meteorological System
mbar	millibar
MM5	Mesoscale Model Version 5
NOGAPS	Naval Operational Global Atmospheric Prediction System
RMSE	root mean square error
UTC	universal time coordinated

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