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PRECIPITATION FORECASTS FOR THE BFM AND MM5

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1. INTRODUCTION

The U.S. Army Research Laboratory (ARL) is supporting the forecaster to make more specific and precise battlefield weather forecasts. One product to assist in short-term forecasting (<=24-h) is an operational mesoscale model, the Battlescale Forecast Model (BFM). For longer-term data, the Pennsylvania State University/ NCAR mesoscale model Version 5 output is available from 6 to 48 hours. The BFM produces many forecasting parameters including temperature, pressure, dew point, relative humidity, and wind speed and direction as well as precipitation amounts. While these outputs provide valuable weather information, Tactical Decision Aids (TDAs) such as The Integrated Weather Effects Decisions Aid (IWEDA) have a need for additional precipitation parameters such as precipitation rates and precipitation types. Both the BFM and the MM5 can be used to derive precipitation amounts and rates, while a post-processing software package has been developed to forecast precipitation types using the model-derived output.

2. MESOSCALE MODELS FOR THE ARMY

With a requirement to provide the Army with small-scale weather information on the order of 500 by 500 km or less, the ARL implemented the Higher Order Turbulence Model for Atmospheric Circulation (HOTMAC) as their model for the IMETS platform. HOTMAC was selected since it is numerically stable at long time steps, globally relocatable, emphasizes boundary-layer physics, is and platform-independent (Yamada and Bunker, 1989).

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In an effort to keep the model run time as fast as possible, the BFM contains no convective cloud parameterization or cloud microphysics package. The model currently is run to 24 h; however, due to military requirements it was necessary to add the MM5 to the IMETS platform to provide forecast grids out to 48 h from the initial forecast time.

2.1 The Battlescale Forecast Model

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 no 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 and shortwave radiation within a single layer for a stratus cloud are calculated using the method of Sasamori (1968). The basic variables that are prognostically forecasted by the model are perturbation potential temperature, total water substance mixing ratio, wind speed, wind direction, pressure, soil temperature, turbulence kinetic energy and length scale, and non-convective precipitation rate.

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 by the Air Force Weather Agency 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 1 latitudinal and longitudinally distance apart 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 output for the grid includes the u and v horizontal wind vector components, potential temperature, and 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 (GMDB).

2.2 The MM5

The Fifth-Generation NCAR/Penn State Mesoscale Model (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 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 and multiple nesting capability, advanced physical parameterization, 3-D data assimilation system via nudging, and it can be run on various platforms (Grell *et a*l, 1995)

The version of the MM5 being used in this study is Version 3 from AFWA with a resolution of 15 km mesh data on 41 vertical levels. It uses the Grell cumulus parameterization, the MRF planetary boundary-layer model, the Reisner mixed phase explicit moisture microphysics package, Dudhia's cloud radiation, and the MM5 five-layer soil model. ARL receives these MM5 data in gridded binary form for the Continental United States twice each day, which are 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.

The current AFWA operational version of MM5 places the lowest model vertical level at 20 magl. To generate data at the standard observation heights of 10 magl and 2 magl, similarity theory is being used at ARL to extrapolate to these lower levels from the lowest MM5 sigma level. In this fashion, temperature, dew point, and wind data at levels 2 magl and 10 magl, are produced at ARL in addition to the 41 MM5 sigma levels of data.

3. **STRATIFORM PRECIPITATION FROM THE BFM AND MM5.**

3.1 Precipitation Rates from the BFM

Since the microphysical processes of stratiform precipitation are not part of the BFM, the stratiform precipitation is parameterized as a function of cloud liquid water. The scheme formulated by Sundqvist *et al* (1989*)* for stratiform precipitation is used in the BFM.

The rate of release of precipitation is described by:

$$P = C_o Q_c \left[1 - \exp\left(- \left(\frac{Q_c}{R * Q_{c,cr}} \right)^2 \right) \right] \quad (1)$$

where

C_o = characteristic time for the conversion of cloud droplets into raindrops
Q_c = mixing ratio of cloud water content
R = cloud fraction
$Q_{c,cr}$ = Cloud water content, at which release of precipitation starts to be efficient

According to Sundqvist $Q_{c,cr}$ should have a value typical of individual cloud types and be invariant to grid resolution. He also suggests a value of 0.0001 for C_o, which equates to a conversion time of approximately 167 minutes. In his study, Sundqvist worked with the operational fine mesh model of the Norwegian Meteorological Institute which uses a horizontal grid resolution of 50 km. In this test, for the BFM, a value of 0.0004 (42-minute conversion rate) was employed for the model runs.

The rate of precipitation P, at a given z^* level is given by:

$$P_r\left(z^*\right)=\left(\frac{\overline{H}+z_{g\max}-Z_g}{\overline{H}}\right)\int_{z^*}^{\overline{H}}\rho\left(z^*Pdz^*\right) \quad (2)$$

where

H = depth of the model atmosphere
Z_{gmax} = highest terrain elevation in the BFM domain
Z_g = terrain elevation
ρ = air density

The final form of the stratiform precipitation rate at the surface is:

$$P_r\left(0\right)=\left(\frac{\overline{H}+z_{g\max}-z_g}{\overline{H}}\right)\frac{1}{\rho_w}\int_0^{\overline{H}}\rho\left(z^*\right)C_{OF}Q_C\left(z^*\right)\left[1-\exp\left(-\left(\frac{Q_c\left(z^*\right)}{CF*Q_{(c,cr)F}}\right)^{1/2}\right)dz^*\right]$$
(3)

where

ρ_w = density of water

The subscript F in the term $Q_{(c,cr)F}$ indicates that the additional parameter for the coalescence and Bergeron-Findeisen mechanism are included. The final precipitation rate is expressed in (mm/h).

3. 2 Precipitation rate from the MM5

The MM5 has many different ways to treat precipitation physics. In the MM5 version being discussed here, the explicit scheme is used with the Reisner mixed-phase ice scheme. The scheme is activated whenever grid-scale saturation is reached. The equations for water vapor, cloud water (ice), and rain water (snow) mixing ratios are based on the conservation of moisture but add the effects of the Reisner microphysics package. An example of these equations, the equation for rain water (snow if below 0° C) mixing ratio are shown below:

$$\frac{\partial p^*q_r}{\partial t}=-m^2\left[\frac{\partial\frac{p^*uq_r}{m}}{\partial x}+\frac{\partial\frac{p^*vq_r}{m}}{\partial y}\right]-\frac{\partial p^*q_r\dot{\sigma}}{\partial\sigma}+\delta_{nh}q_rDIV-\frac{\partial V_f\rho g q_r}{\partial\sigma}$$
$$+p^*\left(P_{RE}+P_{RC}+P_{RA}+P_{SM}+P_{CI}\right)+D_{qc}$$
(4)

where:

m = map factor
p^* = p star
q_r = mixing ratio of cloud water
σ = sigma
δ_{nh} = non-hydrostatic constant
DIV = divergence
V_f = fall speed of rain or snow
ρ = density of air
g = acceleration of gravity
P_{RE} = the evaporation of rain and sublimation/deposition of snow
P_{RC} = conversion of cloud to rain (ice to snow)
P_{RA} = accretion of cloud by rain (ice by snow)
D_{qc} = diffusion term
P_{SM} = snow melt
P_{CI} = heterogeneous freezing of cloud water to cloud ice

The mixing ratio of rain water is used as a key parameter in the fall speed term which determines the rainfall rate at the surface. The equation for the fall speed is shown below:

$$V_f=a\frac{\Gamma(4+b)}{6}\lambda^{-b} \quad (5)$$

where:

V_f = fall speed
Γ = gamma function
a = 841.9946 for rain or 11.72 for snow
b = 0.8 for rain or 0.41 for snow

The value of λ from eq 5 is determined in the eq 6, below:

$$\lambda = \left(\frac{\pi N_o \rho_w}{\rho q_r} \right)^{1/4} \qquad (6)$$

where:

π = 3.1416
N_o = Marshall-Palmer intercept parameter 8×10^6 m^{-4}
ρ = mean density of rain or snow particles (1000 and 100 kg m^{-3}

4. EVALUATION OF PRECITITATION FORECASTS

There were approximately 25 model runs done in a variety of locations in the United States; however, there was an emphasis on typical wintertime cases and stratiform precipitation since the main goal was to study precipitation rates, precipitation type, and the resulting surface visibility.

To verify these data, hourly surface observations were randomly used at a variety of unique terrain locations on the grid. This was done so that the influence of terrain could be included on the resulting precipitation totals. Unfortunately, the precipitation rates produced by the BFM are instantaneous rates, such as 0.06 in/hr while the MM5 rates are an average rate determined by the total precipitation output from the model over a three-hour period. Assumptions must be made that the model precipitation is a steady rate, which may be a safe assumption for stratiform precipitation, although stratiform precipitation can vary with time. An effort was made to eliminate all convective precipitation cases in this study.

4.1 Results of the BFM and MM5 Precipitation Forecasts

4.1.1 Precipitation Rates

The tables below show the number of samples, the root-mean-square error (RMSE), Correlation coefficient, and a comparison between the forecasted average and observed averages. These data in table 1 and table 2 do display rainfall intensity from the models.

Table 1. Statistical analysis of precipitation rates from the BFM

BFM hours	Samples	RMSE (mm/h)	Correlation coefficient	Forecasted Average (mm/h)	Observed Average (mm/h)
00	31	3.87	0.12	0.38	1.81
3	22	1.43	0.15	0.56	1.01
6	26	2.36	0.42	0.63	1.18
9	22	1.40	0.09	0.65	1.13
12	17	1.74	-0.15	0.67	1.05
>12	30	1.28	-0.05	0.61	0.85
Totals	148	2.01	0.10	0.58	1.17

Table 2. Statistical analysis of precipitation rates from the MM5

MM5 (hours)	Samples	RMSE (mm/h)	Correlation coefficient	Fcst Ave (mm/h)	Observed Ave (mm/h)
09	17	3.50	0.02	0.40	1.39
12	22	2.80	0.21	0.83	1.50
15	19	1.25	-0.13	0.35	0.78
18	19	2.86	0.20	1.46	1.22
21	16	1.57	0.33	1.24	0.70
>=24	22	0.94	0.19	0.70	0.41
Total	115	2.15	0.14	0.83	1.00

The sample size for the hourly data is rather small;

however, there are interesting trends noted in these data. For both the BFM and MM5, the initial time period shows the lowest forecasted precipitation rates. The precipitation may take several model time steps between production and when it finally reaches the ground. In the BFM, this may be a function of slow moistening of the atmospheric column and lower mixing ratio, cloud fraction, precipitation rate, along with a high evaporation rate

After the initial forecast period, the BFM precipitation rates are nearly constant through the 24-h model run. Additionally, the observed precipitation shows little variation through the data. This is not the case with the MM5 output, which shows more fluctuation in both the forecast averages and observed averages. Of great interest is the trend in the MM5, where the precipitation rates are less than the observed precipitation rates through the first 15-h of the model runs and then suddenly changes at the 18-h period when the forecasted precipitation becomes greater than the observed rates.

4.1.2 Precipitation Type

An interesting question is: does the precipitation type have any influence in the rainfall rates, snowfall rates or total amounts. In this study, the routine developed at ARL is used to determine if the precipitation will reach the surface as rain, snow, freezing rain, or some mixture of rain and snow. The routine is implicit, thus it is run as part of the post-processor from the BFM and MM5. Using this method, only the lowest 10000 ft AGL is used, since most stratiform precipitation falls from clouds below that level. Listed below are some of the key assumptions of the precipitation-type software:

- Uses the forecasted wet bulb temperatures rather than temperature
- Goes vertically from surface and counts layers above and below 0° C
- If all layers are below freezing, then precipitation will be snow. If all layers are above 0°C then precipitation will be rain at the surface
- Freezing rain is forecasted when some layer above the surface is above 0° C and the surface is at 0° C or less
- Calculates the depth of the elevated warm layer, which will help determine if snow falling will melt
- Calculates the near-surface-layer average temperature to know the depth of any warm or cold layers near the surface
- Does checks to see if snow will melt before reaching ground or rain will freeze at surface
- If the routine finds a borderline case between rain and snow, it becomes a “mixed” case

During the winter season of 2003 nearly 500 surface observations were collected to coincide with areas where the BFM and MM5 were run. The emphasis in the BFM is for all forecasts less than 12-h and for the MM5 from 9 to 24-h. In table 3 the results of the precipitation type study from the BFM are shown, while table 4 shows similar results from the MM5.

Table 3. BFM precipitation-type forecasts (horizontal) and observations (vertical) for all forecast hours (499 samples)

Fcst/Obs	**None**	**Rain**	**Snow**	**Freezing Rain**	**Mixed**
None	249	36	21	0	0
Rain	49	51	5	0	0
Snow	13	14	38	0	1
Freezing Rain	8	5	2	0	1
Mixed	1	6	0	1	0

Table 4. MM5 precipitation-type forecasts (horizontal) and observations (vertical) for all forecast hours (461 samples)

Fcst/Obs	**None**	**Rain**	**Snow**	**Freezing Rain**	**Mixed**
None	218	67	15	0	3
Rain	20	55	1	0	0
Snow	13	8	44	0	3
Freezing Rain	1	6	0	1	0
Mixed	1	4	0	0	1

The two tables show encouraging results, especially in the snow forecasts. In 84 percent of the BFM snow cases, snow was forecasted, while 98 percent of the snow forecasts were correctly predicted in the MM5. There was a higher error in the rain forecasts, although the POD of rain was still 67 percent in the BFM and 75 percent in the MM5. As noted by Passner (2003), the BFM tends to overforecast the surface temperature when the boundary layer is moist, thus it is not surprising to see 18 percent of the snow cases being forecasted as rain cases due to this high temperature bias. The MM5 has a slight bias to underforecast the temperature in moist environments, thus this cold bias helps to drive the MM5 surface temperature lower and results in a very high POD for snow forecasting. The main bias in the precipitation-type software is that too many rain forecasts are actually being observed as snow, freezing rain, or mixed precipitation.

A final topic to investigate was how the precipitation rates varied with the precipitation type in each model. Table 5 shows the differences in the forecasted and observed precipitation rates for rain and snow with the BFM and MM5.

Table 5. Precipitation rates and precipitation types for the BFM and MM5 (all hours)

Model and Precip type	**Samples**	**RMSE (mm/h)**	**Forecast ave (mm/h)**	**Observed Average (mm/h)**
BFM Snow	34	0.80	0.54	0.75
BFM Rain	93	1.32	0.68	1.54
MM5 Snow	31	0.84	0.37	0.58
MM5 Rain	63	2.70	1.04	1.31

The results in table 5 show that precipitation rates and observed rates are significantly lower for snow than for rain. Both models underforecast the snowfall rates, with the BFM underforecasting snowfall rates by 28 percent while the MM5 underforecast the snowfall rates by 36 percent. The BFM does have a more significant error in rainfall rates with an error of 56 percent in the rates while the MM5 rainfall rates are underforeacsted by 21 percent. The rainfall rates are higher than snowfall rates because there is more available liquid water in the atmosphere and the mixing ratio values are higher.

5. SUMMARY AND DISCUSSION

The statistical evaluation of the models provided many useful hints on how to improve and upgrade the model. The BFM is underforecasting precipitation rate by nearly 50 percent, while the MM5 is underforecasting precipitation rates by 17 percent for the overall model sample. The MM5 has an interesting trend, where the model underforecasts rates by 43 percent through 15 hours and then overforecasts the rates by 156 percent from 15 to 48-h after model initiation. Both models produce lower precipitation rates in snow than rain, and it was found that the models rarely produce snowfall rates (liquid equivalent) greater than 1.00 mm/h. The BFM error is logical, given the model's dry bias and the problems with excessive evaporation below cloud base; however the trends in MM5 precipitation rates are more complex since it contains a microphysics package with many assumptions about cloud nuclei sizes, density, and nuclei amounts.

The most vital role of the precipitation rates is that they influence the prevailing surface visibility in the post-processing software. Knapp (1996) developed regression equations based on 2790 surface observations however, Passner (2003) noted that model biases were influencing visibility forecasts and that the equations Knapp formulated were not working well with the BFM and MM5 output. To compensate for these results, rainfall and snowfall rates were used to help determine precipitation. In table 6, the results of a visibility test show the performance of the models under different precipitation conditions.

In these results the model visibility forecasts are accurate when no precipitation is falling. When fog, rain, or snow is observed, the models overforecast visibility in all three cases. The fog cases are using the original visibility equations from Knapp, however the rain and snow cases are based on the adjustments made for precipitation rates. The mean absolute difference is generally the same in all three cases; however the most significant error appears to be with the snow cases which are overforecasted on average by 3.6 miles. It was found that in 74 percent of the snow cases the observed surface visibility was less than two miles, however the average snowfall forecast in this study was 5.75 miles

Table 6. BFM and MM5 visibility errors based on observed winter weather in 2003

Model/Obstruction	Forecast Average (miles)	Observed Average (miles)	Mean Absolute Difference	Samples
BFM No Precipitation	7.68	9.67	2.18	151
MM5 No Precipitation	8.14	9.67	1.68	198
BFM Fog	5.50	3.50	4.00	62
MM5 Fog	5.68	3.68	3.30	50
BFM Rain	5.76	4.80	3.01	112
MM5 Rain	5.32	4.90	3.10	83
BFM Snow	5.49	1.97	3.90	63
MM5 Snow	6.08	2.45	4.46	72

A future step will be to lower the snowfall rates and the forecasted visibilities since the models are not able to physically produce the precipitation intensity that is often observed. The other major change will be to use the 70-minute conversion rate which should enhance the rainfall and snowfall rates. These two techniques should make a dramatic improvement in the post-processed visibility routine. Additional testing will be conducted to evaluate how these changes work with an independent data set in a variety of winter conditions. Additional evaluation of precipitation forecasts must also be completed with small-scale models such as a 5-km MM5 to see if the forecast are sensitive to grid resolution.

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