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STRATIFORM PRECIPITATION RATES AND RESULTING SURFACE VISIBILITY FORECASTS USING THE MM5

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1. INTRODUCTION

The Integrated Meteorological System (IMETS) is a mobile, operational, automated weather data receiving, processing, and disseminating system utilized by Air Force weather forecasters in support of Army operations. The U.S. Army Research Laboratory (ARL) is supporting the forecaster to make more specific and precise battlefield weather forecasts by producing weather products on IMETS (Passner, 1993). On the IMETS, the Pennsylvania State University/ NCAR Mesoscale Model Version 5 (MM5) output is available from 6 to 48 hours and is received from the Air Force Weather Agency (AFWA.) The MM5 is a limited-area, non-hydrostatic, terrain-following, sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation (Dudhia, 1993).

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. 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.

Version 3 of the MM5 was used for this study; it is from the AFWA and has a resolution of 15 km mesh data on 41 vertical levels. The ARL receives these MM5 data in gridded binary form for the Continental United States twice each day, which are initialized at 0600 universal time coordinated (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 (Grell et al, 1995).

The AFWA MM5 version used in this project 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 by 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 by ARL, 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 subgridscale convection and compensating subsidence

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- **MRF planetary boundary-layer 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** − Provides solar and infrared fluxes at the ground and atmospheric tendencies resulting from the radiative processes.
- **MM5 five-layer soil model –** Temperature predicted in 1,2,4,8,16 cm layers with fixed substrate below using the vertical diffusion equation**.**

2. PRECIPITATION RATES FOR THE MM5

The MM5 has many different ways to treat precipitation physics. The explicit schemes treat resolved precipitation physics while implicit schemes treat the non-resolved 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, is:

$$\frac{\partial p^* q_r}{\partial t} = \left[\frac{\frac{\partial p^* uq}{m}}{\partial x} + \frac{\frac{\partial p^* vq}{m}}{\partial y} \right] \frac{\partial p^* q_r \sigma}{\partial \sigma} + \delta_{nh} q_r \mathrm{DIV} \frac{\partial V_f \rho g q}{\partial \sigma} + p^*\left(P_{RE} + P_{Rc} + P_{RA} + P_{SM} + P_{CI}\right) + D_{qc} \qquad (1)$$

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 sublimination/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 terms P_{SM} and P_{CI} are the two terms added to the simple ice phase scheme. In the Reisner scheme, snow does not melt instantaneously above 0 °C. Additionally, supercooled water can exist below 0 °C and unmelted snow can exist above 0 °C. Separate arrays are used to store vapor, cloud, cloud ice, and snow.

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:

$$V_f = a \frac{\Gamma(4+b)}{6} \lambda^{-b} \qquad (2)$$

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 2 is determined in eq 3:

$$\lambda = \left(\frac{\pi N_o \rho_w}{\rho q_r} \right)^{1/4} \tag{3}$$

where

π = 3.1416

N_o = Marshall-Palmer intercept parameter $8x10^6$ m^{-4}

ρ = mean air density of rain or snow particles (1000 and 100 kg m^{-3})

3. EVALUATION OF MM5 PRECIPITATION FORECASTS

Two types of evaluation were done in this study. The first was for "YES/NO" forecasts and used a contingency table to evaluate the result by comparing the forecasted values against the observed values. The standard evaluation techniques include the probability of detection (POD), false alarm rate (FAR), the correct non-event (CNE), critical success index (CSI), true skill score (TSS), and bias. Further error evaluation was done using the mean absolute difference (AD) and root-mean square error (RMSE). Typically, the values of RMSE are proportional to those of the AD (Ott, 1977).

3.1. *Evaluation of MM5 Precipitation Forecasts*

There were approximately 25 model runs done in a variety of locations in the United States in this study; 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 selected at a variety of unique terrain locations on the grid generally separated by 50 km or more. This was done so that the influence of terrain could be included on the resulting precipitation totals. Each hourly surface observation includes a coded value for the accumulated precipitation over the past hour. Unfortunately, the precipitation rates produced by the MM5 are an average rate determined by the total precipitation output from the model over a 3-h period. Assumptions must be made that the model precipitation is 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. This is not always feasible as even the most uniform precipitation sometimes contain mesoscale features that can enhance precipitation rates on smaller scales.

3. 2 *Results of the MM5 Precipitation Forecasts*

The most basic evaluation of the model precipitation forecasts was to investigate how well the model forecasted the "YES/NO" forecast of precipitation. Table 1 displays these data for the winter months of 2003 using 463 surface observations. The results indicate that the MM5 has a POD of forecasting precipitation 82 percent of the time in this study with a fairly high FAR of 0.42 and a bias to overforecast precipitation as seen by the bias of 1.42. The number of cases with observed precipitation is 33 percent which agrees with other work done by Passner (2003).

Table 1. "YES/NO" Forecasts of Precipitation During the Winter Season in 2003.

Model Precipitation	**MM5**
Samples	463
POD	0.82
FAR	0.42
CNE	0.70
CSI	0.51
TSS	0.52
Bias	1.42
Cases with precipitation	33%

3.3 *Precipitation Rates*

It is impossible to derive the instantaneous precipitation from a surface observation; therefore, the precipitation rates, as already mentioned, are not exactly matched. However, these data in table 2 provide a valuable glimpse of rainfall intensity from the models. Table 2 displays the results of the precipitation rates, and as might be expected, the RMSE is higher when precipitation rates are higher, thus there is a definitive relationship between the error and the intensity of the precipitation. Overall, the sample size for the hourly data is small; however, there is an intriguing trend noted in these data for the MM5 where the precipitation rates are less than the observed precipitation rates through the first 12 h of the model runs followed by a sudden reversal at the 15-h forecast period as the forecasted precipitation rate becomes greater than the observed rates.

Table 2. Statistical Analysis of Precipitation Rates from the MM5.

MM5 (hours)	Samples	AD (mm/h)	RMSE (mm/h)	Fcst Ave (mm/h)	Observed Ave (mm/h)
09	42	1.01	2.37	0.84	1.02
12	45	1.24	2.33	0.95	1.20
15	49	1.12	1.90	0.89	0.61
18	52	1.37	2.45	1.43	1.29
21	33	1.18	1.88	1.15	0.82
>=24	83	0.71	1.02	0.81	0.58
Total	304	1.09	1.99	1.01	0.92

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According to Dudhia (2003), the precipitation may take several model time steps between production and when it finally reaches the ground; thus, the precipitation rates may be expected to be less than the observed rates in the early forecast periods. It is encouraging to note that the MM5 does seem to follow the natural variation in rainfall rates such as at 18-h when precipitation rates increase as does the observed precipitation rates.

As seen in table 3, over a 24-h forecast, the MM5 does show a bias to overforecast precipitation and this agrees with the general pattern to overforecast the precipitation rates after the 12-h forecast period as seen in table 2.

Table 3. MM5 24-h total precipitation forecast errors (mm).

MM5 24-h Precip	Samples	AD (mm)	RMSE (mm)	Fcst Ave (mm)	Observed Ave (mm)
MM5	90	8.89	12.20	19.81	13.72

3.4 *Precipitation Type*

An interesting question is: Does the precipitation type have any influence on the rainfall rates, snowfall rates, or total precipitation 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, so it is run as part of the post-processor from the MM5. Using the ARL method, only the lowest 10,000-ft above ground level is used, since most stratiform precipitation falls from clouds below that level and the temperature is usually below 0 °C in typical wintertime precipitation above that level. Listed below are some of the key assumptions of the precipitation-type software:

- Uses the forecasted wet bulb temperatures rather than temperature.
- 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. Calculate the depth of the elevated warm layer, which will help determine if falling snow will melt and later become freezing rain.
- Calculates the near surface-layer average temperature to know the depth of any warm or cold layers near the 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 MM5 was run. In table 4, the results of the precipitation type study from the MM5 are shown.

Table 4 indicates encouraging results, especially in the snow forecasts. In 98 percent of the MM5 snow cases, snow was correctly predicted as the precipitation type. There was a higher error in the rain forecasts, although the POD of rain was still 75 percent in the MM5. It should be noted, the error of forecasting rain and having freezing rain occur is a function of the model not forecasting surface temperatures cold enough. Even an error of 0.1 °C can cause this forecast to be incorrect. As noted by Passner (2003), the MM5 has a slight bias to underforecast the temperature in moist environments, thus this cold bias helps to drive the MM5 boundary-layer temperature lower and results in a higher 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.

Table 4. MM5 Precipitation-type Forecasts (horizontal) and Observations (vertical) for all forecast hours.

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 sample size for freezing rain and mixed precipitation was very small as only about 4 percent of all the precipitation observations were freezing rain and approximately 4 percent were mixed precipitation. As noted in the tables, the precipitation-type software rarely forecasts freezing rain or mixed precipitation, most likely because the models cannot achieve a detailed enough profile of the temperature and moisture.

A final area to investigate was: How do the precipitation rates vary with the precipitation type in the model. Table 5 shows the differences in the forecasted and observed precipitation rates for rain and snow in the MM5.

In table 5, the results do indicate another significant trend; the precipitation rates for snowfall are considerably less than the rates for rain. It is not immediately obvious why this may be, but it may be related to the cloud microphysics and the ability of the atmosphere to hold higher amounts of moisture when it is warmer. In this study, no detailed investigation was done to explain this trend, but the model does seem to follow the observations very well.

Table 5. Precipitation rates for rain and snow (all MM5 forecast hours)

Precipitation Type	Samples	AD (mm/h)	RMSE (mm/h)	Fcst ave (mm/h)	Observed Ave (mm/h)
Snow	71	0.65	0.93	0.63	0.48
Rain	195	1.23	2.19	1.16	1.12

4. PRECIPITATION RATES AND VISIBILITY

The most vital role of the precipitation rates is that they influence the prevailing surface visibility in the post-processing software. At the ARL, a visibility routine was developed using the work of Knapp (1996) with modifications. Knapp developed regression equations based on 2790 surface observations using two equations; one with a known ceiling but no precipitation falling and another with a ceiling along with precipitation. Passner (2003) noted that model biases were influencing visibility forecasts and that the equations Knapp formulated were not working well with the MM5 output. To compensate for these results, rainfall and snowfall rates were used as training to help determine surface visibility. As an example, when snowfall rates of 1.75 to 2.54 mm/hr were produced by the model, the forecasted visibility was one mile.

Table 6 shows the performance of the visibility routine for the model under different precipitation observations. The fog and no precipitation 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 results in table 6 show the model visibility forecasts are accurate when no precipitation is falling. When fog or snow is observed, the models overforecast visibility in these cases. The mean AD is generally the same in all three cases; however, the most significant error appears to be with the snow cases, which visibilities are overforecasted on average by 3.9 miles.

Table 6. MM5 Visibility Errors Based on Observed Winter weather in 2003.

Model/ Obstrcuction	Forecast Ave (miles)	Observed Ave (miles)	Mean AD	Samples
MM5 No Precipitation	7.50	9.71	2.30	327
MM5 Fog	5.24	3.17	3.10	81
MM5 Rain	4.96	5.30	2.92	183
MM5 Snow	5.52	2.60	3.86	102

It is also interesting to investigate how the rainfall and snowfall from the model compare to the observed general rates. Table 7 shows the ability of the model to forecast the correct precipitation rates for both rain and snow.

Table 7. Percent of forecasts and observations in each precipitation rate class

Percent	Trace	0.25-0.50 (mm/h)	0.50-1.00 (mm/h)	1.00-2.00 (mm/h)	2.00+ (mm/h)
MM5 rain forecast (percent)	40	11	14	18	17
Observed rain rates (percent)	23	21	18	14	24
MM5 snow rates forecast (percent)	51	21	21	0	8
Observed snow rates (percent)	41	25	18	11	5

In table 7, the MM5 results are encouraging with the percentage of cases for each precipitation class. For example, in 51 percent of all snow cases the MM5 predicted a trace of snow and in 41 percent of the cases, a trace was reported at the station. The only “negative” result in the table is the rainfall case, where 40 percent of the MM5 forecasts were for a trace of rain and in 23 percent of the cases a trace was observed. The MM5 did slightly underforecast the heavier rainfall cases, but theses differences do not appear to be significant. Unfortunately, the heavy snow and rain cases are rare and do not provide a large enough sample to make confident conclusions of these data. Table 8, shows the corresponding visibility with each precipitation-rate class

Results in table 8 are somewhat inconclusive; however, the expected patterns are noted --- lighter precipitation rates result in higher visibility and heavier precipitation rates are often associated with lower visibility.

Table 8. The observed rainfall rates and the observed visibility at the stations.

Rates/visibility	Trace	0.25-<=0.50 (mm/hr)	0.50-<=1.00 (mm/hr)	1.00-<=2.00 (mm/hr)	> 2.00 (mm/hr)	Total
<=1 mile	2	3	0	0	8	13
1 - <=3 miles	6	9	9	6	10	40
3 - <=5 miles	3	0	7	6	7	23
5- <=7 miles	3	4	1	2	3	13
>7 miles	20	15	9	6	8	58
Total	34	31	26	20	36	147

As an example, when visibility is greater than seven miles, 60 percent of the precipitation rates are less than 0.50 mm/hr. When observed precipitation rates are greater than 2.00 mm/hr, 50 percent of the visibility cases are less than or equal to three miles. The large number of exceptions to these trends does indicate that prevailing visibility is not based on this one variable, the precipitation rate; but does include many other factors that work on many different meteorological scales. The synoptic weather, the mesoscale features, local terrain, proximity to water sources, and microphysics of the clouds can be factors in the observed visibility. It may be impossible for mesoscale models such as the 15-km MM5 to capture all these features; however, given the limitations of this problem the model does provide excellent guidance in the visibility problem as displayed in table 9.

The post-processed MM5 visibility routine does follow the same trends as the observations as seen in the comparison of tables 8 and tables 9. Exactly 50 percent of the cases of greater than 2.00 mm/hr precipitation rates resulted in a surface visibility less than or equal to three miles, while in 78 percent of the cases where the visibility was greater than seven miles, the precipitation rates were less than 0.50 mm/hr. This pattern is also seen in the five- to seven-mile classification, where 75 percent of the cases had precipitation rates less than 0.50 mm/hr. Based on the results of table 9, it appears that the intermediate visibility of three to five miles is the most difficult class for the model and post-processed visibility software to capture. The 85 samples are spread randomly with the precipitation rates and no obvious correlation exists between the forecasted precipitation rate and forecasted visibility.

Table 9. The MM5 forecast for each visibility class for forecasted rainfall rates.

Rates/visibility	**Trace**	**0.25- <=0.50 (mm/hr)**	**0.50- <=1.00 (mm/hr)**	**1.00- <=2.00 (mm/hr)**	**>2.00 (mm/hr)**	**Total**
<=1 mile	4	1	3	2	1	11
1 - <=3 miles	12	4	7	11	20	54
3 - <=5 miles	23	9	10	25	18	85
5- <=7 miles	38	7	11	2	2	60
>7 miles	21	5	2	4	1	33
Total	98	26	33	44	42	243

5. CONCLUSIONS

This study was designed to investigate the precipitation rates, precipitation amounts, and precipitation types forecasted from the MM5. A description of how precipitation is formulated in the model helps to enhance the understanding of how these factors influence the model output. In the MM5, the stratiform precipitation routine is an explicit scheme, where the scheme is activated when grid-scale saturation is reached. There is an explicit treatment of cloud water, rain water, snow, and ice along with feedback to the temperature and moisture field along with the radiation scheme. The MM5 uses the mixed-phase Reisner microphysics package, which builds upon the simple ice routine by permitting supercooled water below 0 °C and has a gradual snow melt as it falls. Additionally, unmelted snow can exist above 0 °C. The value of the mixing ratio is used in the final fall term in the MM5. This fall term is the actual precipitation that reaches the ground (Passner, 2004).

To best summarize the results of this study, table 6 (visibility and observed precipitation types) is the most significant output of this project. The results specify that the MM5 does underforecast the visibility when no precipitation is falling; although, this error is not substantial enough to require any adjustment to the visibility routine and is probably caused by the known MM5 moisture and cloud bias. The average forecast for the rain cases is precise, with a forecast average of 4.96 miles and an observation average of 5.30 miles. The discussion in section 4 does prove that the MM5 and visibility routine work well when rain is observed. However, when fog is observed and when snow is observed, the forecasts for visibility are too high, even if the RMSE does not change dramatically. Based on results in this study, the MM5 does “detect” rain 82 percent of the time, and thus provides a signal that visibility is reduced because of the rainfall. The precipitation-type routine does an excellent job of determining when snow is falling but the visibility routine is not adjusting well to the normally lower precipitation rates and lower visibility for snowfall. The model biases are well noted when snow is observed and a larger error might be expected due to the wide variation of ice-crystal size, cloud nuclei, and water ratio for the crystals which are part of the Resneir mixed phase routine. Since this may be a limitation of the current understanding of cloud properties the best approach to improve this problem is to adjust the visibility routine to accept lower values even if precipitation rates are lower in snow and relative humidity values are high in fog cases. It has been observed that in 74 percent of snow cases the visibility is less than two miles, thus the post-processor should be adjusted so that this model bias can be accounted for. Future steps will be taken to make these adjustments and validate how much improvement is recorded.

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