ALPINE GEOPHYSICS
REGIONAL AIR QUALITY COUNCIL
ENVIRON

Draft Report

Evaluation of Preliminary MM5 Meteorological Model Simulation for the June-July 2006 Denver Ozone SIP Modeling Period Focused on Colorado

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February 25, 2008

TABLE OF CONTENTS

TABLES

FIGURES

1 INTRODUCTION

Over the past decade, emergent requirements for direct numerical simulation of urban and regional scale photochemical and secondary aerosol air quality, spawned largely by particulate matter ($PM_{2.5}$), ozone and regional haze regulations, have led to intensified efforts to construct high-resolution emissions, meteorological and air quality modeling data bases. The concomitant increase in computational throughput of low-cost modern scientific workstations has ushered in a new era of regional air quality modeling. It is now possible, for example, to exercise sophisticated mesoscale prognostic meteorological models and Eulerian and Lagrangian photochemical/aerosol models, simulating ozone, sulfate and nitrate deposition, and secondary organic aerosols (SOA) across the entire United States (U.S.) or over discrete subregions for extended periods (e.g., calendar year).

One such model is the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) (Dudhia, 1993; Grell et al., 1994: www.mmm.ucar.edu/mm5). MM5 is a limited-area, non-hydrostatic, terrain-following model designed to simulate mesoscale atmospheric circulation. The model is supported by several pre- and post-processing programs which are referred to collectively as the MM5 modeling system.

This report describes an application and performance evaluation of MM5 for an atmospheric simulation of the June and July 2006 modeling period for a modeling domain that covers the continental United States at a 36 km grid spacing, the Southwestern United States at 12 km grid spacing, and most of the State of Colorado at 4 km grid resolution. The purpose of the MM5 modeling is to develop meteorological inputs to support photochemical grid modeling for the Denver 8-hour ozone State Implementation Plan (SIP) attainment demonstration modeling.

2 METHODOLOGY

The methodology for this approach is very straightforward. The basic methodology was to apply the MM5 model for June and July 2006 at the various grid resolutions (36 km, 12 km, and 4 km) and to then compare the model results (wind speeds, wind directions, temperatures, etc.) with available surface meteorological observations.

2.1 Model Selection and Application

Below we give a brief summary of the MM5 input data preparation procedure used for this two monthly meteorological modeling exercise.

Model Selection: The publicly available non-hydrostatic version of MM5 (version 3.7.4) was used for this modeling study. Preprocessor programs of the MM5 modeling system including TERRAIN, REGRID, LITTLE_R, and INTERPF were used to develop model inputs.

Horizontal Domain Definition: The computational grid is presented in Figure 2-1. The outer 36 km domain (D01) has 165 x 129 grid cells, selected to maximize the coverage of the ETA analysis region. The mid-scale 12 km domain (D02) has 187 x 157 grid cells, selected to maximize the coverage of the western region around Colorado. The inner 4 km domain (D03) has 151 x 136 grid cells, selected to maximize the coverage of the Denver Metropolitan area as well as the mountain regions to the west and high plains areas to the east of Denver. The projection was in Lambert Conformal Coordinates (LCC) with the "national RPO" grid projection pole of 40^o, -97^o with true latitudes of 33^o and 45^o. The datum set was NWS-84.

Vertical Domain Definition: The MM5 modeling was based on 34 vertical layers from the surface to 100 mb (approximately 15 km above ground level) with an approximately 38 meter deep surface layer. The MM5 vertical domain is presented in both sigma and height coordinates in Table 2-1.

Topographic Inputs: Topographic information for the MM5 was developed using the NCAR and the United States Geological Survey (USGS) terrain databases. The grid was based on the 2 min (~4 km) Geophysical Data Center global data. Terrain data was interpolated to the model grid using a Cressman-type objective analysis scheme. To avoid interpolating elevated terrain over water bodies, after the terrain databases were interpolated onto the MM5 grid, the NCAR graphic water body database was used to correct elevations over water bodies.

Vegetation Type and Land Use Inputs: Vegetation type and land use information was developed using the most recently released PSU/NCAR databases provided with the MM5 distribution. Standard MM5 surface characteristics corresponding to each land use category were employed.

Atmospheric Data Inputs: The first guess meteorological fields were taken from the NCAR ETA archives. Surface and upper-air observations used in the objective analyses, following the procedures outlined by Stauffer and Seaman at PSU, were quality-inspected by MM5 pre-processors using automated gross-error checks and "buddy" checks. In addition, rawinsonde soundings were subject to vertical consistency checks. The synoptic-scale data used for this initialization (and in the analysis nudging discussed below) were obtained from the conventional National Weather Service (NWS) twice-daily radiosondes and 3-hourly NWS surface observations.

Water Temperature Inputs: The ETA database contains a "skin temperature" field. This can be and was used as the water temperature input to these MM5 simulations. Past studies have shown that these skin temperatures, used as the water temperature surrogates, can lead to temperature errors along coastlines. However, for this analysis which focuses on bulk continental scale transport across the central United States, this issue is likely not important and the skin temperatures were used.

FDDA Data Assimilation: This simulation used analysis based nudging. For these simulations analysis nudging coefficients of 2.5×10^{-4} and 1.0×10^{-4} were used for winds and temperature.

Physics Options: The MM5 model physics options were employed in this analysis as follows:

- Kain-Fritsch 2 Cumulus Parameterization on 36/12 km Domain;
- No Cumulus Parameterization on 4 km Domain;
- Pleim-Xiu Land Surface Model (LSM) and Asymmetric Convective Mixing (ACM) Planetary Boundary Layer (PBL) Schemes;
- Reisner 2 Mixed Phase Moisture Scheme; and
- RRTM Atmospheric Radiation Scheme

Application Methodology: The MM5 model was executed in 5-day blocks initialized at 12 GMT every 4 days with a 90 second time step. Model results were output every 60 minutes and output files were split at 24 hour intervals. Twelve (12) hours of spin-up was included in each 4-day block before the data was used in this atmospheric simulation and subsequent evaluation. The model was run with 36 km and 12 km resolution nests with light smoothing feedback and the 4 km grid as a one-way nest.

2.2 Evaluation Approach

The model evaluation approach was based on a combination of qualitative and quantitative analyses. The qualitative approach was to compare the model estimated monthly total precipitation with the monthly Center for Prediction of Climate (CPC) precipitation analysis using graphical outputs. The statistical approach was to examine tabulations of the model bias and error for temperature, and mixing ratio and the index of agreement for the wind fields and compare these to similar 36 km, 12 km, and 4 km simulations.

Interpretation of bulk statistics over a continental or regional scale domain is problematic. To detect if the model is missing important sub-regional features is difficult. For this analysis the statistics were performed on a state by state basis, a Regional Planning Organization (RPO) basis, and on a domain-wide for the continental 36 km domain and the regional 12 km domain. For the 4 km domain, the statistics were generated for the area covered by the domain which is most of Colorado. As with the continental scale and regional scale calculations, the interpretation of the statistics may be problematic given the significant differences across the State in elevation and microclimates. Nonetheless, these statistics are offered as some measure of the quality of the data set generated.

The observed database for winds, temperature, and water mixing ratio used in this analysis was the NOAA Forecast Systems Lab (FSL) MADIS surface observations. The rain observations are taken from the CPC retrospective rainfall archives available at: http://www.cpc.ncep.noaa.gov/products/precip/realtime/retro.shtml.

Table 2-1. MM5 Vertical Domain Specification.

.k(MM5)	Sigma	Pressure.(mb)	Height(m)	Depth(m)
34	0.000	10000	15674	2004
33	0.050	14500	13670	1585
32	0.100	19000	12085	1321
31	0.150	23500	10764	1139
30	0.200	28000	9625	1004
29	0.250	32500	8621	900
28	0.300	37000	7720	817
27	0.350	41500	6903	750
26	0.400	46000	6153	693
25	0.450	50500	5461	645
24	0.500	55000	4816	604
23	0.550	59500	4212	568
22	0.600	64000	3644	536
21	0.650	68500	3108	508
20	0.700	73000	2600	388
19	0.740	76600	2212	282
18	0.770	79300	1930	274
17	0.800	82000	1657	178
16	0.820	83800	1478	175
15	0.840	85600	1303	172
14	0.860	87400	1130	169
13	0.880	89200	961	167
12	0.900	91000	794	82
11	0.910	91900	712	82
10	0.920	92800	631	81
9	0.930	93700	550	80
8	0.940	94600	469	80
7	0.950	95500	389	79
6	0.960	96400	310	78
5	0.970	97300	232	78
4	0.980	98200	154	39
3	0.985	98650	115	39
2	0.990	99100	77	38
1	0.995	99550	38	38
0	1.000	100000	0	0

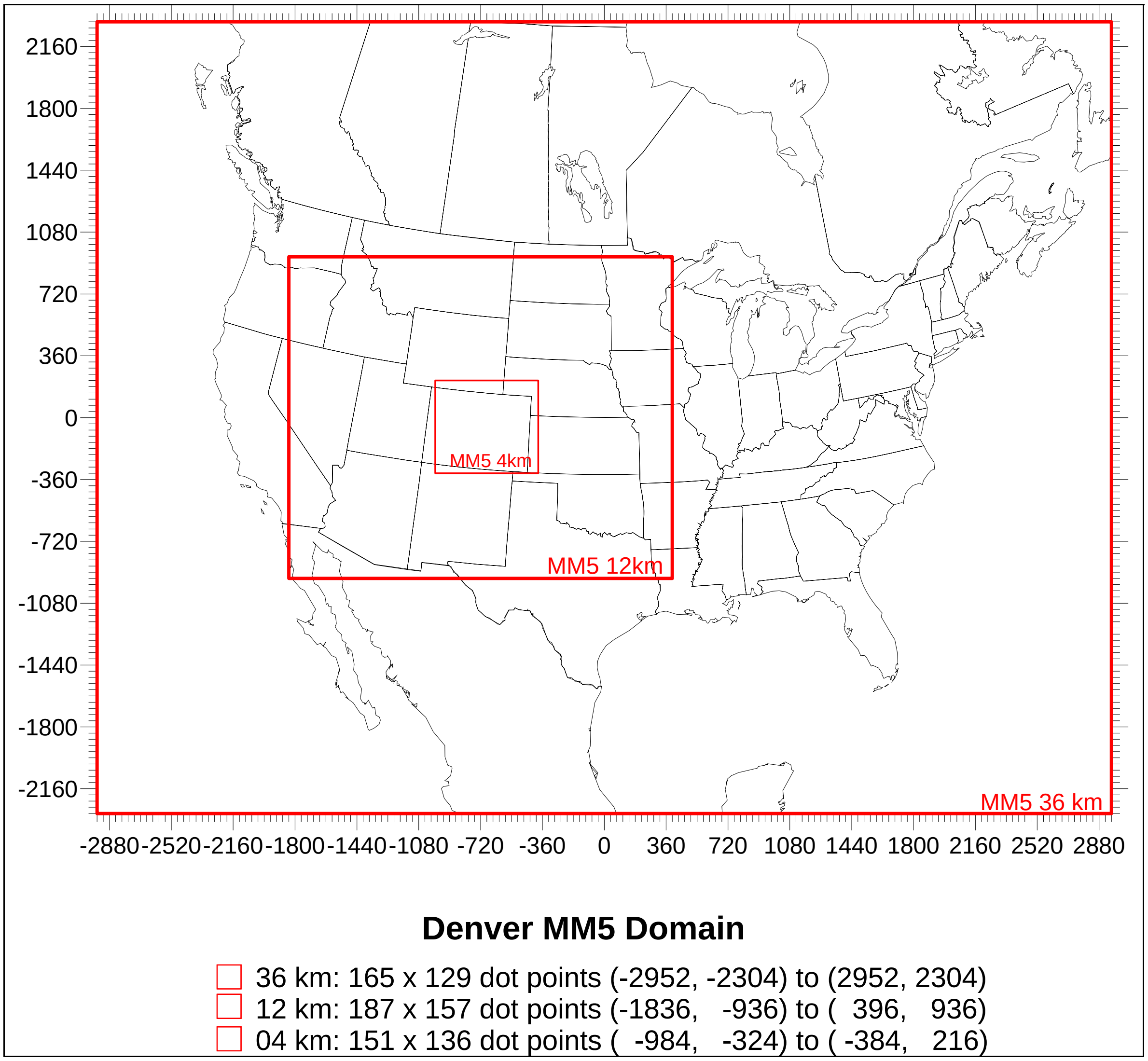

Figure 2-1. 36/12/4 km MM5 Domain.

3 MM5 PERFORMANCE EVALUATION RESULTS

Both quantitative and qualitative model evaluation results of the MM5 meteorological modeling for the overall region at the 36 km, 12 km, and 4 km grid spacing are presented in this section.

3.1 Quantitative Model Evaluation Results

Statistical model evaluation results are presented in this section. A nested, muli-month model evaluation is very difficult to summarize in a single document. With this in mind, this section presents results so potential data users can independently judge the adequacy of the model simulation. Overall comparisons are offered herein to judge the model efficacy, but this review does not necessarily cover all potential user needs and applications.

Tables 3-1 through 3-15 present the statistical metrics for each state, for each Regional Planning Organization (RPO) area as appropriate, and for the full area as a portion of the United States that is covered by each of the 36 km, 12 km, and 4 km modeling domains (called “ALL” in each table). For reference, a graphic of RPO boundaries is presented in Figure 3-1 and the individual boundaries of the domains are presented in Figure 2-1. In these comparisons the vertical level 1 (~19 m) model estimates are compared directly with the nominal ~2 m temperature and moisture and ~10 m wind measurements.

To evaluate the performance of the MM5 2006 36 km, 12 km, and 4 km simulations for the U.S., for the western U.S., and for Colorado, respectively, a number of performance benchmarks for comparison were used. Emery and co-workers (2001), have derived and proposed a set of daily performance “benchmarks” for typical meteorological model performance. These standards were based upon the evaluation of about 30 MM5 and RAMS meteorological simulations in support of air quality applications performed over several years and reported by Tesche et al. (2001). The purpose of these benchmarks was not to give a passing or failing grade to any one particular meteorological model application, but rather to put its results into the proper context of other models and meteorological data sets. The key to the benchmarks is to understand how good or poor the results are relative to other model applications run for the U.S. Thus, this section compares the calculated statistical measures against these benchmarks to assess the MM5 performance in terms of its viability for use in modeling and meteorological assessments and Section 4 presents a comparison to other similar model applications. These benchmarks include bias and error in temperature and mixing ratio as well as the Wind Speed Index of Agreement (IA) between the models and data bases. The benchmark for acceptability for each variable is:

- Temperature bias: <±0.5 K
- Temperature error: <2.0 K
- Mixing ratio bias: <±1.0 g/kg
- Mixing ratio error: <2.0 g/kg
- Wind Speed Index of Agreement (IA): 0 = worst, 1 = best, 0.6 = acceptable

3.1.1 Temperature Bias and Error

Temperature bias statistics are presented in Tables 3-1 through 3-3 for the 36 km, 12 km, and 4 km modeling domains. Each is evaluated in turn.

Temperature bias statistics are presented in Table 3-1 for the 36 km modeling domain. As can be seen in Table 3-1, when the temperatures are averaged over the June-July 2006 period for the entire modeling domain (ALL), the model has a bias of -0.12 K, thus underestimating on average temperature across the U.S. In reviewing these results on a state-by-state and region-by-region basis, the most obvious trend is that the western states and a handful of Eastern Coastal states (Florida, New York, Virginia, and Rhode Island) are underestimated by a few tenths of a degree Kelvin (guideline within the +/-0.5 K benchmark) up to a bias of -2.13 K in California with several western states being just outside of the guideline range (Arizona, Colorado, Nevada, New Mexico, Wyoming, Montana, and Oregon ranging from -0.59 to -1.42 K). All other states and regional RPOs have temperature bias on the positive side generally within the guideline benchmark. Differences between June and July 2006 temperature bias is generally insignificant indicating that the above observations on the June-July 2006 averages hold for each individual month’s performance review as well.

Temperature bias statistics are presented in Table 3-2 for the 12 km domain. As can be seen in Table 3-2, when the temperatures are averaged over the June-July 2006 period for the entire 12 km modeling domain (ALL), the model has a slight negative bias of -0.01 K for the 12 km domain, which is an improvement over the 36 km results. As with the 36 km Western U.S. temperature bias, most of the states within the 12 km domain have bias that is slightly negative and within the guideline benchmark bias, except for Nevada (with -0.73 K). Little difference was discerned between the June and July 2006 bias for each state reported in the 12 km domain in Table 3-2 except for Utah with a positive bias in June (0.40 K) and a negative bias in July (-0.09 K), both of which were within guidelines.

Temperature bias statistics are presented in Table 3-3 for the 4 km domain. As can be seen in Table 3-3, when the temperature biases are averaged over the June-July 2006 period for the entire 4 km Colorado modeling domain (Mean), the model has a bias of -0.20 K. The model has a negative temperature bias in June 2006 and a positive temperature bias in July 2006 over the 4 km domain. Both months were within the guideline range of the temperature bias threshold of <±0.5 K for the 4 km domain.

Temperature error data are presented in Table 3-4 for the 36 km modeling domain. The overall temperature error (ALL category) over all states and for the June-July 2006 period is 1.53 K on the 36 km domain. All mean annual temperature errors over each state and region were in the range from the lowest value of 0.84 K in Delaware to the highest error of 3.05 K in Nevada. Far Western states in the vicinity of Colorado were all generally greater than the benchmark of 2.0 K including Arizona, Colorado, Nevada, Wyoming, Idaho, California, Oregon, and Utah with exception of New Mexico, Montana, and Washington. The average of the WRAP RPO states was 2.30 K. All other states and RPOs for this June-July 2006 period had temperature errors less than the benchmark over the 36 km domain. Most individual monthly temperature errors mimicked the Mean results (guideline performance) except for the Montana July 2006 temperature error which was 2.13 K.

Temperature error data are presented in Table 3-5 for the 12 km grid spaced western area modeling domain. The overall temperature error over the June-July 2006 period (Mean) for the 12 km domain (ALL category) was 1.42 K which is a slight improvement over the 36 km domain results. On a state by state basis for those in this western 12 km domain, all states improved in terms of their temperature error (had errors less than the 36 km domain) although two states, namely, Colorado and Nevada (2.06 and 2.05 K, respectively) were slightly just above the guideline benchmark.

Temperature error data are presented in Table 3-6 for the 4 km modeling domain. The overall June-July 2006 temperature error (Mean) is 1.78 K. Both months were within the guideline benchmark for the 4 km domain.

3.1.2 Mixing Ratio Bias and Error

Mixing ratio bias data are presented in Table 3-7 for the 36 km modeling domain. Averaged over the June-July 2006 period, over all states, the model has a bias of 0.10 g/kg for the 36 km domain as shown by the "ALL" category in Table 3-7. The MM5 model results were well within the guideline range of the mixing ratio threshold of ±1.0 g/kg for all states and RPOs. The range of underprediction bias was from a low of -0.71 g/kg in Idaho to -0.1 g/kg in California and the range of overprediction bias was from a low of 0.00 g/kg in Tennessee to 0.68 g/kg in New Mexico. Regional tendencies that were evident over the 36 km domain was that most Midwestern states around or adjacent to the Ohio River Valley all had negative mixing ratio bias and extreme Southwestern states had the highest positive mixing ratio bias. Little June to July variations in the mixing ratio bias were evident across most states although a few states had higher changes in bias (e.g., Arizona from 1.06 in June to 0.26 g/kg in July and New Mexico from 1.32 in June to 0.04 g/kg in July0 and others had swings from positive to negative mixing ratio bias (e.g., Colorado from 0.39 in June to -0.94 g/kg in July and Montana from -0.42 in June to 0.45 g/kg in July). Only two states, namely, Arizona and New Mexico, had June values (1.06 and 1.32, respectively) greater than the benchmark of ±1.0 g/kg.

Mixing ratio bias data are presented in Table 3-8 for the 12 km modeling domain. As can be seen in Table 3-8, when the mixing ratio biases are averaged over the June-July 2006 period for the entire 12 km modeling domain (ALL), the model has a slight positive bias of 0.09 g/kg for the 12 km domain, which is about the same as for the 36 km domain results. For these southwestern states the mixing ratio biases were all well within the guideline range of the benchmark of ±1.0 g/kg with slight improvement in bias in some states and slight degradation of bias in other states.

Mixing ratio bias data are presented in Table 3-9 for the 4 km modeling domain. The overall June-July 2006 mixing ratio bias (Mean) is 0.18 g/kg averaged over 4 km domain. As with the 36 km and 12 km results for Colorado, the mixing ratio changed from a June positive bias of 0.86 g/kg to a July negative bias of -0.45 g/kg. All mixing ratio bias was well within the acceptability benchmark of ±1.0 g/kg.

Mixing ratio error results are presented in Table 3-10 for the 36 km domain. The mean error for the June-July 2006 data set was 1.33 g/kg for the whole 36 km domain (ALL). The range of Mean errors was from a low of 0.94 g/kg in Maine to a high of 1.83 g/kg in New Mexico. The model shows a mean error throughout the year in each state and RPO that is within the guideline benchmark value of 2.0 g/kg. A comparison of the values of mean error for each state and RPO over both June and July show little difference.

Mixing ratio error results are presented in Table 3-11 for the 12 km domain. The mean error for the June-July 2006 data set for the 12 km domain was 1.51 g/kg. The 12 km grid domain modeling shows mean mixing ratio errors that are generally within the guideline value of 2.0 g/kg. For New Mexico, the June 12 km value was 2.13 g/kg. The monthly values of mean error are highest for July 2006 MM5 results except for New Mexico.

Mixing ratio error results are presented in Table 3-12 for the 4 km domain. The mean mixing ratio error is 1.64 g/kg for the 4 km modeling domain. The mixing ratio errors for June and July 2006 were similar and were 1.60 to 1.68 g/kg, respectively. These errors while appearing to degrade from the 36 km to the 12 km to the 4 km domains actually were about the same when considering the performance in Colorado ranging from 1.59 to 1.70 to 1.68 over the various domains of the MM5 model degraded somewhat over the from the 36 km The model shows that all mixing ratio error values were within the acceptability benchmark of 2.0 g/kg.

3.1.3 Wind Index of Agreement

Comparisons between the June-July 2006 36 km, 12 km, and 4 km domain MM5 modeling of winds and those of the NOAA Forecast Systems Lab (FSL) MADIS surface observations were made using the Wind Index of Agreement (IA). Recall that the benckmark is a Wind Speed Index of Agreement equal to 0.6. Values below that benckmark are generally poor agreement and values above that benchmark are better with an IA of 1.0 being the best. Note also that the Index of Agreement metric is sensitive to the number of monitors being used in the calculation, with more monitors tending to give higher Index of Agreement scores.

The Wind IAs for the 36 km domain are presented in Table 3-13. The domain-wide June-July 2006 averaged Wind IA is 0.89 for the 36 km domain. No significant monthly differences were noted between June and July in any one state or RPO. For all states and RPOs except New Hampshire (0.44), Vermont (0.56), Connecticut (0.56), and Delaware (0.51), the Wind IA fell in the guideline (0.6) to best (1.0) range of comparison. For the Western states the Wind IA ranged from 0.75 to 0.81 for each state and the WRAP RPO was 0.88.

The Wind IAs for the 12 km modeling domain are presented in Table 3-14. The June-July 2006 average Wind IA is 0.88 for the 12 km domain. For all states and months in the 12 km domain, the Wind IA fell in the guideline (0.6) to best (1.0) range of comparison. Specifically for the 12 km states the Wind IA ranged from 0.75 to 0.81 showing very good wind agreement for each state.

The Wind IAs for the 4 km modeling domain are presented in Table 3-15. The June-July 2006 average Wind IA is 0.83 for the 4 km domain. The wind IA for each month was about the same at 0.83 and 0.84, respectively.

3.1.4 Spatial Mean Temperature and Mixing Ratio

This section presents spatial mean time series plots on a monthly basis for both temperature and mixing ratio for the 4 km modeling domain. The “observed” (shown by a “$*$” in the figures) spatial mean temperature or mixing ratio was computed for each hour by averaging all valid observed station data within the modeling domain (30-40 stations). The “model” estimated spatial mean (solid red line in the figures) was computed for each hour by averaging the model estimates at all station locations that reported valid data for that hour. These 4 km domain-wide hourly averages for observed and modeled temperature and mixing ratio data were then plotted versus time to demonstrate the comparison of the two sets of data and allow a qualitative evaluation of the MM5 data. These straightforward plots were useful for discerning overall trends in model performance and provide a convenient tool to quickly identify if the MM5 Model is tending to over or underestimate modeled fields.

Figures 3-2 and 3-3 present the spatial mean temperatures by month within the 4 km modeling domain. Review of these two June and July 2006 mean spatial temperature profiles indicates that the MM5-generated temperature fields capture the synoptic and diurnal trends of temperature across the domain quite well. This is shown by noting the general agreement in the patterns of temperature for the modeled and observed values as a function of time. Also shown in these patterns is the general good agreement of the MM5 model in following the diurnal pattern of the temperatures. The greatest differences in temperatures are noted where the MM5 data underpredict the high peak temperatures and overpredict the low peak temperatures. The model versus observed temperatures are generally within a few degrees of the observed values.

Figures 3-4 through 3-5 present the spatial mean mixing ratios over the 4 km modeling domain. Review of the mean spatial mixing ratio profiles for June and July 2006 indicate the MM5-generated mixing ratio fields capture the synoptic trends as well as the diurnal patterns across the domain quite well. This is shown in the figures by noting the general agreement in the patterns of mixing ratio as a function of time over each month. Although this general trend was estimated well by the MM5 data, some underestimation and overestimation was noted in some periods of time. More overestimates were made by the model in June (Figure 3-4) when mixing ratios were lower (of the two months) and more underestimates in July 2006 (Figure 3-5) when the mixing ratios were higher.

3.1.5 Spatial and Temporal Mean Wind Speed Index of Agreement, Wind Speed and Wind Direction

This section presents spatial mean time series plots on a monthly basis for the Wind Speed Index of Agreement (IA), wind speed, and wind direction. The model estimated spatial wind speed IA was computed for each hour by averaging the model estimates at all station locations that reported valid data for that hour and comparing those to observed data. The IA provides a measure of the quantitative comparability. The mean wind speeds were computed using the calculated vector averaged hourly domain-wide observed and modeled data. The “observed” spatial vector averaged wind speed was computed for each hour by averaging all valid observed station wind speed data within the modeling domain (30-40 stations). The “model” estimated spatial wind speed was computed for each hour by averaging the model estimates at all station locations that reported valid data for that hour. The mean wind direction was calculated from the hourly domain-wide averaged observed versus modeled data similar to the wind speeds. These domain-wide hourly averages of wind speed IA, vector wind speed, and mean wind direction for observed and modeled data were then plotted versus time to demonstrate the comparison of the two sets of data. This allowed a qualitative evaluation of the MM5 data performance as compared to the average observed data. These straightforward plots were useful for discerning overall trends in model performance and provide a convenient tool to quickly identify if the MM5 Model is tending to over or underestimate modeled fields.

Figures 3-6 and 3-7 provide the spatial mean of the Wind Speed Index of Agreement as a function of time over the 4 km domain for June and July 2006 simulations. In both plots the IA is generally greater than the minimum guideline benchmark of 0.6 with a few exceptions in mid-June and mid to late July. The diurnal pattern indicates that MM5 performs best during the daylight hours where the IA is highest and poorest in the nighttime hours when wind speeds are lower.

Figure 3-8 provides the spatial mean profiles of the wind directions for modeled and observed data as a function of time over the 4 km domain for the June 2006 simulations. Review of the June wind direction plots indicate the spatially averaged MM5 generated wind direction fields capture the synoptic trends of wind direction across the domain quite well. This is shown by noting the general agreement in the patterns of wind direction between the observed and modeled data as a function of time. Also shown in these patterns is the general good agreement of the MM5 model in following the diurnal pattern of wind direction for each day. The agreement between the observations and modeled wind directions were best when winds were persistent, e.g., June 13-15 where modeled and observed values were within about 5-10^o of each other. On days when diurnal variations were significant the MM5 wind direction averages tend to miss some of the daily wind shifts by 50-90^o but still follow the general pattern of change over several days to weeks.

Figure 3-9 provides the spatial mean profiles of the wind speeds for modeled and observed data as a function of time over the 4 km domain for the June 2006 simulations. Review of the June wind speed plots indicate the spatially averaged MM5 generated wind speeds fields capture the synoptic trends of wind direction across the domain quite well. This is shown by noting the general agreement in the patterns of wind speed between the observed and modeled data as a function of time. Also shown in these patterns is the general good agreement of the MM5 model in following the diurnal pattern of wind speed for each day. Where wind speeds are lowest the model tends to overpredict the speeds compared to observed values. The MM5 model did particularly well in calculating the high values on June 15.

Figures 3-10 and 3-11 provide the spatial mean profiles of the wind directions and wind speeds for modeled and observed data as a function of time over the 4 km domain for the July 2006 simulations. Review of the July wind direction and wind speed plots indicate the spatially averaged MM5 generated wind direction fields capture the synoptic and diurnal trends across the domain quite well. Other comparisons are similar to those for June noted above.

3.2 Qualitative Monthly Precipitation Analysis

This section presents qualitative comparisons of MM5 estimated precipitation with the CPC retrospective analysis data. When comparing the CPC and MM5-generated precipitation data, note should be taken that the CPC analysis covers only the Continental U.S. and does not extend offshore or into Canada or Mexico. The MM5 fields, on the other hand, cover the entire 36 km domain. Also note that the CPC analysis is based on a 0.25 x 0.25 degree (~40 x 40 km) grid and the MM5 is based on a comparable grid of 36 x 36 km and much finer grids of 12 x 12 km, and 4 x 4 km. Neither the 40km or 36 km grid spacing capture small precipitation features effectively, while both the 12 km and 4 km grid spacing will capture and display such features.

Total precipitation comparisons for June and July 2006 over the 36 km domain are presented in Figures 3-12 through 3-15. For each month, the first plot presents the CPC analysis data (e.g., Figure 3-12) and the second plot represents the MM5 total precipitation (e.g., Figure 3-13). Given that the CPC analysis data are considered to be the standard for precipitation, MM5 provides a reasonable representation of the spatial distribution of precipitation over the contiguous U.S. for June and July of 2006. The poorest agreement is in the southwest U.S. for both months where the MM5 precipitation estimates are much greater across Nevada, Colorado, Utah, Wyoming, Arizona, and New Mexico. In June MM5 precipitation is heavier along the south east coast than CPC and in Montana and New Mexico. The July MM5 pattern is similar to CPC but the MM5 results are much higher in the Southeast U.S. and in the terrain induced high intensity precipitation over New Mexico. The MM5 model treats more specifically the terrain which leads to the potential differences in the MM5 results in the Rockies in the summertime.

Total precipitation comparisons for June and July 2006 over the 12 km domain are presented in Figures 3-16 through 3-19. As with the 36 km simulations, the MM5 data provide a more refined treatment of terrain-induced precipitation and therefore in the mountainous Southwest U.S. more widespread precipitation is calculated. In both the June and July 2006 periods the MM5 results are higher in magnitude and spatial extent of the precipitation. The refinement of the 12 km grid size is obvious when comparing the CPC precipitation to that of the MM5 simulations as the MM5 graphics appear to have much finer detail.

Total precipitation comparisons for June and July 2006 over the 4 km domain are presented in Figures 3-20 through 3-21. Within the spatial limitations of the CPC analysis data, MM5 does a reasonably good job representing the general spatial coverage of the precipitation shown in the CPC data. The MM5 plots show much more precipitation over the central Colorado Rockies in both months than CPC data. Much higher and widespread precipitation was estimated by MM5 in June. The July simulations did well in finding the rainshadow over central Colorado along the western edge of the front range but gave much higher precipitation over western Colorado.

Table 3-1. Temperature Bias (K) for June and July 2006 MM5 by Month and by State and Region in the 36 km Domain.

Region	June '06	July '06	Mean
AL	0.25	-0.04	0.11
ALL	-0.08	-0.15	-0.12
AR	0.42	0.18	0.30
AZ	-0.67	-0.72	-0.70
CA	-2.02	-2.25	-2.13
CENRAP	0.19	0.04	0.11
CO	-1.17	-0.82	-1.00
CT	0.17	0.25	0.21
DE	0.17	0.28	0.22
FL	-0.19	-0.05	-0.12
GA	0.21	0.01	0.11
IA	0.48	0.44	0.46
ID	-0.37	-0.05	-0.21
IL	0.57	0.48	0.52
IN	0.49	0.42	0.45
KS	0.10	0.07	0.09
KY	0.48	0.31	0.39
LA	0.37	0.38	0.38
MA	0.02	0.11	0.06
MANE_VU	0.03	0.10	0.06
MD	0.00	0.01	0.00
ME	0.06	0.06	0.06
MI	0.17	0.19	0.18
MN	0.32	0.12	0.22
MO	0.22	0.06	0.14
MS	0.46	0.21	0.34
MT	-0.54	-0.64	-0.59
MW	0.48	0.40	0.44
NC	0.31	0.08	0.19
ND	0.37	0.51	0.44
NE	0.09	0.10	0.09
NH	0.46	0.66	0.56
NJ	0.00	0.16	0.08
NM	-0.72	-0.56	-0.64
NV	-0.95	-1.11	-1.03
NY	-0.25	-0.24	-0.25
OH	0.43	0.35	0.39
OK	0.34	0.03	0.19
OR	-1.13	-1.03	-1.08
PA	0.16	0.23	0.19
RI	-0.03	-0.12	-0.07
SC	0.29	0.19	0.24
SD	0.22	0.20	0.21
TN	0.48	0.36	0.42
TX	-0.11	-0.32	-0.22
UT	-0.17	-0.79	-0.48
VA	-0.11	-0.05	-0.08
VISTAS	0.16	0.07	0.11
VT	0.01	0.03	0.02
WA	-0.52	-0.40	-0.46
WI	0.82	0.62	0.72
WRAP	-1.02	-1.02	-1.02
WV	0.33	0.36	0.35
WY	-1.47	-1.38	-1.42

Table 3-2. Temperature Bias (K) for June and July 2006 MM5 by Month and by State in the 12 km Domain.

Region	June '06	July '06	Mean
ALL	0.02	-0.04	-0.01
AZ	-0.41	-0.43	-0.42
CO	-0.60	-0.20	-0.40
ID	0.13	0.31	0.22
NM	-0.47	-0.27	-0.37
NV	-0.67	-0.78	-0.73
UT	0.40	-0.09	0.16
WY	-0.52	-0.43	-0.47

Table 3-3. Temperature Bias (K) for June and July 2006 MM5 in the 4 km **Domain.**

Region	June '06	July '06	Mean
ALL	-0.42	0.01	-0.20

Table 3-4. Temperature Error (K) for June and July 2006 MM5 by Month and by State and Region in the 36 km Domain.

Region	June '06	July '06	Mean
AL	1.49	1.51	1.50
ALL	1.53	1.54	1.53
AR	1.21	1.30	1.25
AZ	2.11	2.14	2.13
CA	2.94	3.16	3.05
CENRAP	1.29	1.27	1.28
CO	2.79	2.54	2.66
CT	1.19	1.20	1.20
DE	0.85	0.83	0.84
FL	1.55	1.42	1.48
GA	1.35	1.34	1.35
IA	1.26	1.19	1.23
ID	1.90	2.39	2.14
IL	1.20	1.19	1.20
IN	1.12	0.99	1.06
KS	1.20	1.14	1.17
KY	1.09	0.99	1.04
LA	1.65	1.45	1.55
MA	1.19	1.12	1.15
MANE_VU	1.22	1.23	1.23
MD	1.28	1.30	1.29
ME	1.07	1.12	1.10
MI	1.50	1.41	1.45
MN	1.35	1.40	1.38
MO	1.14	1.12	1.13
MS	1.31	1.21	1.26
MT	1.72	2.13	1.93
MW	1.34	1.30	1.32
NC	1.30	1.23	1.26
ND	1.21	1.39	1.30
NE	1.30	1.29	1.29
NH	1.74	1.92	1.83
NJ	1.14	1.14	1.14
NM	1.93	1.73	1.83
NV	2.32	2.55	2.43
NY	1.28	1.27	1.27

Region	June '06	July '06	Mean
OH	1.17	1.14	1.15
OK	1.27	1.30	1.28
OR	1.96	2.19	2.08
PA	1.12	1.08	1.10
RI	1.20	1.28	1.24
SC	1.11	1.04	1.08
SD	1.47	1.54	1.50
TN	1.25	1.30	1.27
TX	1.23	1.18	1.20
UT	2.22	2.43	2.33
VA	1.31	1.23	1.27
VISTAS	1.35	1.29	1.32
VT	1.31	1.36	1.34
WA	1.60	1.81	1.70
WI	1.45	1.49	1.47
WRAP	2.23	2.37	2.30
WV	1.35	1.28	1.32
WY	2.38	2.55	2.47

Table 3-5. Temperature Error (K) for June and July 2006 MM5 by Month and by State in the 12 km Domain.

Region	June '06	July '06	Mean
ALL	1.41	1.43	1.42
AZ	1.65	1.57	1.61
CO	2.19	1.92	2.06
ID	1.54	2.00	1.77
NM	1.69	1.48	1.59
NV	1.95	2.14	2.05
UT	1.86	1.93	1.89
WY	1.76	1.92	1.84

Table 3-6. Temperature Error (K) for June and July 2006 MM5.

Region	June '06	July '06	Mean
ALL	1.93	1.64	1.78

Table 3-7. Mixing Ratio Bias (g/kg) for June and July 2006 MM5 by Month and by State and Region in the 36 km Domain.

Region	June '06	July '06	Mean
AL	0.54	0.64	0.59
ALL	0.15	0.05	0.10
AR	-0.23	0.04	-0.09
AZ	1.06	0.26	0.66
CA	-0.01	-0.02	-0.01
CENRAP	0.07	0.18	0.13
CO	0.39	-0.94	-0.28
CT	0.23	-0.18	0.02
DE	0.13	-0.36	-0.12
FL	0.70	0.17	0.44
GA	0.38	0.25	0.31
IA	-0.31	-0.38	-0.34
ID	-0.76	-0.66	-0.71
IL	-0.24	-0.31	-0.28
IN	-0.40	-0.39	-0.39

Region	June '06	July '06	Mean
KS	0.24	0.25	0.25
KY	0.14	-0.42	-0.14
LA	0.63	0.57	0.60
MA	0.35	0.14	0.25
MANE_VU	0.38	0.02	0.20
MD	0.39	-0.13	0.13
ME	0.37	0.01	0.19
MI	-0.12	0.00	-0.06
MN	-0.36	0.01	-0.18
MO	-0.04	0.00	-0.02
MS	0.40	0.50	0.45
MT	-0.42	0.45	0.02
MW	-0.17	-0.11	-0.14
NC	0.50	0.04	0.27
ND	-0.05	0.40	0.17
NE	0.34	0.17	0.25
NH	0.44	0.03	0.23
NJ	0.41	-0.02	0.19
NM	1.32	0.04	0.68
NV	0.20	0.03	0.12
NY	0.33	0.06	0.20
OH	-0.05	-0.11	-0.08
OK	-0.40	0.03	-0.19
OR	-0.22	0.24	0.01
PA	0.52	0.07	0.29
RI	0.13	-0.01	0.06
SC	0.55	0.09	0.32
SD	0.47	0.61	0.54
TN	0.13	-0.13	0.00
TX	0.57	0.54	0.56
UT	-0.38	-0.18	-0.28
VA	0.10	-0.51	-0.20
VISTAS	0.43	0.05	0.24
VT	0.41	-0.10	0.16
WA	-0.34	0.09	-0.13
WI	-0.16	0.08	-0.04
WRAP	0.10	-0.01	0.05
WV	0.48	-0.16	0.16
WY	-0.13	0.18	0.03

Table 3-8. Mixing Ratio Bias (g/kg) for June and July 2006 MM5 by Month and by State and Region in the 12 km Domain.

Region	June '06	July '06	Mean
ALL	0.11	0.06	0.09
AZ	1.01	0.15	0.58
CO	0.53	-0.93	-0.20
ID	-0.54	-0.43	-0.49
NM	1.37	0.02	0.69
NV	0.18	0.00	0.09
UT	-0.36	-0.27	-0.31
WY	0.01	0.31	0.16

Table 3-9. Mixing Ratio Bias (g/kg) for June and July 2006.

Region	June '06	July '06	Mean
ALL	0.81	-0.45	0.18

Table 3-10. Mixing Ratio Error (g/kg) for June and July 2006 MM5 by Month and by State and Region in the 36 km Domain**.**

Region	June '06	July '06	Mean
AL	1.52	1.55	1.53
ALL	1.25	1.41	1.33
AR	1.28	1.62	1.45
AZ	1.54	1.74	1.64
CA	1.09	1.34	1.22
CENRAP	1.37	1.50	1.43
CO	1.40	1.77	1.59
CT	0.91	1.24	1.08
DE	0.97	1.47	1.22
FL	1.52	1.36	1.44
GA	1.65	1.77	1.71
IA	1.31	1.61	1.46
ID	1.31	1.49	1.40
IL	1.20	1.50	1.35
IN	1.28	1.34	1.31
KS	1.36	1.46	1.41
KY	1.25	1.44	1.35
LA	1.59	1.50	1.55
MA	0.85	1.10	0.98
MANE_VU	0.95	1.20	1.08
MD	1.01	1.39	1.20
ME	0.90	0.99	0.94
MI	0.96	1.13	1.04
MN	1.16	1.38	1.27
MO	1.16	1.29	1.22
MS	1.56	1.58	1.57
MT	1.12	1.30	1.21
MW	1.08	1.29	1.18
NC	1.36	1.53	1.44
ND	1.12	1.38	1.25
NE	1.35	1.35	1.35
NH	0.94	1.08	1.01
NJ	1.08	1.44	1.26
NM	1.99	1.66	1.83
NV	1.01	1.42	1.21
NY	0.90	1.13	1.01
OH	1.08	1.22	1.15
OK	1.49	1.62	1.56
OR	0.93	1.13	1.03
PA	1.04	1.30	1.17
RI	0.93	1.22	1.08
SC	1.40	1.37	1.38
SD	1.18	1.36	1.27
TN	1.26	1.36	1.31
TX	1.53	1.58	1.56
UT	1.31	1.55	1.43
VA	1.18	1.66	1.42
VISTAS	1.40	1.51	1.45
VT	0.96	1.07	1.01

Region	June '06	July '06	Mean
WA	0.90	1.03	0.96
WI	1.02	1.28	1.15
WRAP	1.21	1.40	1.31
WV	1.08	1.20	1.14
WY	1.20	1.27	1.24

Table 3-11. Mixing Ratio Error (g/kg) for June and July 2006 MM5 by Month and by State and Region in the 12 km Domain.

Region	June '06	July '06	Mean
ALL	1.42	1.61	1.51
AZ	1.59	1.90	1.75
CO	1.55	1.85	1.70
ID	1.29	1.51	1.40
NM	2.13	1.85	1.99
NV	1.06	1.60	1.33
UT	1.40	1.73	1.57
WY	1.30	1.41	1.36

Table 3-12. Mixing Ratio Error (g/kg) for June and July 2006.

Region	June '06	July '06	Mean
ALL	1.60	1.68	1.64

Table 3-13. Wind Index of Agreement for June and July 2006 MM5 by Month and by State and Region in the 36 km Domain.

Region	June '06	July '06	Mean
AL	0.72	0.73	0.73
ALL	0.90	0.88	0.89
AR	0.70	0.70	0.70
AZ	0.75	0.75	0.75
CA	0.80	0.78	0.79
CENRAP	0.87	0.87	0.87
CO	0.80	0.80	0.80
CT	0.56	0.57	0.56
DE	0.50	0.52	0.51
FL	0.79	0.79	0.79
GA	0.68	0.69	0.69
IA	0.74	0.71	0.73
ID	0.79	0.78	0.78
IL	0.72	0.74	0.73
IN	0.65	0.68	0.66
KS	0.78	0.76	0.77
KY	0.65	0.62	0.63
LA	0.67	0.68	0.68
MA	0.71	0.69	0.70
MANE_VU	0.76	0.74	0.75
MD	0.67	0.63	0.65
ME	0.66	0.63	0.64
MI	0.69	0.70	0.69
MN	0.79	0.81	0.80
MO	0.75	0.73	0.74
MS	0.69	0.71	0.70
MT	0.81	0.81	0.81
MW	0.77	0.78	0.77

Region	June '06	July '06	Mean
NC	0.69	0.66	0.68
ND	0.78	0.81	0.79
NE	0.81	0.81	0.81
NH	0.46	0.43	0.44
NJ	0.64	0.61	0.63
NM	0.79	0.79	0.79
NV	0.80	0.75	0.77
NY	0.76	0.76	0.76
OH	0.69	0.69	0.69
OK	0.75	0.71	0.73
OR	0.76	0.78	0.77
PA	0.69	0.68	0.69
RI	0.77	0.75	0.76
SC	0.72	0.72	0.72
SD	0.82	0.83	0.82
TN	0.66	0.64	0.65
TX	0.82	0.79	0.81
UT	0.78	0.74	0.76
VA	0.71	0.68	0.69
VISTAS	0.82	0.81	0.81
VT	0.56	0.55	0.56
WA	0.81	0.83	0.82
WI	0.67	0.67	0.67
WRAP	0.88	0.88	0.88
WV	0.61	0.58	0.60
WY	0.80	0.81	0.81

Table 3-14. Wind Index of Agreement for June and July 2006 MM5 by Month and by State and Region in the 12 km Domain.

Region	June '06	July '06	Mean
ALL	0.89	0.88	0.88
AZ	0.75	0.76	0.75
CO	0.81	0.82	0.81
ID	0.80	0.78	0.79
NM	0.78	0.80	0.79
NV	0.77	0.74	0.75
UT	0.75	0.74	0.75
WY	0.80	0.81	0.81

Table 3-15. Wind Index of Agreement for June and July 2006.

Region	June '06	July '06	Mean
ALL	0.83	0.84	0.83

Figure 3-1. Regional Planning Organization (RPO) Boundaries.

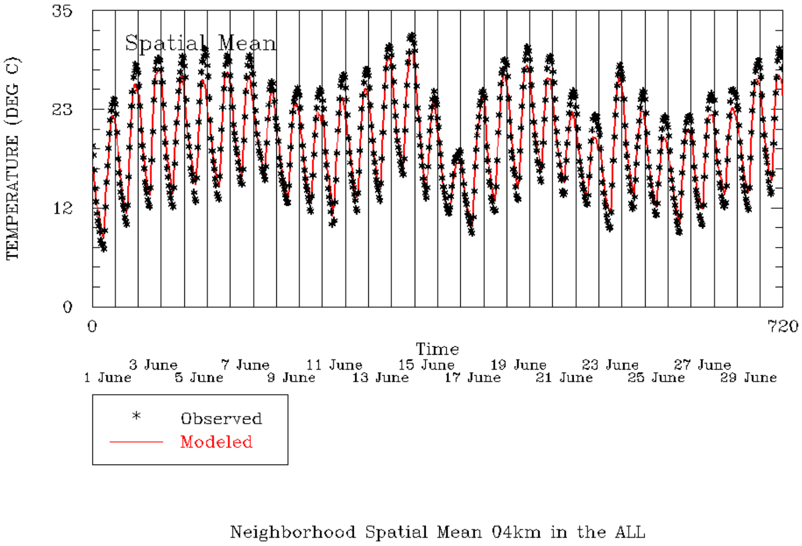

Figure 3-2: Spatial Mean Temperature (Deg. C) for June 2006 within the 4 km Domain.

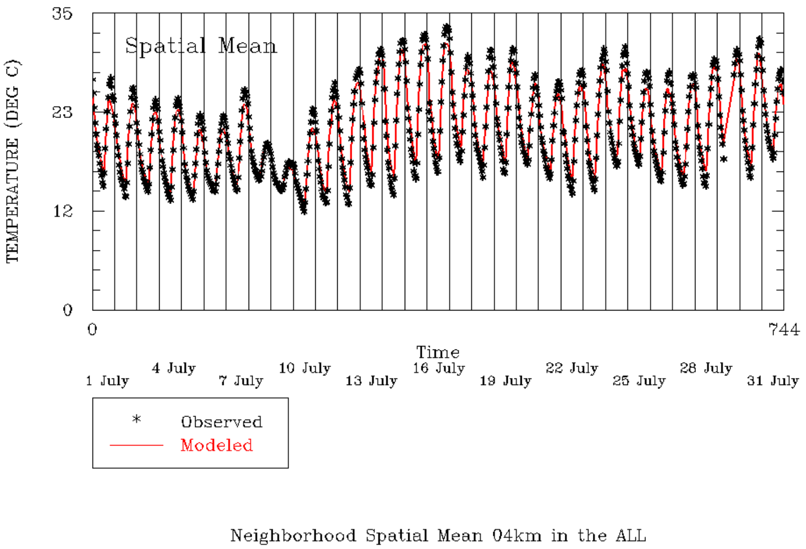

Figure 3-3. Spatial Mean Temperature (Deg. C) for July 2006 within the 4 km Domain**.**

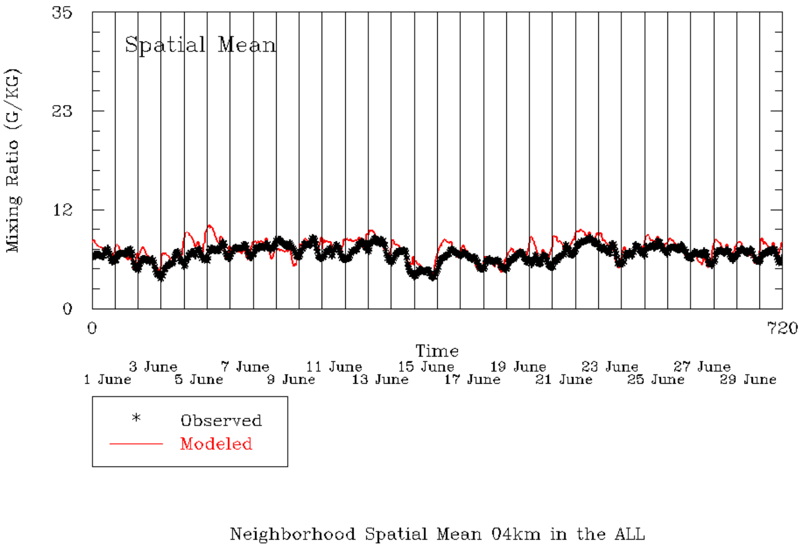

Figure 3-4. Spatial Mean Mixing Ratio (g/kg) for June 2006 within the 4 km Domain.

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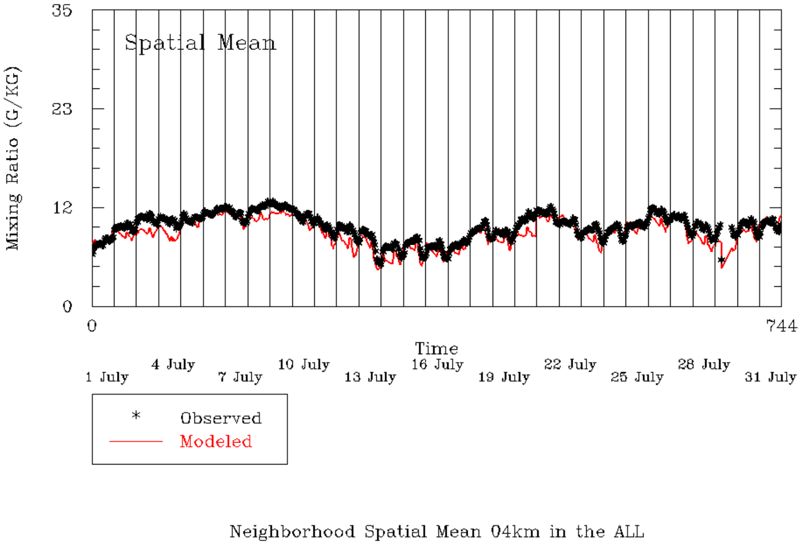

Figure 3-5. Spatial Mean Mixing Ratio (g/kg) for July 2006 within the 4 km Domain.

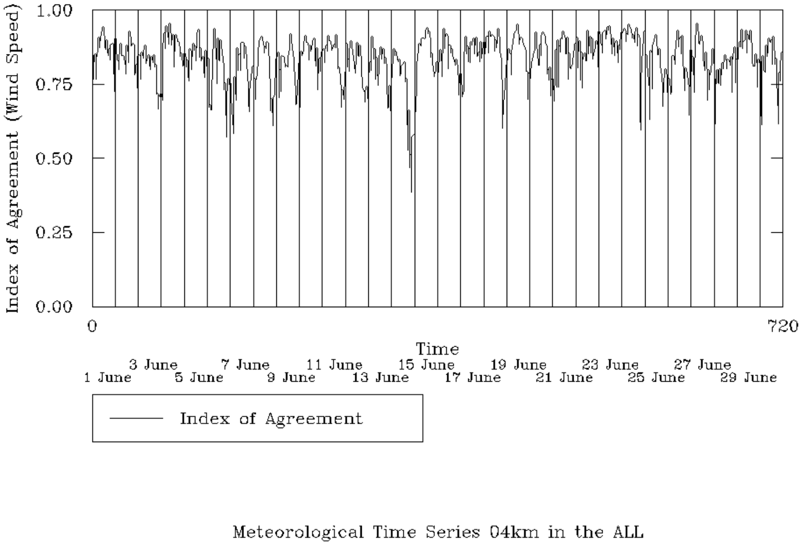

Figure 3-6. Spatial Mean Index of Agreement for June 2006 within the 4 km Domain.

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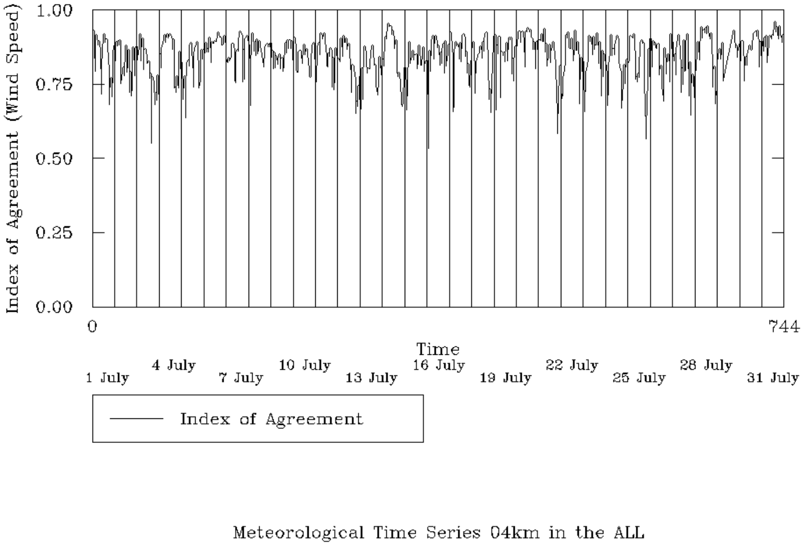

Figure 3-7. Spatial Mean Index of Agreement for July 2006 within the 4 km Domain

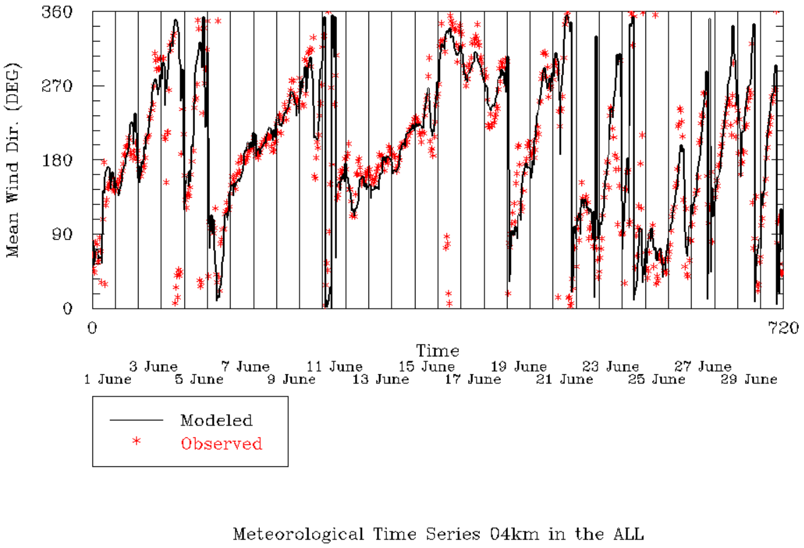

Figure 3-8. Spatial Mean Wind Direction (deg.) for June 2006 within the 4 km Domain.

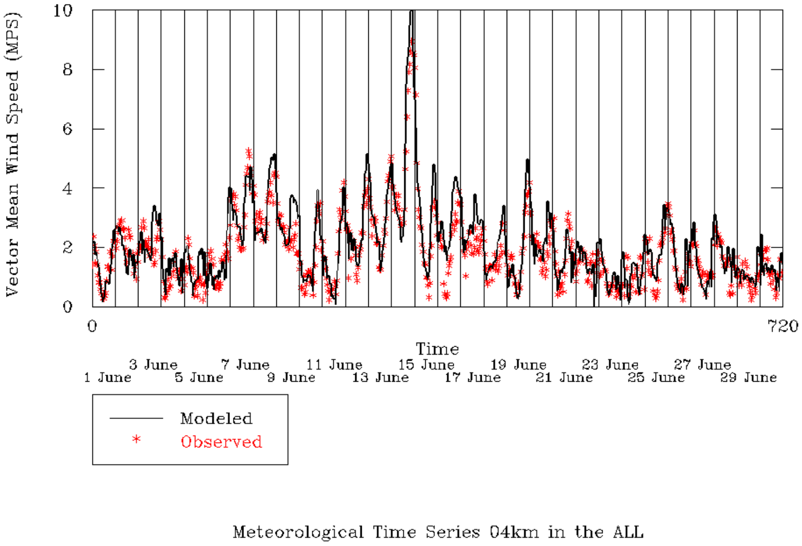

Figure 3-9. Vector Mean Wind Speed (m/s) for June 2006 within the 4 km Domain.

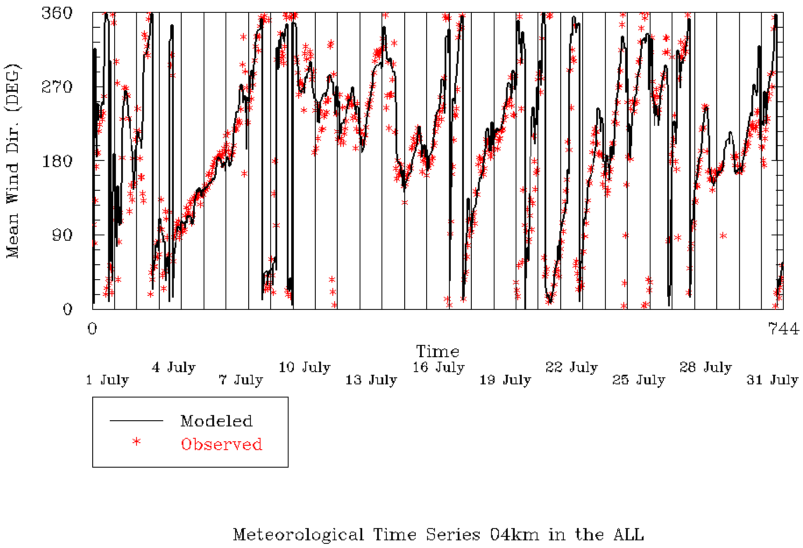

Figure 3-10. Spatial Mean Wind Direction (deg.) for July 2006 within the 4 km Domain.

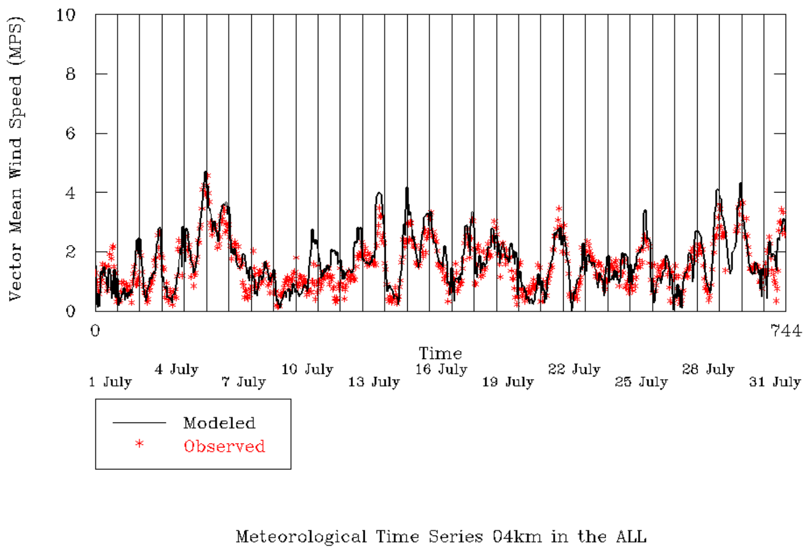

Figure 3-11. Vector Mean Wind Speed (m/s) for July 2006 within the 4 km Domain**.**

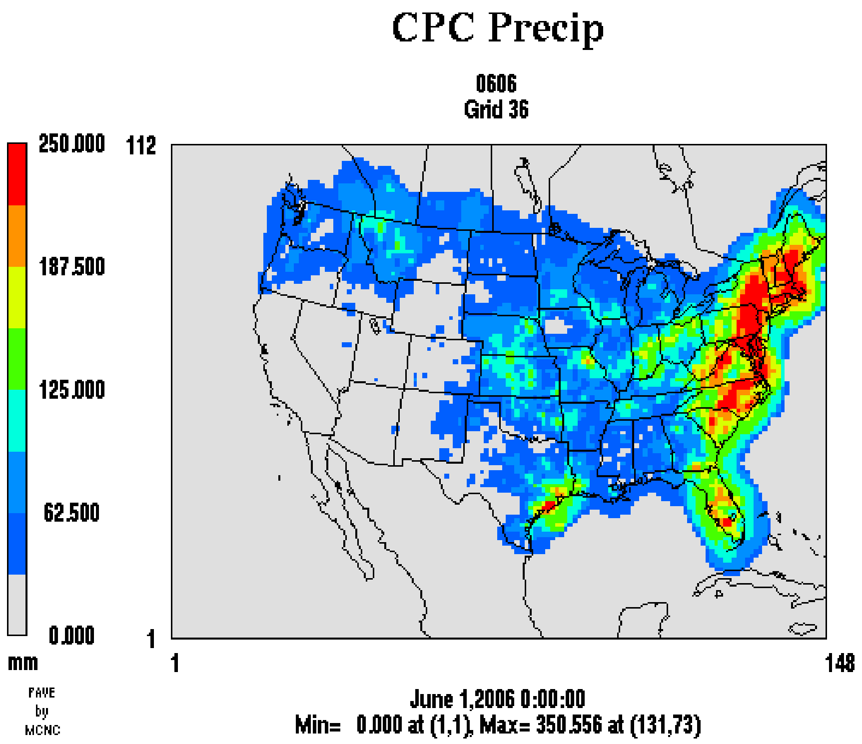

Figure 3-12. CPC Analyzed Precipitation for June 2006 over the 36 km Domain.

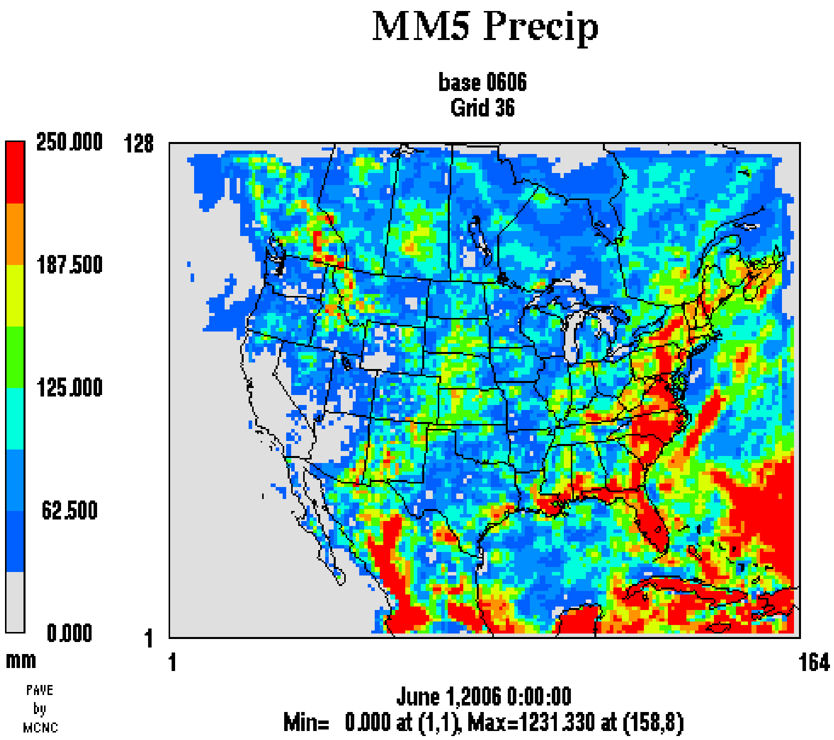

Figure 3-13. MM5 Estimated Precipitation for June 2006 over the 36 km Domain.

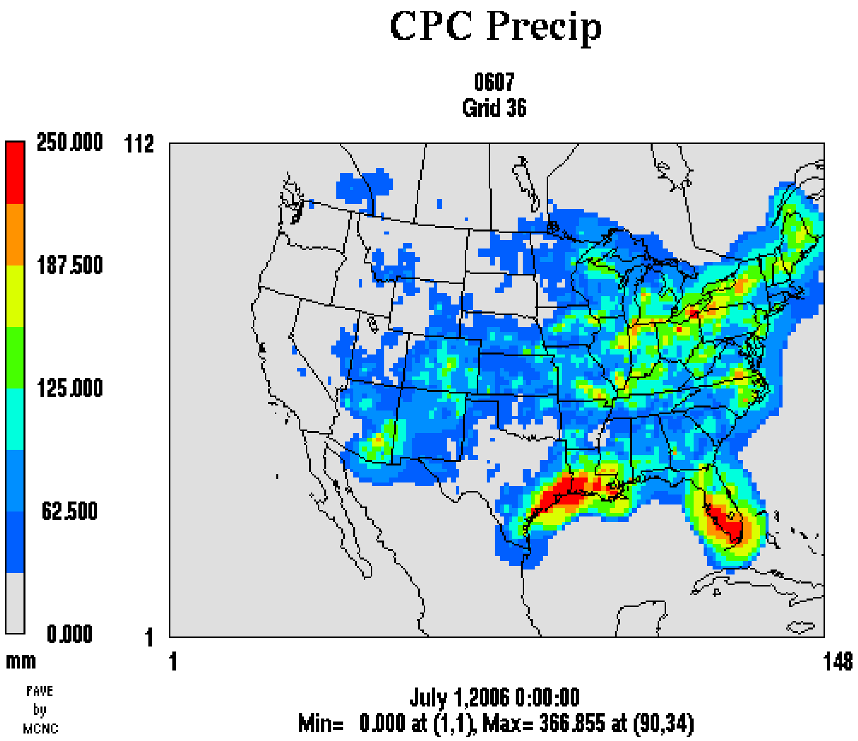

Figure 3-14. CPC Analyzed Precipitation for July 2006 over the 36 km Domain.

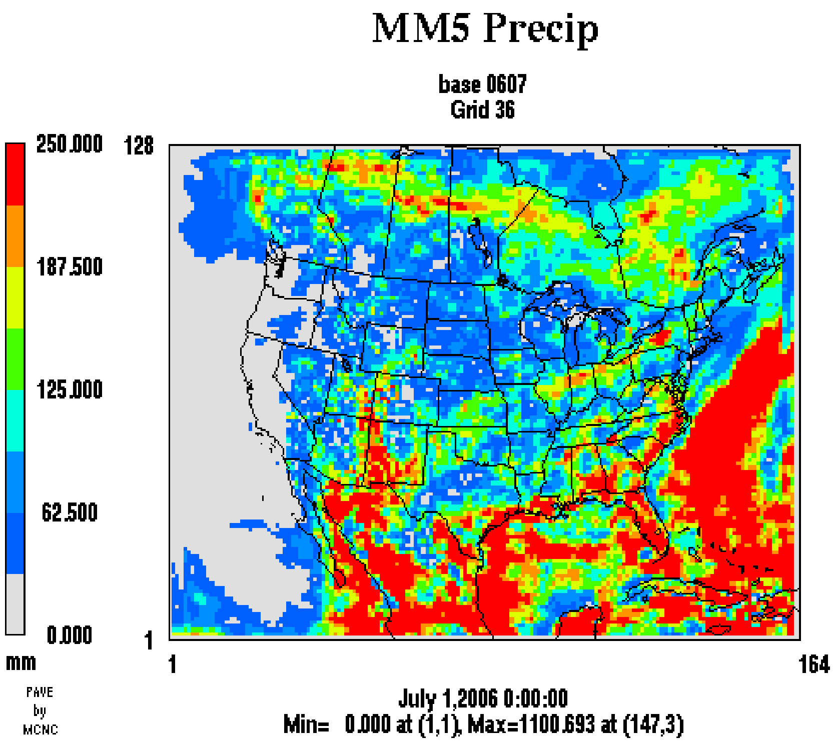

Figure 3-15. MM5 Estimated Precipitation for July 2006 over the 36 km Domain.

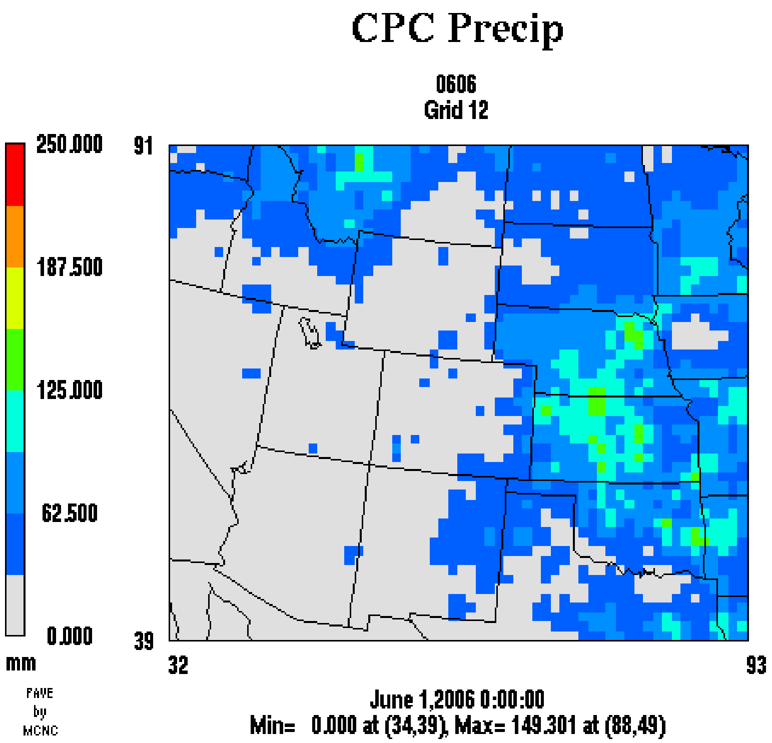

Figure 3-16. CPC Analyzed Precipitation for June 2006 over the 12 km Domain.

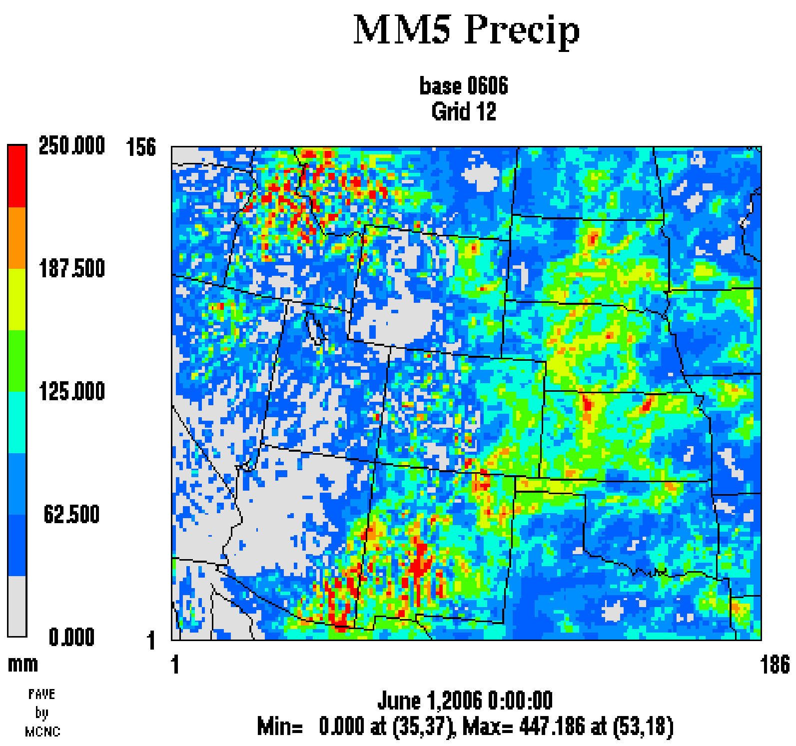

Figure 3-17. MM5 Estimated Precipitation for June 2006 over the 12 km Domain.

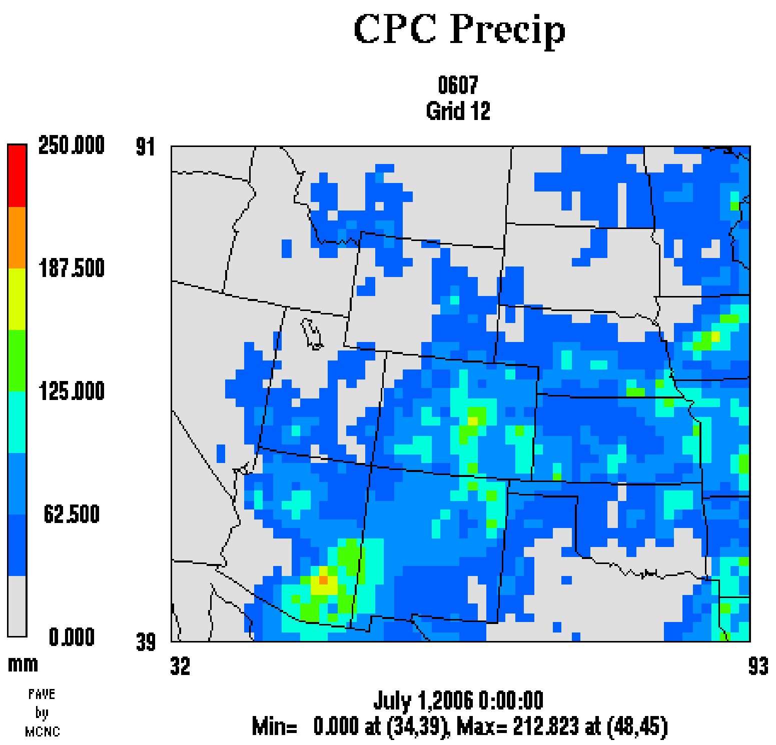

Figure 3-18. CPC Analyzed Precipitation for July 2006 over the 12 km Domain.

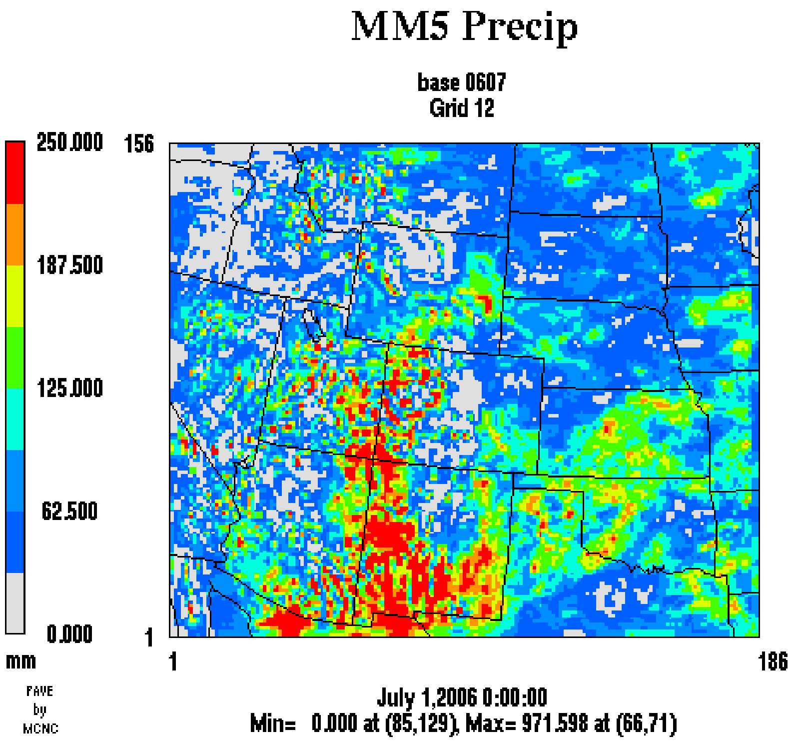

Figure 3-19. MM5 Estimated Precipitation for July 2006 over the 12 km Domain.

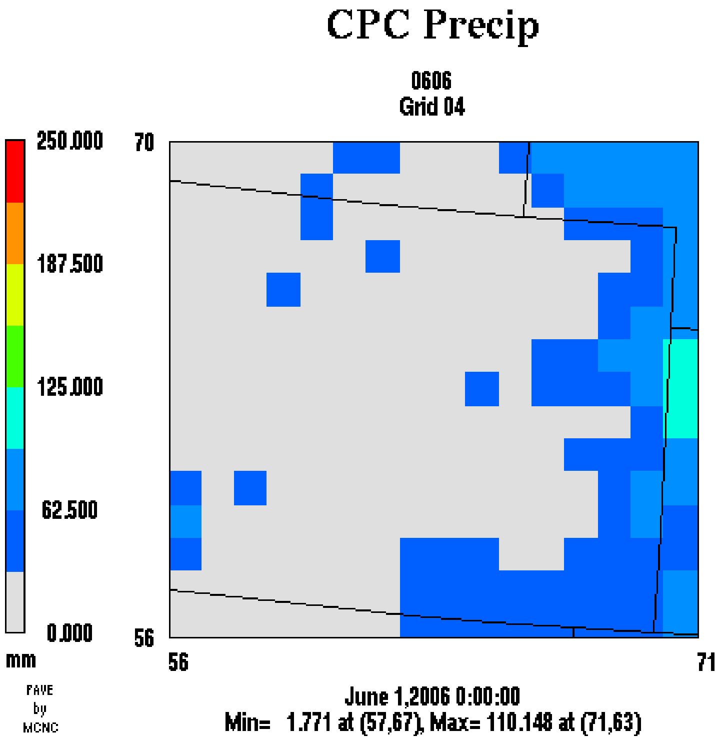

Figure 3-20. CPC Analyzed Precipitation for June 2006 over the 4 km Domain.

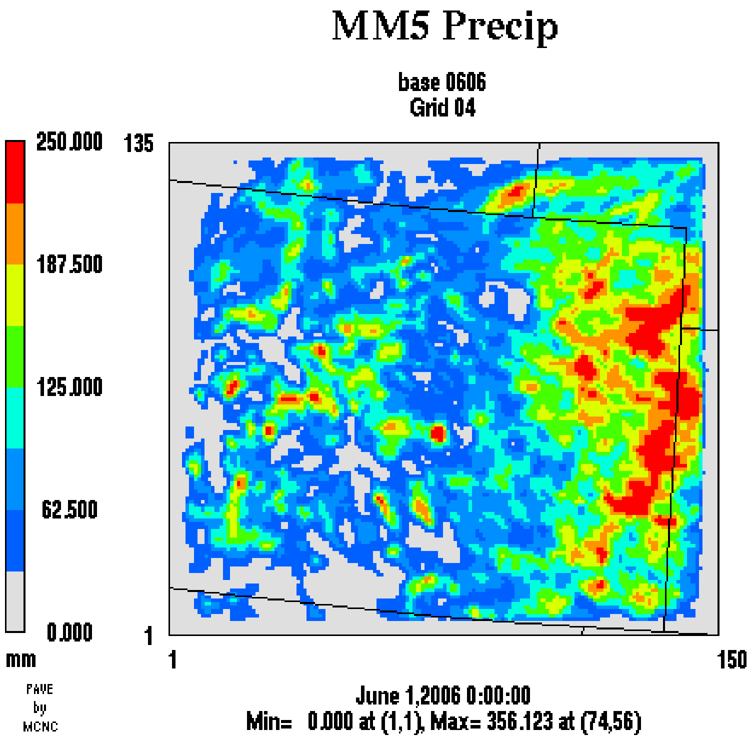

Figure 3-21. MM5 Estimated Precipitation for June 2006 over the 4 km Domain.

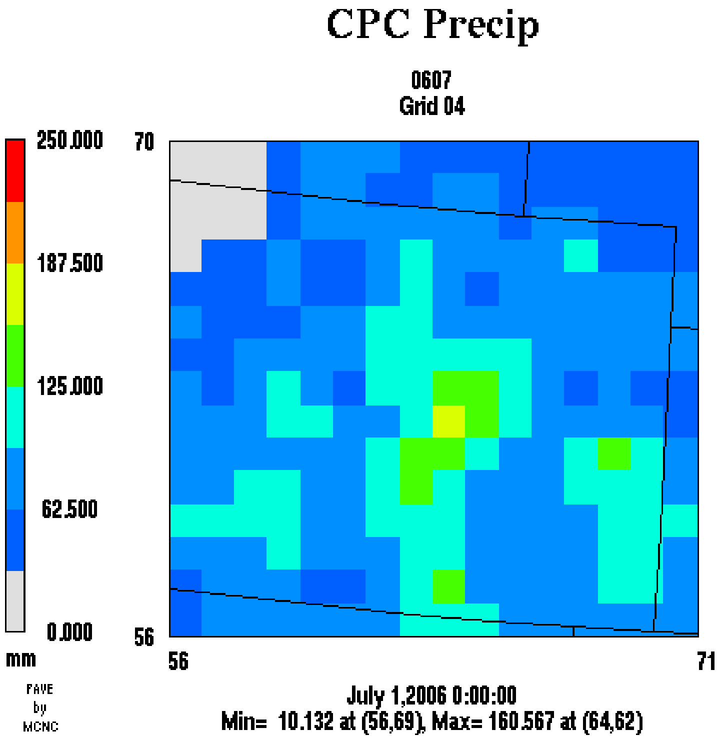

Figure 3-22. CPC Analyzed Precipitation for July 2006 over the 4 km Domain.

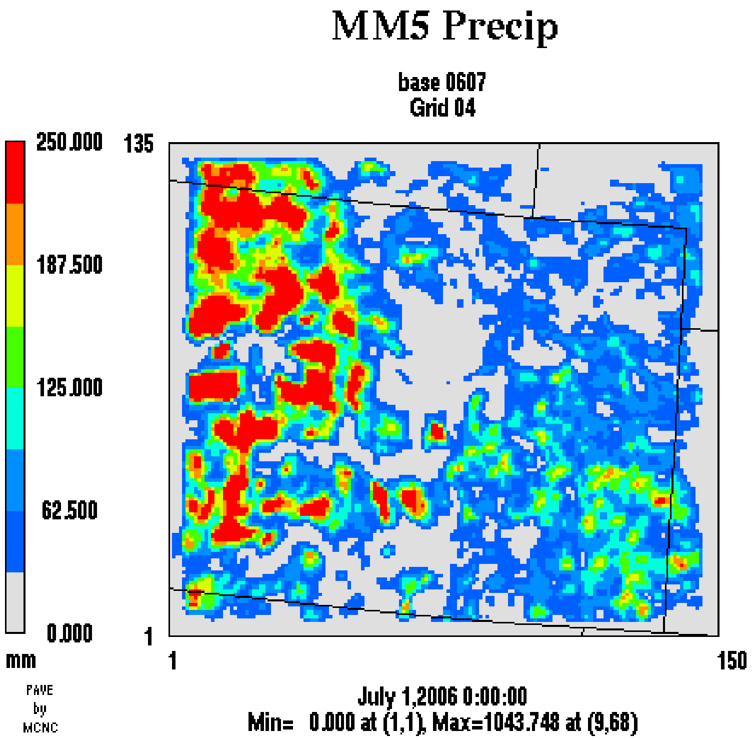

Figure 3-23. MM5 Estimated Precipitation for July 2006 over the 4 km Domain.

4 Upper-Air Meteorological Analysis

To compare the performance of the model aloft, radiosonde comparison plots were prepared using the “Raobplot” program developed by Matthew Johnson of the Iowa DNR. Radiosonde data were selected from the Denver upper air site. Radiosonde plots were prepared for each day during June and July of 2006 (when Denver experienced its worst ozone episodes). For presentation and specific comparison purposes, plots are presented herein in a time step of 36 hours during the episodic period of July 20-30, 2006 starting with 00Z on July 21, 2006. Thus, there are four 00Z soundings on July 20, 23, 26, and 29 and four 12Z soundings on July 21, 24, 27, and 30. No regard to synoptic-scale weather patterns was considered in interpreting these comparisons.

Figures 4-1 through 4-8 present the Skew T- log p soundings from observations (dark line) and MM5 simulations (red line) for every 36 hours during the episodic period of July 20-30, 2006. Thus, the first figure, Figure 4-1 represents the sounding taken at 00Z on July 20 in Denver (which translates to 1700 hours or 5:00 PM local time disregarding daylight savings time on July 19). As can be seen, both the temperature and moisture profiles match reasonably well with the greatest disparities at the lower levels and at the 200mb height. Comparisons are best above the 550-600 mb height away from influences of the earth’s surface. The magnitude of the winds is in reasonable agreement throughout the soundings but the wind directions agree best above about 400mb. Surface wind directions in the first 850 to 600mb levels are more north northeasterly from the MM5 sounding than the northwesterly observations.

Figure 4-2 presents a morning sounding for Denver, that is, the 12Z sounding (0500 or 5:00 AM local time) on July 21. As can be seen both the temperature and moisture soundings overall are reproduced well by the MM5 simulations. The MM5 lower level temperature sounding does not account for the depth of the inversion layer as well as the observations and underestimates the amount of moisture at the surface layers. Winds throughout the sounding generally agree very well both in magnitude and direction.

Figure 4-3 represents the sounding taken at 00Z (1700 hours or 5:00 PM local time) on July 23 in Denver. As can be seen, both the temperature and moisture profiles match reasonably well with very little disagreement. The observed moisture profile tends to have more variation than the MM5 sounding and is lower in the upper atmosphere. The magnitude of the winds is in reasonable agreement throughout the soundings as are the wind directions except in the 700-500mb level where MM5 data are more north northeasterly than the north northwesterly observations.

Figure 4-4 presents a morning sounding for Denver, that is, the 12Z sounding (0500 or 5:00 AM local time) on July 24. As can be seen both the temperature and moisture soundings overall are reproduced well by the MM5 simulations. The MM5 lower level temperature sounding creates a more significant temperature inversion layer than the observations but matches the observations quite well above that. MM5 data are slightly less than the observations for moisture at the surface. Winds throughout the sounding generally agree very well both in magnitude and direction except for the surface where the MM5 wind directions from the northwest vary from the observed west directions.

Figure 4-5 represents the sounding taken at 00Z (1700 hours or 5:00 PM local time) on July 26 in Denver. As can be seen, both the temperature and moisture profiles match reasonably well with very little disagreement. The observed moisture profile tends to have more variation than the MM5 sounding and is lower in the upper atmosphere. The MM5 temperature sounding misses the shallow inversion layer detected in the observations. The magnitude of the winds is in reasonable agreement throughout the soundings as are the wind directions except in the 750-700mb level where the observations are from the east southeast and the MM5 winds are more north northwesterly.

Figure 4-6 presents a morning sounding for Denver, that is, the 12Z sounding (0500 or 5:00 AM local time) on July 27. As can be seen both the temperature sounding overall is reproduced well by the MM5 simulations. The MM5 moisture sounding tends to underpredict the moisture throughout most of the sounding. The MM5 lower level temperature sounding creates a stronger temperature inversion layer than the observations but matches the observations quite well above that. Winds throughout the sounding generally agree very well both in magnitude and direction with a few exceptions at selected sounding levels (~610 and 350mb).

Figure 4-7 represents the sounding taken at 00Z (1700 hours or 5:00 PM local time) on July 29 in Denver. As can be seen, both the temperature and moisture profiles match reasonably well with very little disagreement. Both the observed and MM5 moisture profiles have variation throughout the sounding with them alternating as to which one is higher and lower. The MM5 temperature sounding misses the shallow superadiabatic condition at the surface but matches the remainder of the sounding very well. The magnitude of the winds is in reasonable agreement throughout the soundings as are the wind directions except in the surface to 700mb level where the observations are from the southeast and the MM5 winds are from the south and south southeast.

Figure 4-8 presents a morning sounding for Denver, that is, the 12Z sounding (0500 or 5:00 AM local time) on July 30. As can be seen both the temperature sounding overall is reproduced well by the MM5 simulations. Even the strong inversion layer at the surface is reproduced well by the MM5 data. Within this same layer, however, the MM5 moisture sounding is at odds with the observations up to where the inversion layer ceases. Much disparity between the MM5 and observed moisture data takes place from the surface up to about 500mb. Winds throughout the sounding generally agree very well both in magnitude and direction with the exception of the 400-300mb level where the observations are from the south at 400 mb and from the north at 300mb while the MM5 simulation generally has them from the west over this layer.

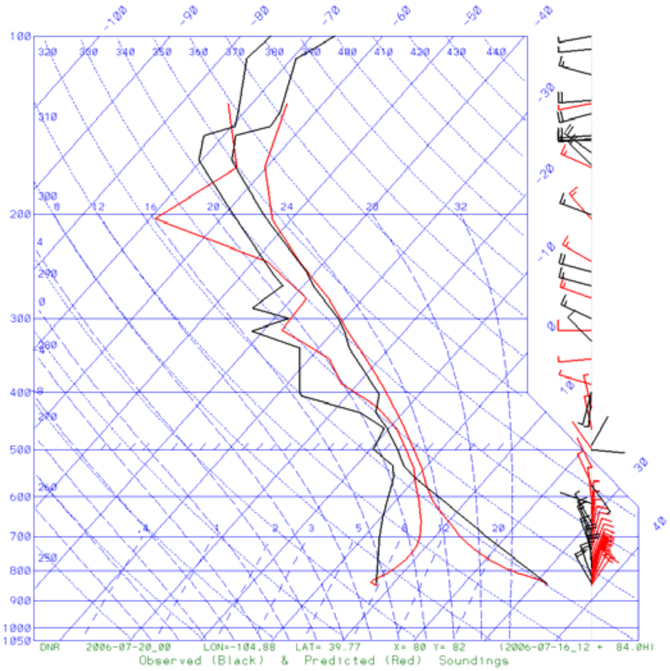

Figure 4-1. Radiosonde Sounding Comparison at Denver on 0Z 20 July 2006.

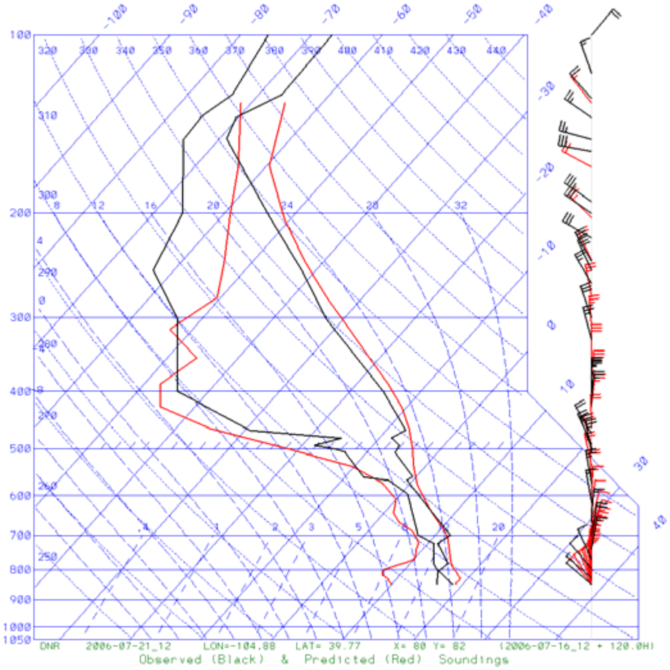

Figure 4-2. Radiosonde Sounding Comparison at Denver on 12Z 21 July 2006.

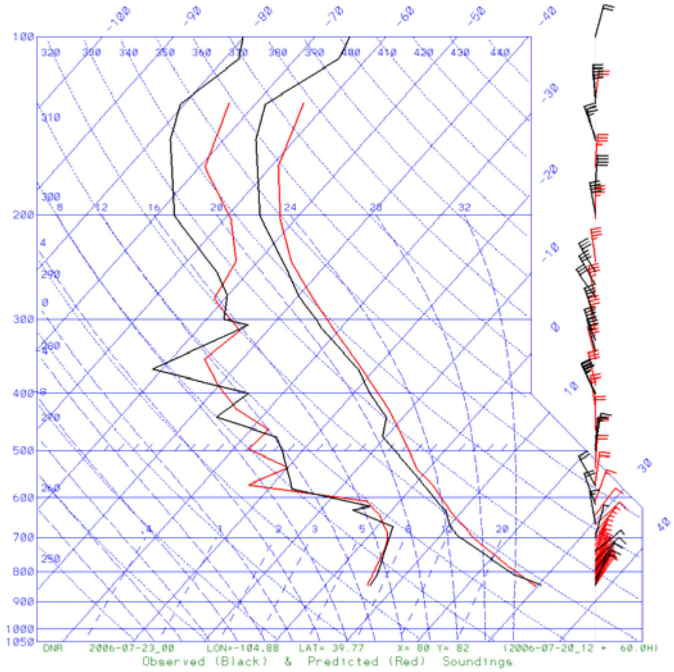

Figure 4-3. Radiosonde Sounding Comparison at Denver on 0Z 23 July 2006.

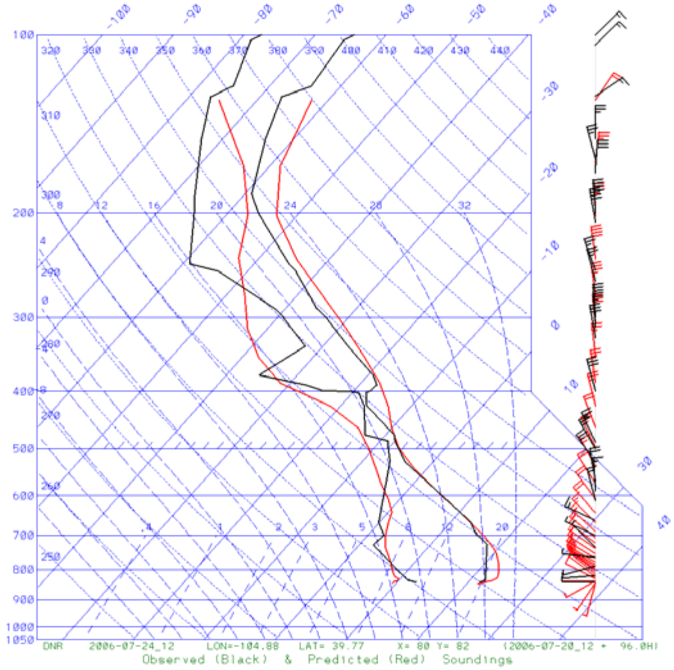

Figure 4-4. Radiosonde Sounding Comparison at Denver on 12Z 24 July 2006.

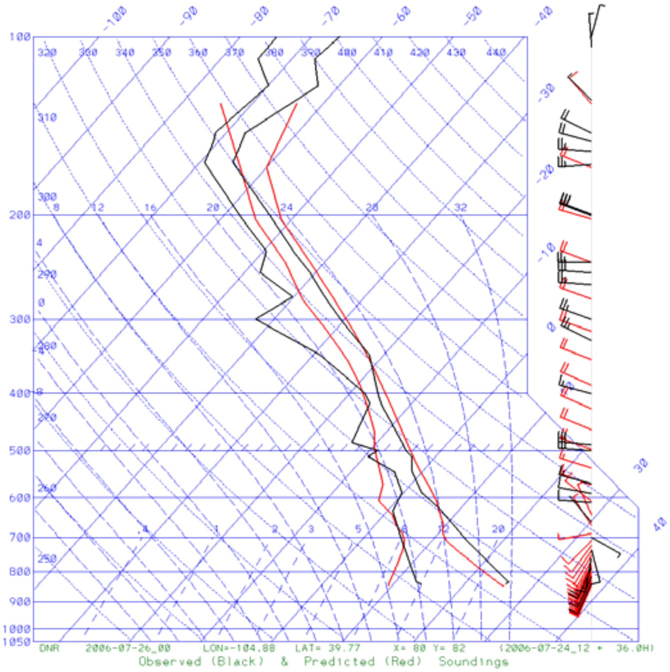

Figure 4-5. Radiosonde Sounding Comparison at Denver on 0Z 26 July 2006.

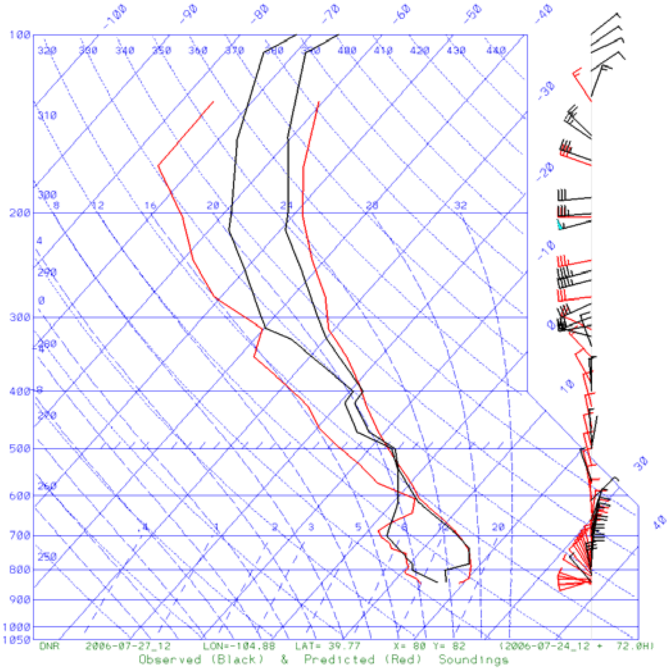

Figure 4-6. Radiosonde Sounding Comparison at Denver on 12Z 27 July 2006.

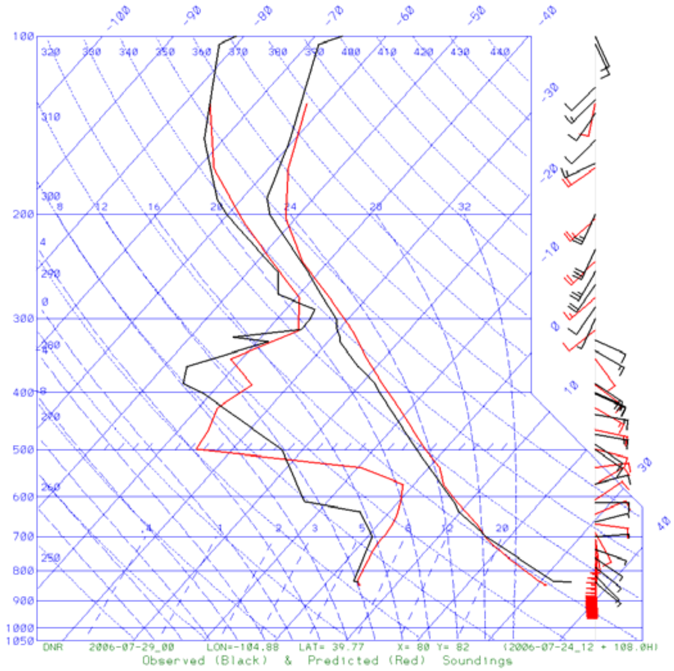

Figure 4-7. Radiosonde Sounding Comparison at Denver on 0Z 29 July 2006**.**

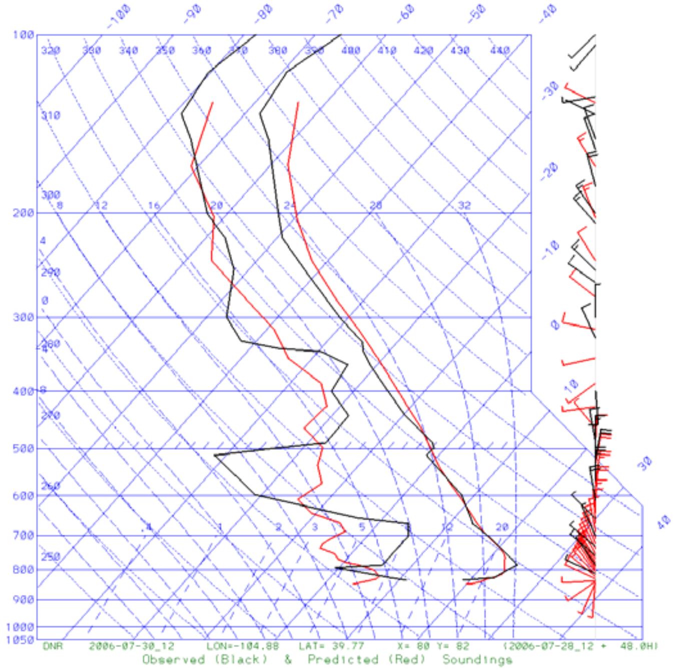

Figure 4-8. Radiosonde Sounding Comparison at Denver on 12Z 30 July 2006**.**

5 Comparison with Other MM5 Simulations

This section presents a comparison of this June-July 2006 4 km MM5 simulation with other 4 km annual meteorological simulations that have been completed recently by the ENVIRON/Alpine Team. Tables 5-1 through 5-5 present these comparisons on the basis of the temperature bias and error, the mixing ratio bias and error, and the wind index of agreement.

5.1 Comparison to Other 4 km Simulations

Comparisons between the RAQC June-July 2006 MM5 simulation for Colorado and other 4 km simulations were conducted. All available MM5 simulations over roughly the same domain at a 4 km grid resolution using the same vertical grid definitions as the 4 km grid simulations are compared. The three New Mexico Environment Department (NMED) MM5 simulations for 2003, 2004, and 2005 (McNally and Schewe, 2006 and Schewe and McNally, 2006) were generated for the use in modeling studies centered over the Four Corners area. The CDPHE 2003 (McNally and Schewe, 2007) simulation was conducted over a 4 km domain that was somewhat larger than the State of Colorado. Thus, the spatial coverage of the simulations were somewhat different. The CDPHE 2003 and the NMED 2003-2005 simulations were annual simulations, but for comparison, only June and July simulations were conducted and are presented in this report. The analysis of these simulations was performed using the Alpine Geophysics, MAPS analysis package (McNally and Tesche, 1994).

The same benchmarks as described in Section 3 were used in this comparison. Recall the purpose of these benchmarks was not to give a passing or failing grade to any one particular meteorological model application, but rather to put its results into the context of other models and meteorological data sets. The benchmarks include bias and error in temperature and mixing ratio as well the Wind Speed Index of Agreement (IA) between the models and data bases. As a reference the performance benchmarks are repeated here:

- Temperature bias: <±0.5 K
- Temperature error: <2.0 K
- Mixing ratio bias: <±1.0 g/kg
- Mixing ratio error: <2.0 g/kg
- Wind Speed Index of Agreement (IA): 0.0 = worst, 0.6=acceptable, 1.0 = best

Temperature bias for both this study and the three years of NMED data is presented in Table 5-1. This RAQC 2006 MM5 application was within the range of the temperature bias benchmark of <±0.5 K with a -0.21 K average over both months and individual month biases of -0.42 and 0.01. When comparing the RAQC 2006 performance to other study simulations, this RAQC 2006 simulation performed as well or better than the others both on a monthly basis as well as an average basis.

Temperature error is presented in Table 5-2. For this RAQC 2006 application of MM5 the temperature error of 1.79 K was within the guideline temperature error of 2.0 K. All other simulations were higher than the guideline range by a degree or more.

Mixing ratio bias over the 4 km simulation domain for the RAQC 2006 MM5 data set is presented in Table 5-3. The domain-wide bias for this RAQC 2006 MM5 simulation was 0.18 g/kg which is within the acceptability benchmark of ±1.0 g/kg. While this mean value of the RAQC 2006 data appears to be better than other simulations, closer review indicates this may be an artifact of the average of the June and July monthly values. The June mixing ratio bias was 0.81 and the July bias was -0.45. Both values are still within the benchmark. Performance by other simulations were similar and generally within the benchmark but were all on the positive side of the bias.

Mixing ratio error over the 4 km simulation domain is presented in Table 5-4 The domain-wide error for this RAQC 2006 MM5 simulation was 1.64 g/kg which is less than the benchmark of 2.0 g/kg. The mixing ratio bias was within the range of the acceptability benchmark for both months and compared well in both magnitude and variability to other data sets.

Wind speed index of agreement (IA) is presented in Table 5-5. The domain-wide IA for the RAQC 2006 simulation was 0.84 which is above the minimally guideline value of 0.6 and tending toward the best agreement level of 1.0. This RAQC 2006 data was comparable to all other data sets.

Table 5-1. Temperature Bias (K) For June and July 4 km MM5 Simulations.

Region	Jun	Jul	Mean
RAQC 2006	-0.42	0.01	-0.21
CDPHE 2003	0.73	-0.25	0.24
NMED 2003	0.49	-0.11	0.19
NMED 2004	0.87	0.97	0.92
NMED 2005	0.94	0.58	0.76

Table 5-2. Temperature Error (K) for June and July 4 km MM5 Simulations**.**

Region	Jun	Jul	Mean
RAQC 2006	1.93	1.64	1.79
CDPHE 2003	3.07	3.82	3.45
NMED 2003	3.36	3.70	3.53
NMED 2004	3.51	3.28	3.40
NMED 2005	3.51	3.71	3.61

Table 5-3. Mixing Ratio Bias (g/kg) for June and July 4 km MM5 Simulations**.**

Region	Jun	Jul	Mean
RAQC 2006	0.81	-0.45	0.18
CDPHE 2003	0.30	1.71	1.01
NMED 2003	0.51	1.24	0.88
NMED 2004	0.72	0.62	0.67
NMED 2005	0.52	1.37	0.95

Table 5-4. Mixing Ratio Error (g/kg) for June and July 4 km MM5 Simulations.

Region	Jun	Jul	Mean
RAQC 2006	1.60	1.68	1.64
CDPHE 2003	1.36	2.25	1.81
NMED 2003	1.37	1.88	1.63
NMED 2004	1.50	1.73	1.62
NMED 2005	1.49	1.91	1.70

Table 5-5. Wind Index of Agreement for June and July 4 km MM5 Simulation.

Region	Jun	Jul	Mean
RAQC 2006	0.83	0.84	0.84
CDPHE 2003	0.83	0.83	0.83
NMED 2003	0.80	0.80	0.80
NMED 2004	0.81	0.81	0.81
NMED 2005	0.80	0.80	0.80

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