MM5 Performance Evaluation and Quality Assurance Review for the White River Field Office Ozone Assessment

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Acronyms

ADP	Automated Data Processing
ASOS	Automated Surface Observing System
BLM	Bureau of Land Management
CAMx	Comprehensive Air Quality Model with Extensions
CDPHE	Colorado Department of Public Health and Environment
CPC	Climate Prediction Center
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FDDA	Four-dimensional data assimilation
g	Gram
IOA	Index of Agreement
K	Kelvin
kg	Kilogram
km	Kilometer
LADCO	Lake Michigan Air Directors Consortium
mb	Millibar
m/s	Meters Per Second
MCIP	Meteorology-Chemistry Interface Processor
MM5	NCAR / Penn State Mesoscale Model Fifth Generation
NCEP	National Centers for Environmental Protection
NPS-ARD	National Park Service Air Resources Division
PBL	Planetary Boundary Layer
QA	Quality Assurance
RMPA	Resource Management Plan Amendment
RMSE	Root Mean Squared Error
RoMANS	Rocky Mountain Atmospheric Nitrogen and Sulfur Study
RRTM	Rapid Radiative Transfer Model
TDL	Techniques Data Laboratory
URS	URS Corporation
USGS	United States Geological Survey
UTC	Coordinated Universal Time
WRFO	White River Field Office

1.0 Introduction

The White River Field Office (WRFO) of the Colorado Bureau of Land Management (BLM) is currently preparing a Resource Management Plan Amendment and Environmental Impact Statement (RMPA and EIS). As part of the RMPA and EIS, the BLM will conduct an analysis of ozone impacts that may be expected from proposed oil and gas development in the area. The ozone assessment will be conducted using the Comprehensive Air Quality Model with Extensions (CAMx), a three-dimensional Eulerian photochemical grid model. The CAMx model must be supplied with high-resolution meteorological data fields for the modeling period in question. For this purpose, the BLM will utilize meteorological data prepared by the National Park Service Air Resources Division (NPS-ARD) for the year 2006.

The NPS-ARD has partnered with several Federal and university groups to create the Rocky Mountain Atmospheric Nitrogen and Sulfur Study (RoMANS). The purpose of the RoMANS study is to further the understanding of the origins of nitrogen and sulfur emissions that are currently affecting visibility and ecosystems in the Rocky Mountain region of Colorado (NPS-ARD and CDPHE, 2006). The NPS-ARD chose the Fifth Generation Penn State University/National Center for Atmospheric Research Mesoscale Model (MM5) version 3.7 to create the annual meteorological data fields in support of the RoMANS study. The BLM will utilize these same MM5 data fields for the WRFO RMPA and EIS ozone impact assessment. In order to verify that the MM5 data are of sufficient quality to be used for this purpose, URS Corporation (URS) has conducted a performance evaluation and quality assurance (QA) review (analysis) of the MM5 data generated by NPS-ARD. The results of the 4km analysis are presented in this document.

2.0 Modeling System

The MM5 modeling system is the latest in a series that developed from a mesoscale model used by Anthes at Penn State in the early 1970s that was later documented by Anthes and Warner (1978). Since that time, it has undergone many changes designed to broaden its usage. These include (i) a multiple-nest capability, (ii) nonhydrostatic dynamics, (iii) multitasking capability on shared- and distributed-memory machines, (iv) a four-dimensional data-assimilation capability, and (v) more physics options.

This section reviews the configuration that NPS-ARD used for the MM5 model runs. The following section provides a brief QA review of the run scripts provided by NPS-ARD.

2.1 Configuration

The input data, physics options, and model configuration that the NPS-ARD used for the meteorological modeling are summarized in the following sections.

2.1.1 Terrain

Terrestrial data are horizontally interpolated from U.S. Geological Survey (USGS) data to the MM5 grid using the TERRAIN program. The data that are available as input to TERRAIN includes terrain elevation, landuse/vegetation, land-water mask, soil types, vegetation fraction, and soil moisture. The NPS-ARD used 10-minute data (approximately 19km) for the 36km domain and 2-minute data (approximately 4km) for the 12km and 4km domains. Figure 2.1 shows the three domains used in the modeling.

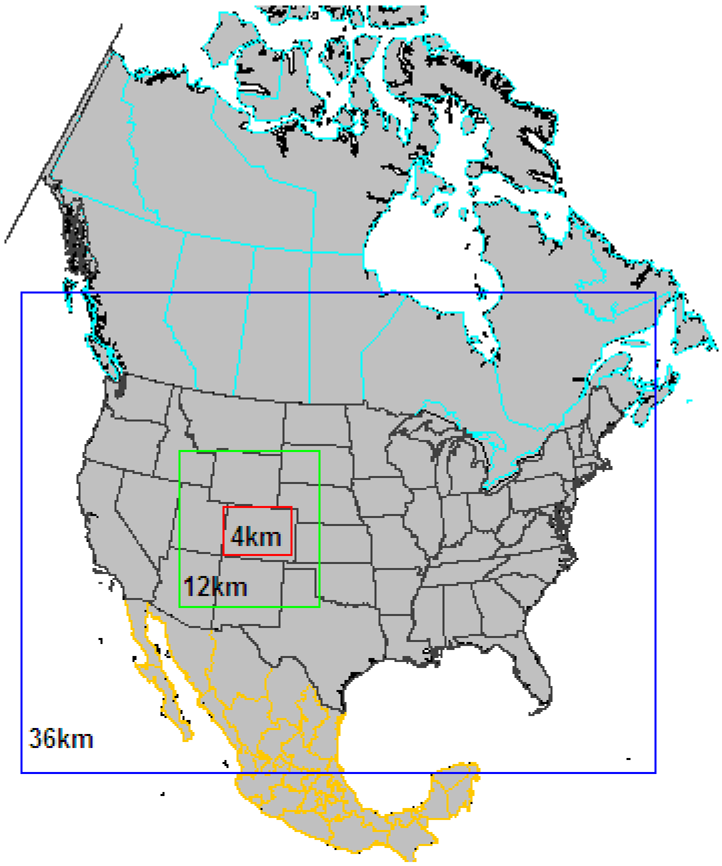


Figure 2.1. Modeling domains used in the RoMANS study.

2.1.2 PREGRID/REGRIDDER

Gridded meteorological data is input and interpolated to the horizontal grid defined by the TERRAIN program. The NPS-ARD used the North American Regional Reanalysis dataset to initialize the model. The analysis data provide the following data; air temperature, humidity, sea level pressure, surface winds, upper level winds, vertical wind motion, vorticity, and sea surface temperature.

2.1.3 little_r

Objective analysis was performed by the little_r program. The NPS-ARD used the National Centers for Environmental Protection (NCEP) Automated Data Processing (ADP) Global Surface Observations and the NCEP ADP Global Upper Air Observations datasets to perform the objective analysis. These data provide air temperature, cloud amount, and frequency, dew point temperature, precipitation amount, station height, surface pressure, surface winds, visibility, atmospheric pressure measurements, tropopause height, and upper level winds. These data were incorporated into the meteorological analysis output from REGRID.

2.1.4 INTERPF

The INTERPF program takes the outputs from REGRID and little_r and interpolates the data from pressure coordinates to the sigma levels of the MM5 domain. Outputs from this program include a model initial condition file, lateral boundary condition file, and a lower boundary condition file. Table 2.1 provides details on the vertical structure of the meteorology data.

Table 2.1. Vertical Structure for MM5 Modeling.

Layer	Sigma	Pressure (mb)	Height (m)	Layer Thickness (m)
35	0.000	100	14662	1841
34	0.050	145	12822	1466
33	0.100	190	11356	1228
32	0.150	235	10127	1062
31	0.200	280	9066	939
30	0.250	325	8127	843
29	0.300	370	7284	767
28	0.350	415	6517	704
27	0.400	460	5812	652
26	0.450	505	5160	607
25	0.500	550	4553	569
24	0.550	595	3984	536
23	0.600	640	3448	506
22	0.650	685	2942	367
21	0.700	730	2462	367
20	0.740	766	2095	266
19	0.770	793	1828	259
18	0.800	820	1569	169
17	0.820	838	1400	166
16	0.840	856	1235	163
15	0.860	874	1071	160
14	0.880	892	911	158
13	0.900	910	753	78
12	0.910	919	675	77
11	0.920	928	598	77
10	0.930	937	521	76
9	0.940	946	445	76
8	0.950	955	369	75
7	0.960	964	294	74
6	0.970	973	220	74
5	0.980	982	146	37
4	0.985	986.5	109	37
3	0.990	991	73	37
2	0.995	995.5	36	18
1	0.9975	997.75	18	18
0	1.000	1000	0	0

2.1.5 MM5

2.1.5.1 Physics Options

The physics options used by the NPS-ARD in the 4km MM5 simulations are summarized in Table 2.2.

Table 2.2. 4km MM5 Physics Options.

Option	Configuration
Cumulus Scheme	None
Microphysics	Reisner's mixed phase with graupel
Planetary Boundary Layer (PBL)	MRF
Land Surface Model	Pleim-Xiu
Radiation	Rapid Radiative Transfer Model (RRTM) long-wave
Four-Dimensional Data Array (FDDA)	None
Surface Analysis Nudging	None
Observational Nudging	Yes (for winds only)
Observational Nudging Coefficient	0.0004
Observational Nudging Radius of Influence	240 km

2.1.5.2 Multi-Scale FDDA

Since the MM5 model was applied retrospectively, four-dimensional data assimilation (FDDA) was used to blend model predictions and observational data to yield temporally and spatially complete datasets that are grounded by actual observations. Specifically, model predictions were blended with three-dimensional wind, temperature, and humidity analysis fields (as opposed to individual observations) generated on a 3-hour basis from the National Weather Service. This practice is referred to as "analysis nudging" and helps prevent model predictions from widely diverging from actual observations. In order to ensure that terrain features are the dominate influence for wind fields in the 4km domain, analysis nudging was used only for the 12km and 36km MM5 domains. Observational nudging was turned on only for the 4km domain.

2.2 Script Review

URS has completed a QA review of the scripts used by NPS-ARD. Scripts were obtained for all of the programs that make up the MM5 modeling system. The scripts were checked for errors or for anything that may have adversely affected the modeling. URS found the scripts to be in good order.

3.0 Model Performance Evaluation

3.1 Background

A seven point approach to model performance evaluation for meteorological modeling has been outlined by T.W. Tesche (1994). The evaluation can be split into two components: a scientific evaluation and an operational evaluation (Emery and Tai, 2001). Due to the nature of this evaluation and the limited time to perform it, this evaluation focused on the operational aspect alone.

3.2 Methods

3.2.1 Statistical Evaluation

The most common analysis in a model performance evaluation uses statistical measures. A subset of standard statistical measures has begun to emerge. These standards are presented in Table 3.1. There are no criteria in existence for acceptable model performance based on the standard metrics. However, those proposed by Emery and Tai (2001) have been adopted by the meteorological modeling community (see Table 3.2).

Table 3.1. Standard Statistical Measures Used in Performance Evaluations.

Metric	Wind Speed	Wind Direction	Temperature	Humidity
Observed vs. Predicted Time-series	daily & hourly averaged	daily & hourly averaged	daily & hourly averaged	daily & hourly averaged
Bias	daily & hourly averaged	daily & hourly averaged	daily & hourly averaged	daily & hourly averaged
Gross Error	daily averaged	daily averaged	daily averaged	daily averaged
Total RMSE	daily & hourly averaged		daily & hourly averaged	daily & hourly averaged
Index of Agreement	daily & hourly averaged		daily & hourly averaged	daily & hourly averaged

Table 3.2. Statistical Metric Guidelines for Daily Averaged Values.

Wind Speed	Wind Direction	Temperature	Humidity
Mean Bias $\leq |0.5|$ m/s	Mean Bias $\leq |10|$ deg	Mean Bias $\leq |0.5|$ K	Mean Bias $\leq |1.0|$ g/kg
RMSE $\leq$ 2m/s	Gross Error $\leq$ 30 deg	Gross Error $\leq$ 2 K	Gross Error $\leq$ 2 g/kg
IOA $\geq$ 0.6		IOA $\geq$ 0.8	IOA $\geq$ 0.6

Baker et al. (2004) describes each metric, as summarized below.

- Mean bias is defined as "the degree of correspondence between the mean prediction and the mean observation, with lower numbers indicative of better performance."

- Gross Error is defined as the mean absolute error, is the mean of the absolute value of the residuals from a fitted statistical model. Lower numbers indicate better model performance.

- Root mean squared error (RMSE) should approach zero for good model performance.

- Index of agreement (IOA) is defined as "a relative measure of the degree of which predictions are error free." The IOA approaches one for good model performance.

For this evaluation, the meteorological data output from MM5 was compared with the Techniques Data Laboratory (TDL) U.S. and Canada surface hourly observations (ds472.0). The statistical measures were generated using the METSTAT program and its accompanying Microsoft® Excel macro developed by ENVIRON. Since statistics generated over large geographic areas are subject to error cancellation, some have broken down large domains into smaller subdomains for the purpose of calculating statistical metrics. However, with the limited scope of this evaluation all statistics are based on the 4km grid.

It is difficult to show all of the statistical results for an annual simulation. However, Kirk Baker (currently with U.S. EPA) of Lake Michigan Air Directors Consortium (LADCO) developed a new graphical display referred to as a "Bakergram" that allows the display of an entire year's worth of daily averaged statistics in one plot. These Bakergrams are shown for select metrics for wind speed, wind direction, temperature, and humidity.

3.2.2 Surface Evaluation

The surface evaluation compares MM5 meteorological predictions to surface meteorological observations. The evaluation consists of several spatial plots of daily averaged MM5 predicted values with surface observations overlaid on the plots. Spatial plots are provided for temperature, humidity, and wind vectors. In addition, wind rose plots compare predicted winds with observed winds at three selected stations. This report also includes time-series plots of modeled values and observations at selected sites in the 4km domain.

3.2.3 Upper Air Evaluation

An upper air evaluation was also performed. This consisted of creating sounding plots using the RAOBPLOT software tool created by the Iowa Department of Natural Resources (Johnson, 2007). This program generates plots of observed radiosonde data and MM5 predictions on a thermodynamic diagram. The upper air evaluation graphically illustrates model performance in the upper layers of the domain.

3.2.4 Precipitation Evaluation

The precipitation data for this evaluation were created from the Climate Prediction Center (CPC) gridded daily precipitation dataset (http://www.cpc.ncep.noaa.gov/products/precip/realtime/retro.html). The CPC daily precipitation data are provided on a grid that covers the U.S. mainland. The grid resolution is 0.25°x0.25°. The data were converted into an observation file whose data was overlaid on MM5 precipitation predictions.

4.0 Surface Evaluation

4.1 Statistical Analysis

As mentioned in Section 3.0, statistical metrics were generated using the METSTAT software package. Figure 4.1 shows the locations of the observation stations used in the calculation of the statistics.

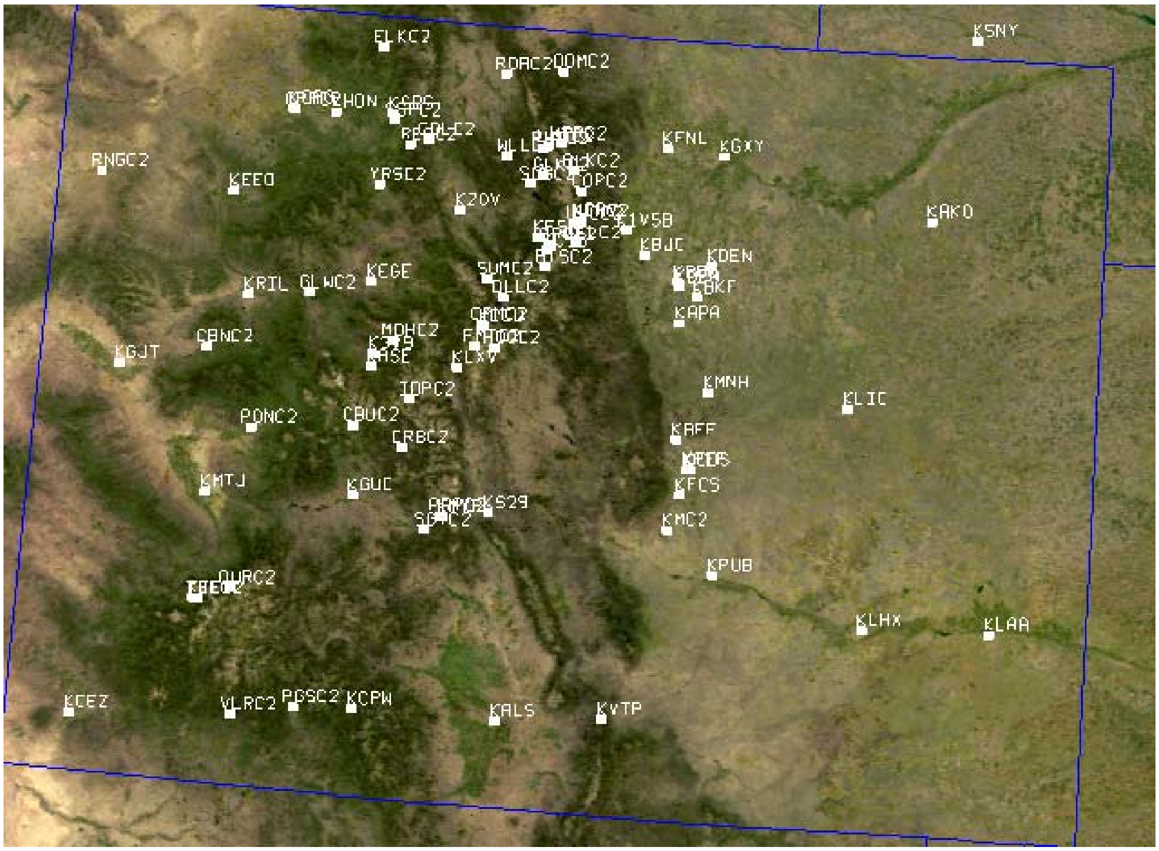
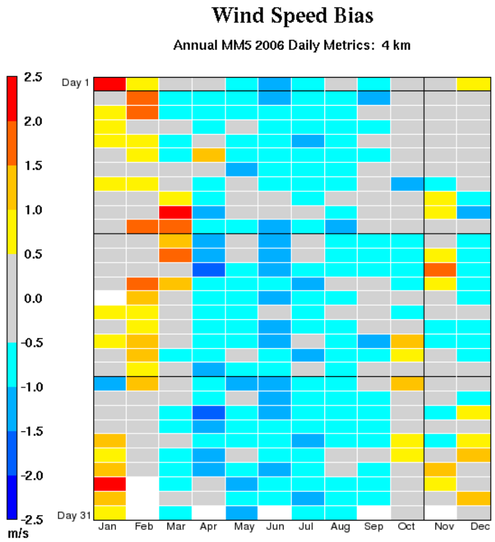


Figure 4.1. Observation stations in the 4km domain that were used in the calculation of the statistics.

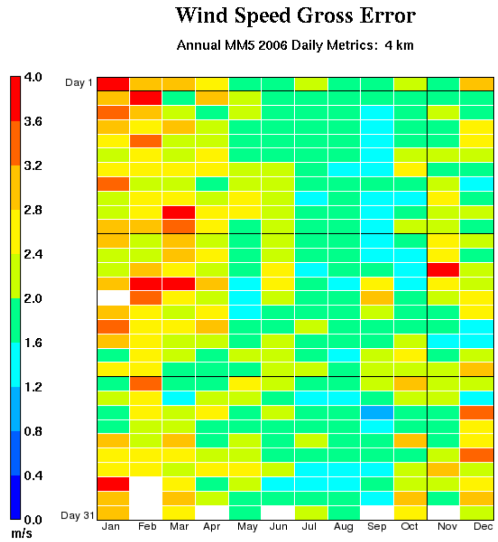
Daily averaged statistics for winds, temperatures,, and humidity are shown in Bakergrams presented in Figures 4-2 through 4-5. These plots are organized so that a column represents each month and a row represents specific days of the month. For example, the first day of each month is located in the top row. White squares represent days that have no data or days that do not exist, such as April 31st. No data existed for the 16th of January in the observational dataset.

Bakergram color coding is described at the bottom of each graph. When defined, the criteria are given in equation form and the associated colors for the criteria are included below the equation. For example, the wind speed bias plot indicates that the mean bias should be within the absolute value of 0.5 m/s, which is indicated by "Mean bias ≤ $|0.5|$." Values falling inside the criteria proposed by Emery and Tai (2001) will be gray. In addition, the color just above and just below gray may also fall inside the criteria. This is due to the fact that the bins above and below the gray bin include the criteria's bounding value. If a particular day's bias value is equal to 0.5 m/s, then it will be yellow, but still inside the criteria.

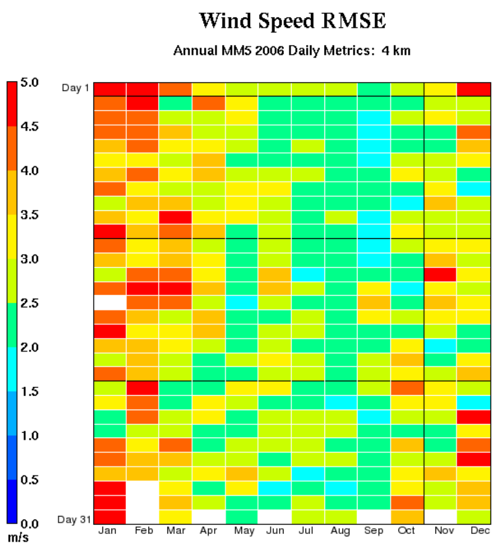
As shown in the wind speed Bakergrams in Figure 4.2, MM5 slightly over-predicted wind speed in the winter (December through early March) for the 4km domain, but under-predicted during spring and summer months (late March through August). The gross error is greater in the winter than in summer. Wind speed RMSE is greater in the fall and winter, then decreases in late spring and throughout the summer. The IOA is reasonably good year-round. Wind speed Bakergrams for the 36km and 12km domains are shown in Appendix A, and indicate better model performance over the coarser domains.



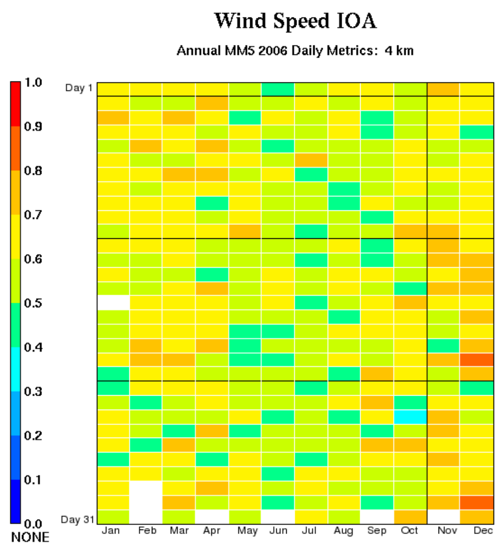
Mean Bias ≤ │ 0.5 │ m/s
Light Blue → Gray → Yellow



Although no specific criteria exist, gross error should be low.



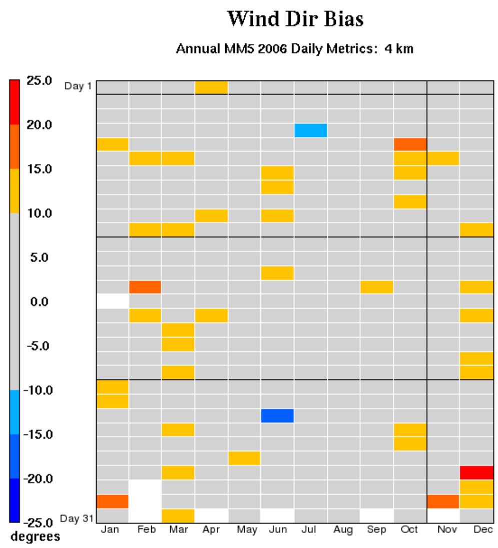
RMSE ≤ 2 m/s
Dark Blue → Light Blue → Dark Green



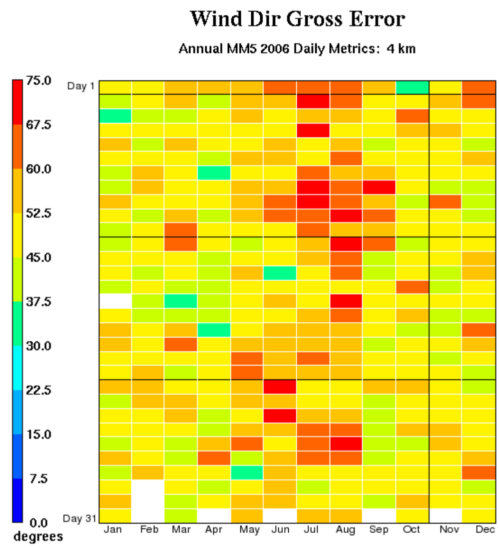
IOA ≥ 0.6
Red → Orange → Yellow

Figure 4.2. Daily averaged wind speed statistics for the RoMANS 4km domain.

As shown in Figure 4.3, wind direction statistical analysis indicates low bias year-round, with only a few days showing an over-prediction. Gross error increased during the summer months, though the error was significantly less for the 36km and 12 km domains shown in Appendix A.

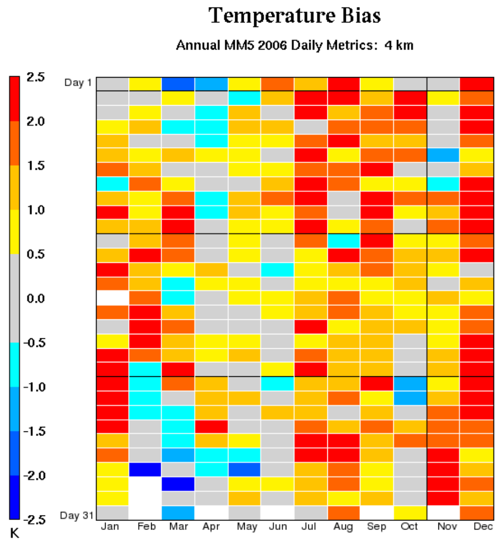


Mean Bias ≤ │ 10 │ degrees
Light Blue → Gray → Yellow-Orange

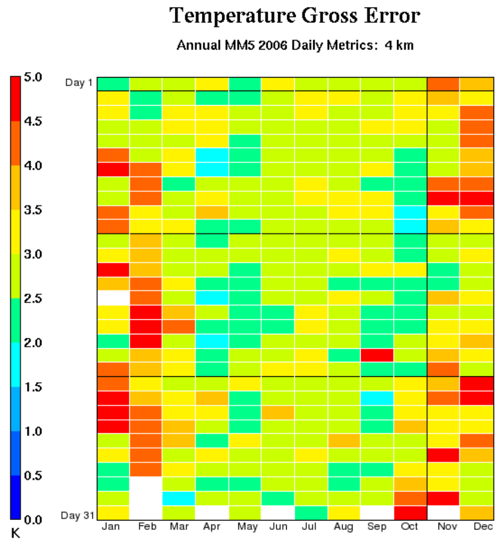


Gross Error ≤ 30 degrees
Dark Blue → Light Blue → Dark Green

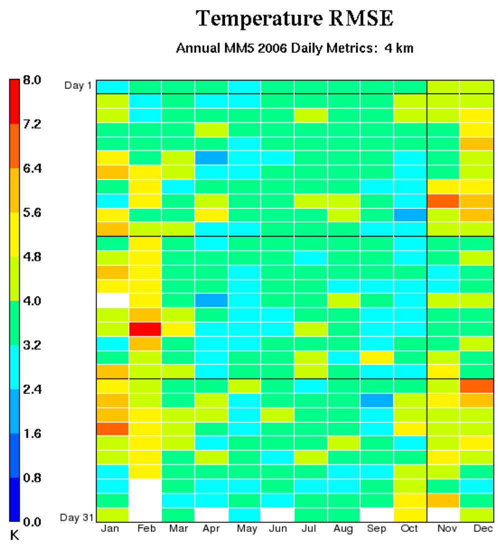
Figure 4.3. Daily averaged wind direction statistics for the RoMANS 4km domain.



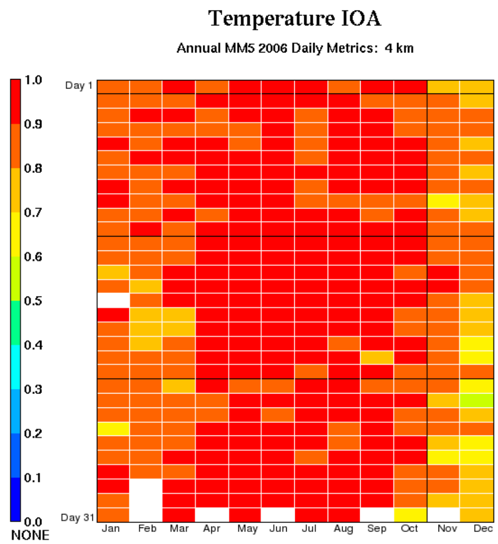
Mean Bias ≤ | 0.5 | K
Light Blue → Gray → Yellow



Gross Error ≤ 2 K
Dark Blue → Light Blue → Dark Green

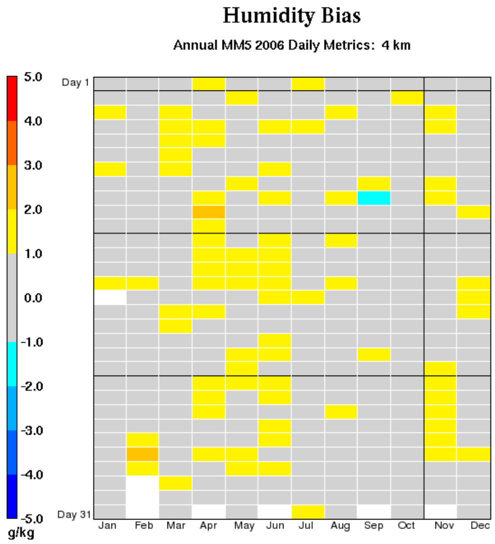


Although no specific criteria exist, RMSE should be low.

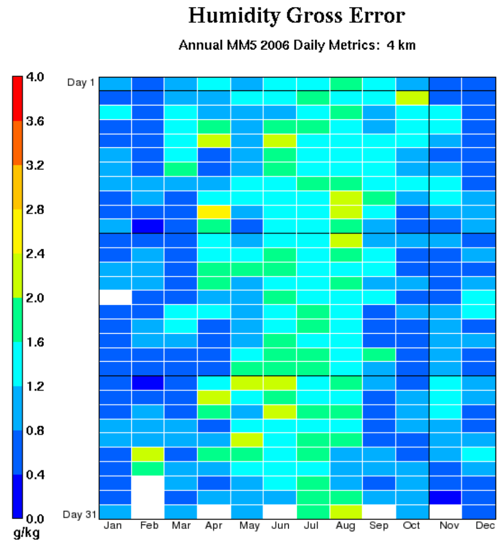


IOA ≥ 0.8
Red → Orange

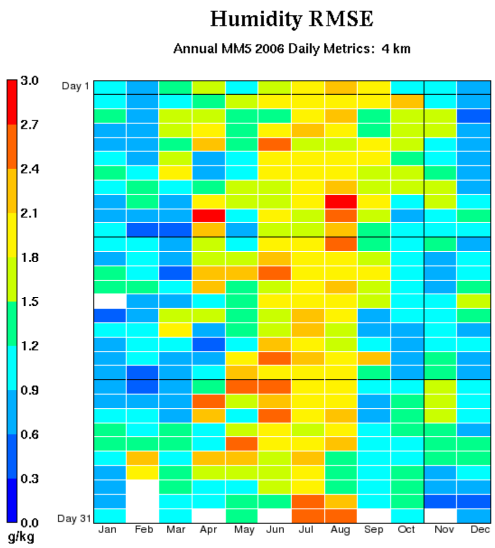
Figure 4.4. Daily averaged temperature statistics for the RoMANS 4km domain.



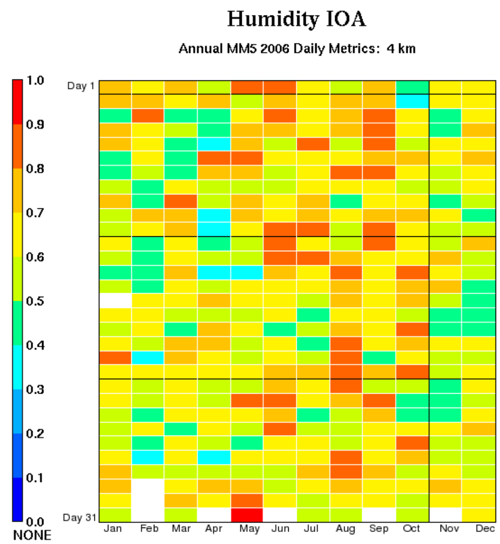
Mean Bias ≤ |1.0| g/kg
Light Blue → Gray → Yellow



Gross Error ≤ 2 g/kg
Dark Blue → Light Blue → Dark Green → Light Green



Although no specific criteria exist, RMSE should be low.



IOA ≥ 0.6
Red → Orange → Yellow

Figure 4.5. Daily averaged mixing ratio statistics for the RoMANS 4km domain.

Turning now to the temperature (Fig. 4.4), the model is showing a warm bias for most of the year. This warm bias could possibly lead to overestimation of emissions, especially biogenic, mobile, and point source emissions. However, the warm bias could also possibly raise the PBL height which would allow for more mixing and possibly lower emissions. The gross error is above the criteria in the late fall and winter, but the spring and summer months are much lower. The RMSE is similar in that the spring and summer months have the lowest values. The IOA for temperature is very close to one for most of the year, with only December showing lower values. Overall, model performance with regard to temperature is reasonably good. Temperature

Bakergrams for the 36km and 12km domains are shown in Appendix A, and indicate better model performance over the coarser domains.

The daily averaged mixing ratio (Fig. 4.5) has extremely low bias with only two days being outside the acceptable range. The gross error was also very low year-round for mixing ratio. The IOA is best during the summer, with the values in the fall and winter being the only ones below the criteria. The model performed well with respect to the humidity year-round over all domains (see Appendix A).

4.2 Surface Analysis

Plots of observations overlaid on predicted values for temperature and mixing ratio were analyzed as part of the surface analysis. For winds, the observed wind vectors are plotted on top of wind vectors that were predicted by the model. While plots for each day in 2006 were analyzed, only plots for four days, one from each season, are presented below.

Predicted temperatures (Fig. 4.6) tend to agree well with the observations on the plains, but the model predictions tend to be too cool in the mountains. Predicted mixing ratios (Fig. 4.7) tend to agree well with observations across the entire domain.

Modeled wind vector plots on topographic maps of Colorado are shown in Appendix D. Three days with different wind directions were chosen for display. On January 3, 2006, winds were generally blowing from the west. On May 15, 2006, the winds were blowing from the east (an upslope pattern). On June 14, 2006, winds were blowing from the south. In these plots, every modeled wind vector in the 4km domain is shown in black, while wind barbs indicating observed wind speed and direction are shown in red. Modeled wind vectors tend to agree well with observations. There are a few instances (and particular locations) where predicted wind directions diverge significantly. Many of these instances occur in areas of complex terrain. On the days when the wind is blowing from the west or the south, the agreement is very good. On the day when the wind is blowing from the east, which is less frequent, wind direction agreement is not as good. Overall, the model does a good job of predicting the wind directions.

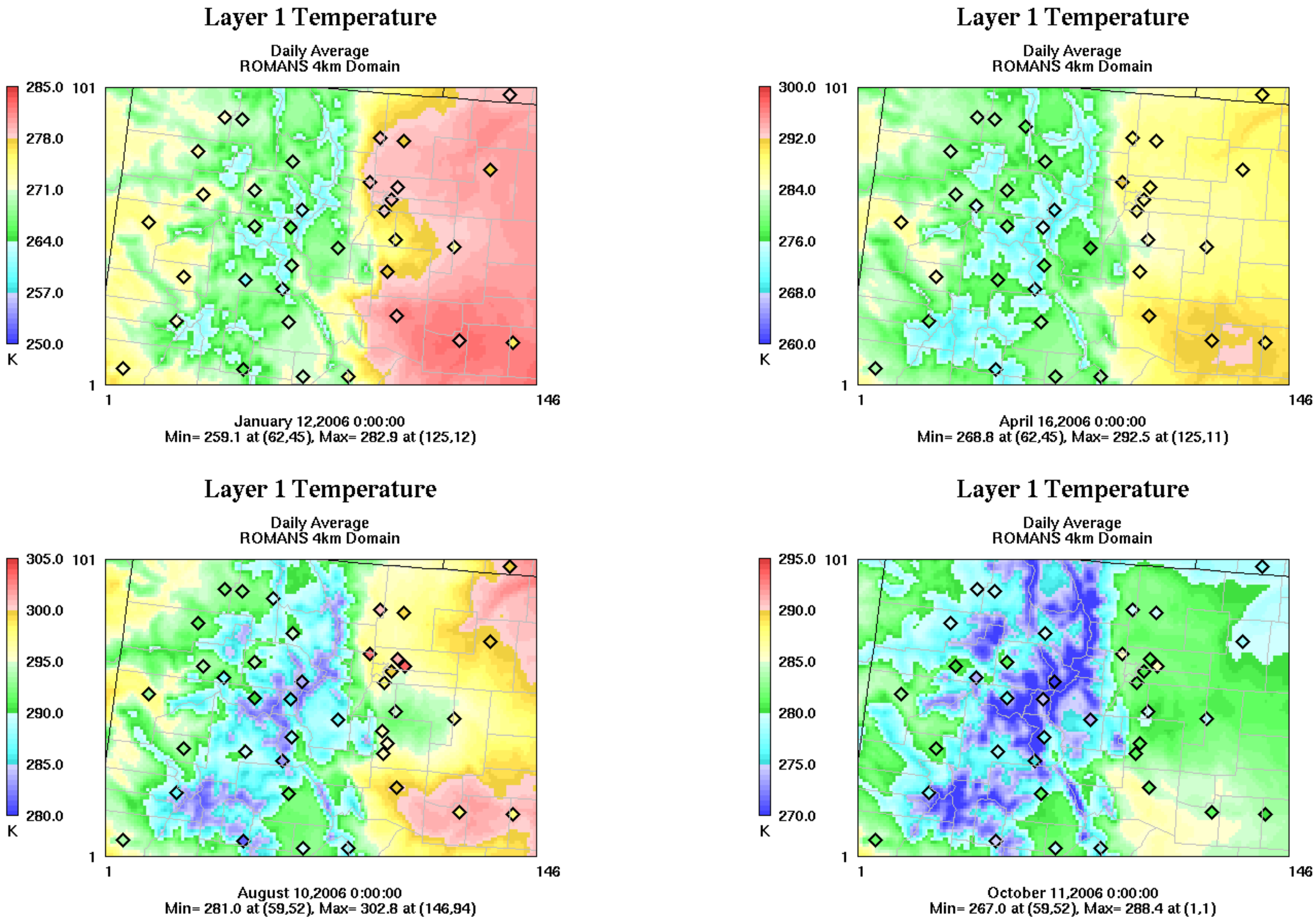


Figure 4.6. Daily averaged temperature observations overlaid on daily averaged temperature predictions.

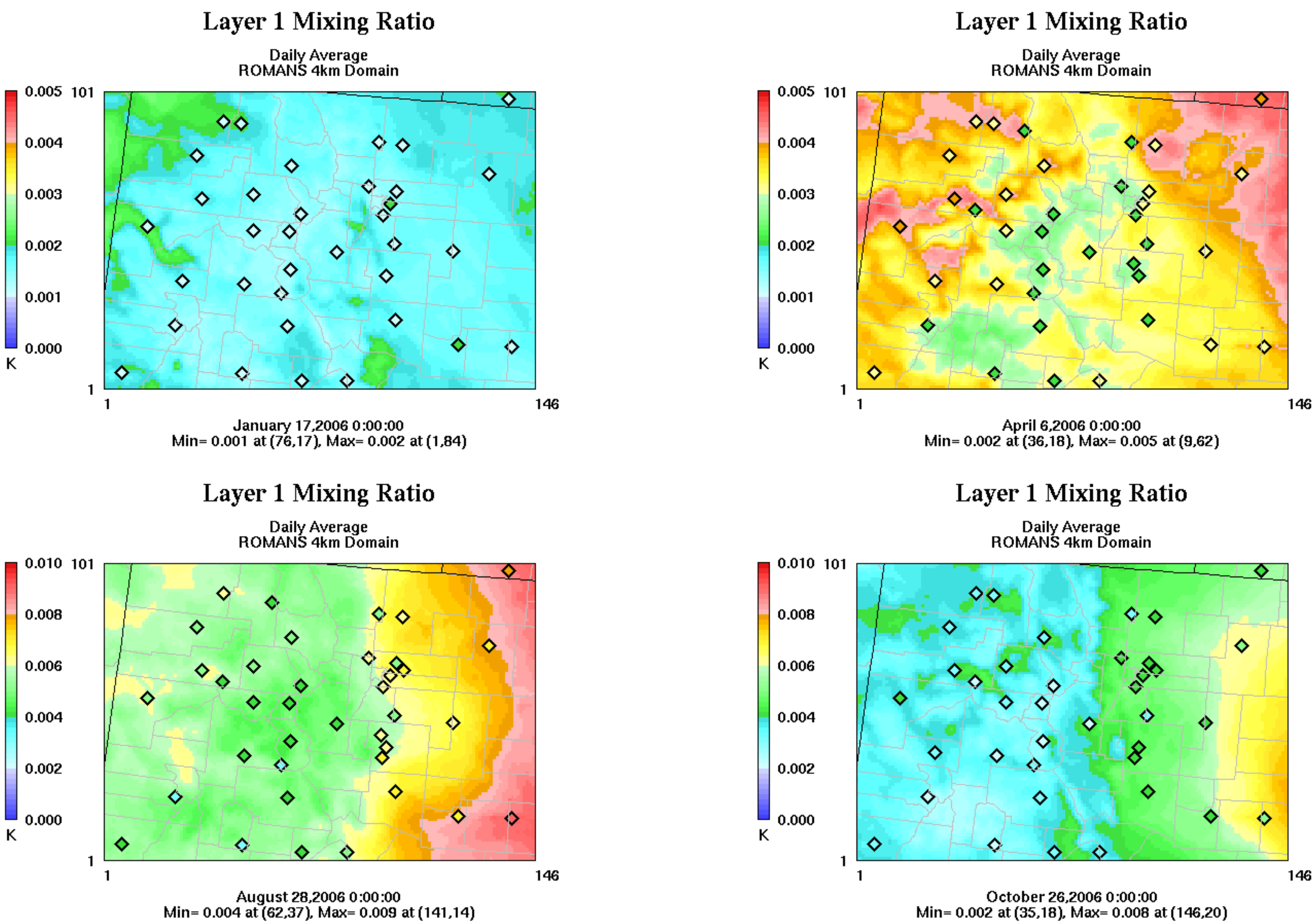


Figure 4.7. Daily averaged mixing ratio observations overlaid on daily averaged mixing ratio predictions.

The figures (Fig. 4.8) below examine the winds in another way. The provided wind rose plots show the direction and speed of winds for the entire selected day. Three stations are shown in the figure, KDEN – Denver International ASOS, KMYP – Salida Mountain and KEEO – Meeker ASOS. The Denver site is on the Front Range of the Rockies. The Salida Mountain site is in the higher elevations of the Rockies and the Meeker station is in the west of the state, near the Utah border. The figures on the left display actual measured winds, while those on the right display modeled winds.

All the sites show fairly good agreement with the average wind direction. Modeled wind speeds at the Meeker site are lower than observed values, while the other sites' modeled wind speeds are greater than observed values.

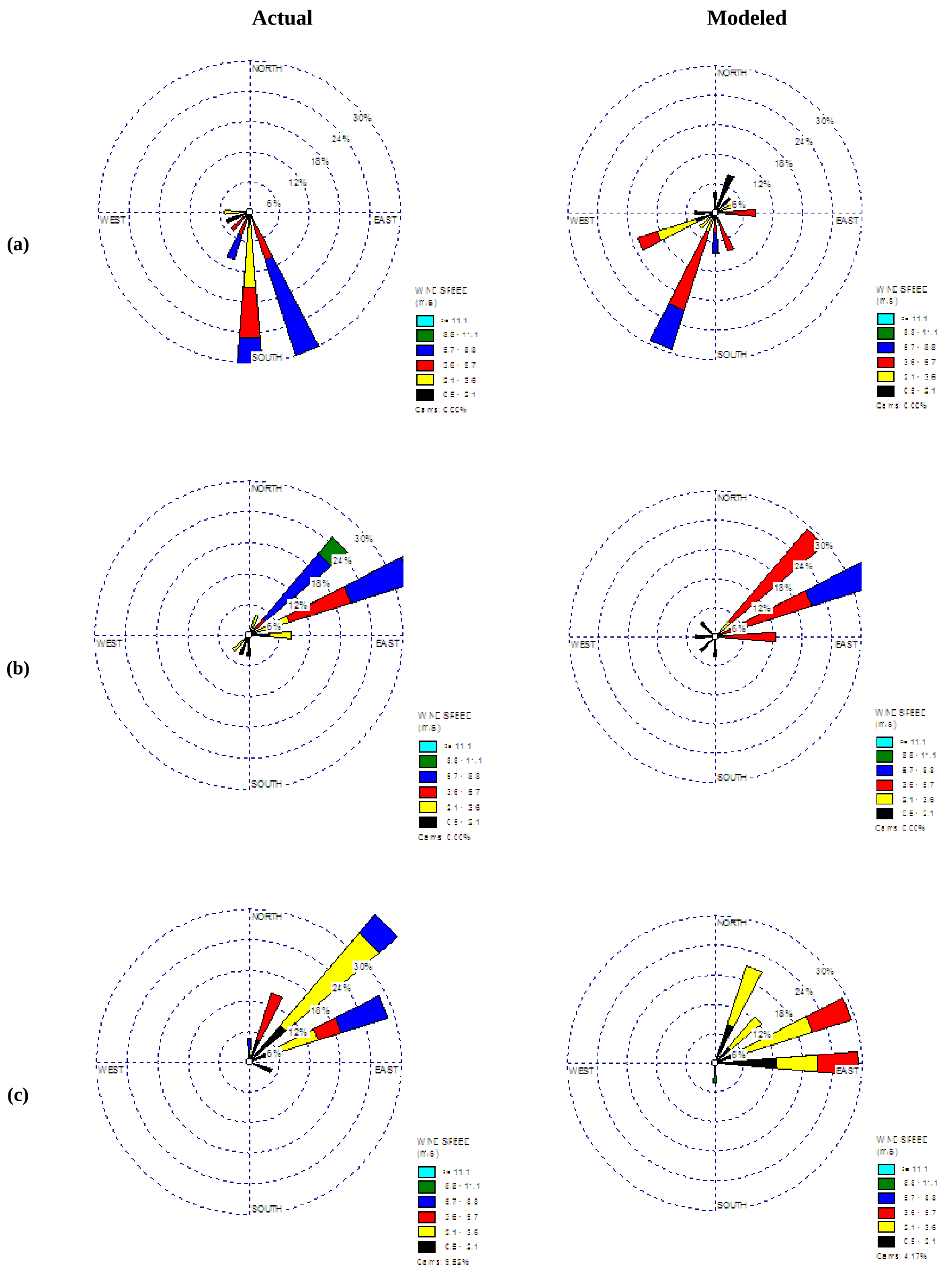


Figure 4.8. Wind rose plots at (a) Denver for August 15, 2006, (b) Salida Mountain for May 15, 2006, and (c) Meeker for May 15, 2006.

The next part of the surface analysis focuses on daily average time series plots for a month in each season. Due to the larger number of monitors in the domain, only the three locations used in the wind rose analysis are shown. Plots included in C show the daily average temperature for the observation site (shown in green) and the model (shown in blue) for the four months. Good agreement between model predictions and observations is shown, with only a few exceptions. In February at the Denver site, the model over-predicts the temperature from the 16^{th} to the 20^{th}. The model under-predicts the entire month of November at the Salida Mountain site.

Time series plots included in Appendix B show similar graphs for mixing ratio. The model slightly over-predicts the mixing ratio at all sites for all days of the month.

4.3 Upper Air Analysis

The upper air analysis was performed by creating skew-T thermodynamic plots using the RAOBPLOT program created by the Iowa Department of Natural Resources. This diagram shows the observational data alongside model predictions for easy comparison. The plots were created at the Denver/Stapleton and Grand Junction radiosonde sites in Colorado since they are the only radiosonde sites in the domain. Figure 4.9 shows, in yellow, the location of these sites.

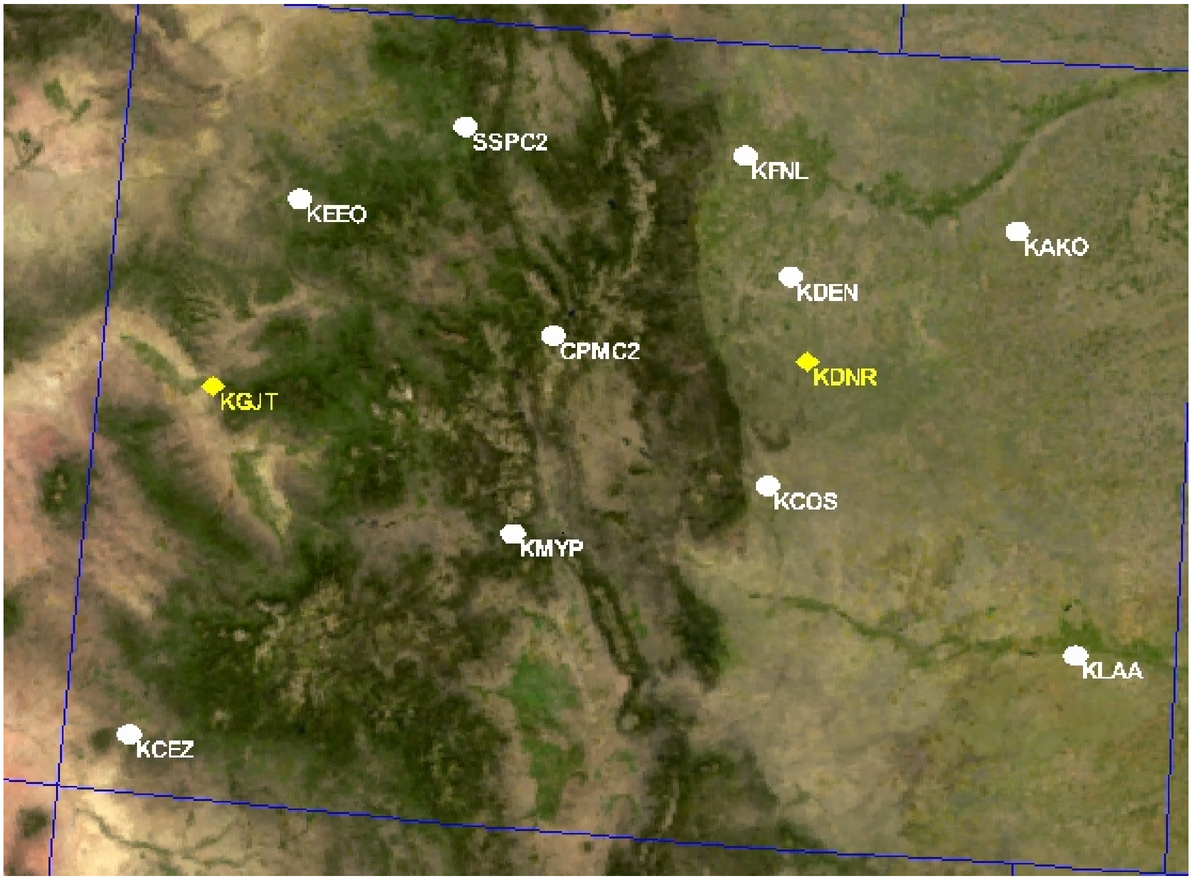


Figure 4.9. Location of radiosonde sites (yellow) in the 4km domain.

Figure 4.10 shows a RAOBPLOT output for the Denver/Stapleton site on November 15, 2006 at 12:00 UTC. The agreement of temperature, mixing ratio, and winds is all very good. One thing to note for the Denver station is that the modeled values, depicted with red lines, start over 100 mb higher than the observations do. This is because the MM5 grid cell that corresponds with the Denver station has a higher elevation than the actual station itself. The Grand Junction site also shows good agreement between predicted and observed values (Fig. 4.11). Notice that the predicted and observed values begin at almost the same elevation at the Grand Junction site.

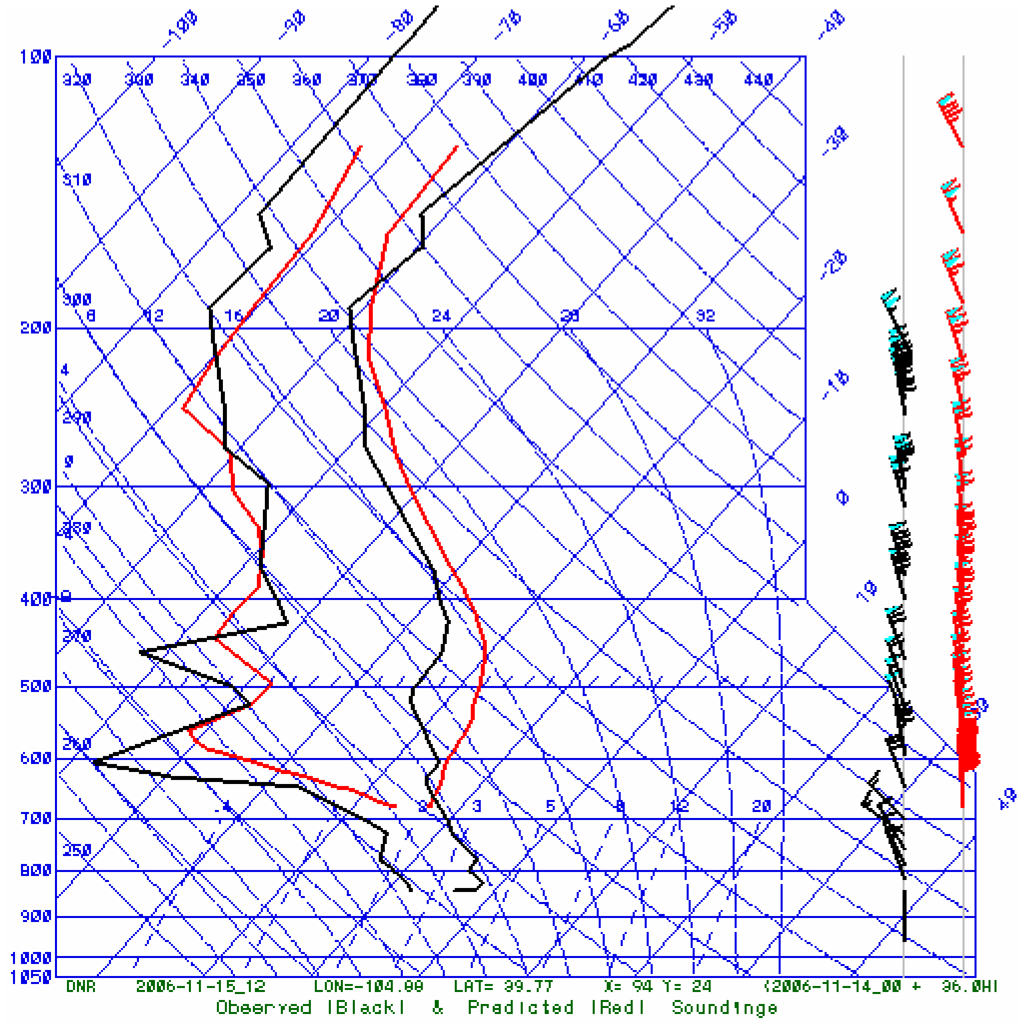


Figure 4.10. Radiosonde sounding at the Denver/Stapleton raob site on November 15, 2006 at 12:00 UTC.

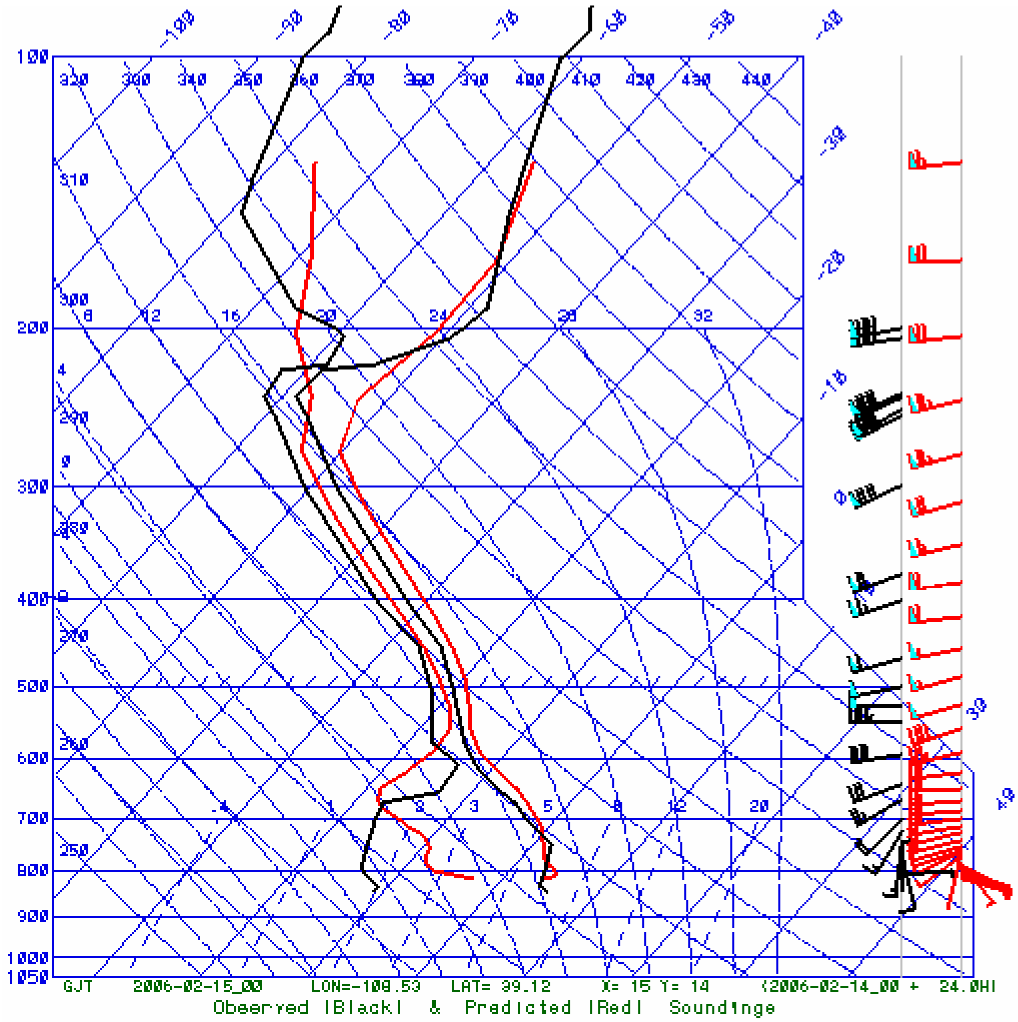


Figure 4.11. Radiosonde sounding at the Grand Junction raob site on November 15, 2006 at 12:00 UTC.

4.4 Precipitation Analysis

The precipitation analysis was performed by overlaying the CPC (Climate Prediction Center) daily total precipitation observations on top of the daily total modeled precipitation. The CPC data were based on the daily total ending at 12:00 UTC each day, so the MM5 output data were totaled in the same way. The results for the middle days of four months in each season are shown in Figure 4.12. The model is doing well in predicting where rain occurred, but it generally over-predicted rainfall quantities. Since the WRFO air quality photochemical analysis will predict ozone concentrations only, over-prediction of precipitation should not significantly affect ozone predictions.

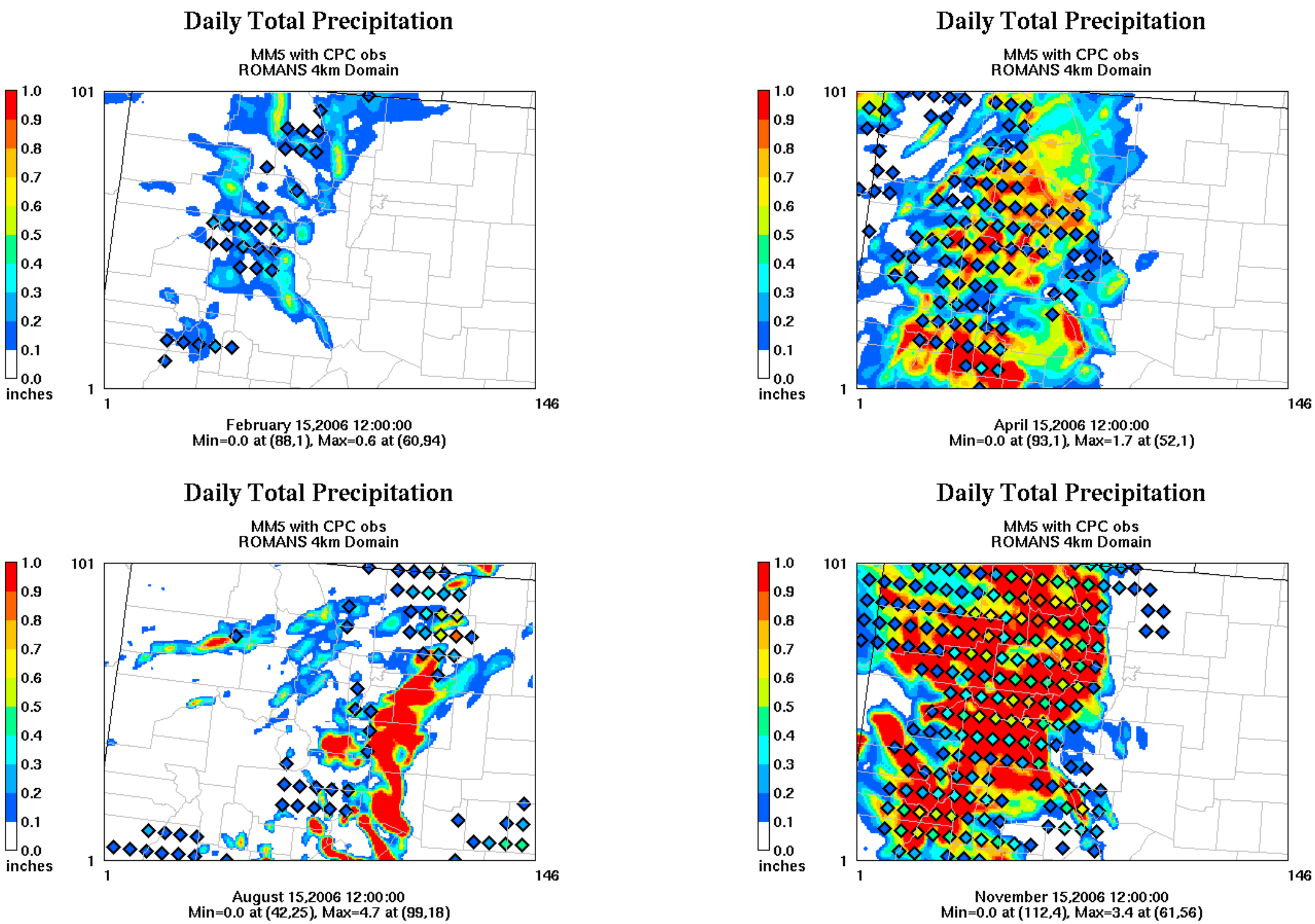


Figure 4.12. Daily total precipitation with observational values overlaid.

5.0 Conclusions

This analysis of MM5 modeling results included a variety of statistical, surface, upper air, and precipitation analyses. Results of these analyses appear to be within acceptable ranges, with some seasonal and location-based variations.

While additional MM5 runs could potentially improve MM5 model performance, resources and time were limited. Analysis of MM5 results typically identifies imperfections in MM5 predictions. These imperfections are expected to be greater in areas with complex terrain, such as Colorado. The 4km meteorological datasets are deemed acceptable for use in air quality modeling studies focused on the State of Colorado.

5.1 Temperature

The surface statistical evaluation reveals that the model has a warm bias for most of the year. The greatest gross error occurs during winter months, and relatively high temperature bias exists in all months except for April through May. Specifically, the model over-predicts the daily highs in the late spring and summer and over-predicts the daily lows in the late fall and winter. However, the model under-predicts some daily highs in the high mountains during the winter months.

Warm bias will increase several types of weather-dependent emissions, including biogenic emissions (particularly isoprene), mobile emissions, and certain point source emissions. The increased emissions, coupled with increased temperatures, are likely to over-predict ozone impacts. Consequently, CAMx results would likely be conservative.

5.2 Humidity and Precipitation

There is very low bias for humidity all year round. The time-series plots reveal that the model usually over-predicts humidity, but not by a large margin.

The precipitation evaluation revealed what was expected. Good agreement occurred during cooler months when precipitation is more widespread and worse agreement occurred in the warm months when convective precipitation is dominant. The complex terrain of Colorado also plays an important role in the development of precipitation and this can be difficult for the model to resolve. Precipitation has a greater impact on visibility predictions than on ozone predictions. Because the WRFO air quality analysis focuses on ozone impacts, the level of over-prediction with regard to precipitation is not likely to significantly skew predicted ozone impacts during CAMx modeling.

5.3 Wind Speed and Direction

The statistics show that the wind speed is under-predicted in the warm months and over-predicted in the colder months. The wind direction bias is low year-round, but the acceptable margin is quite wide. The daily average wind directions do agree well with observations, with only a few instances of model winds and observational winds diverging by 90 degrees or more. Most of these instances occurred in areas of complex terrain.

URS looked at MM5 model performance from both a terrain-following perspective and a statistical perspective. As seen on detailed terrain maps in Appendix D, predicted wind vectors indicate excellent terrain-following performance. However, in some locations and on some days, observed wind directions differ significantly from predicted directions. When viewed against a detailed terrain background (as shown in example plots included in Appendix D), differences in observed and predicted wind vectors frequently occur in areas where wind direction is shifting due to major nearby terrain features. URS believes that, in some locations, MM5's 4km grid resolution may not be fine enough to capture terrain-induced wind patterns at the location of the meteorological monitoring station.

5.4 Upper Air Evaluation

The upper air evaluation returned very good results. Good agreement was found between the winds, temperature, and mixing ratio at both radiosonde sites in Colorado for all parameters. The warm bias can also be seen in the upper air plots

5.5 Winter Month Predictions

Winter months generally show poorer model performance, particularly from December through February. Due to the tendency for high ozone impacts to occur during the summer, the poorer model performance during cold-weather months may not have a significant impact on the WRFO CAMx modeling. With regard to the WRFO air quality analysis, ozone monitoring results described in the photochemical grid modeling protocol indicate high ozone concentrations during spring and summer months. Consequently, good MM5 model performance during the spring and summer is more important than performance during the December through February time frame.

5.6 Comparison of 36km, 12km, and 4km Plots

The MM5 output data shows better performance in the 36km and 12km domains than in the 4km domain. This is contrary to the expectations that higher resolution should yield better model performance. Therefore, URS believes that it is important to view the data at the 4km level for the following reasons:

- To be aware of MM5 model limitations due to 4km grid cell resolution in extremely complex terrain, and
- To be aware of potential impacts of the MM5 data on the White River air quality analysis.

6.0 References

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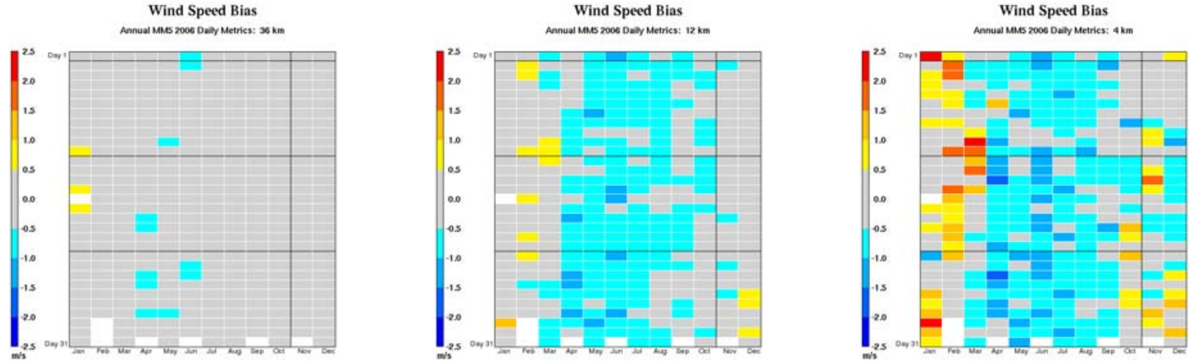
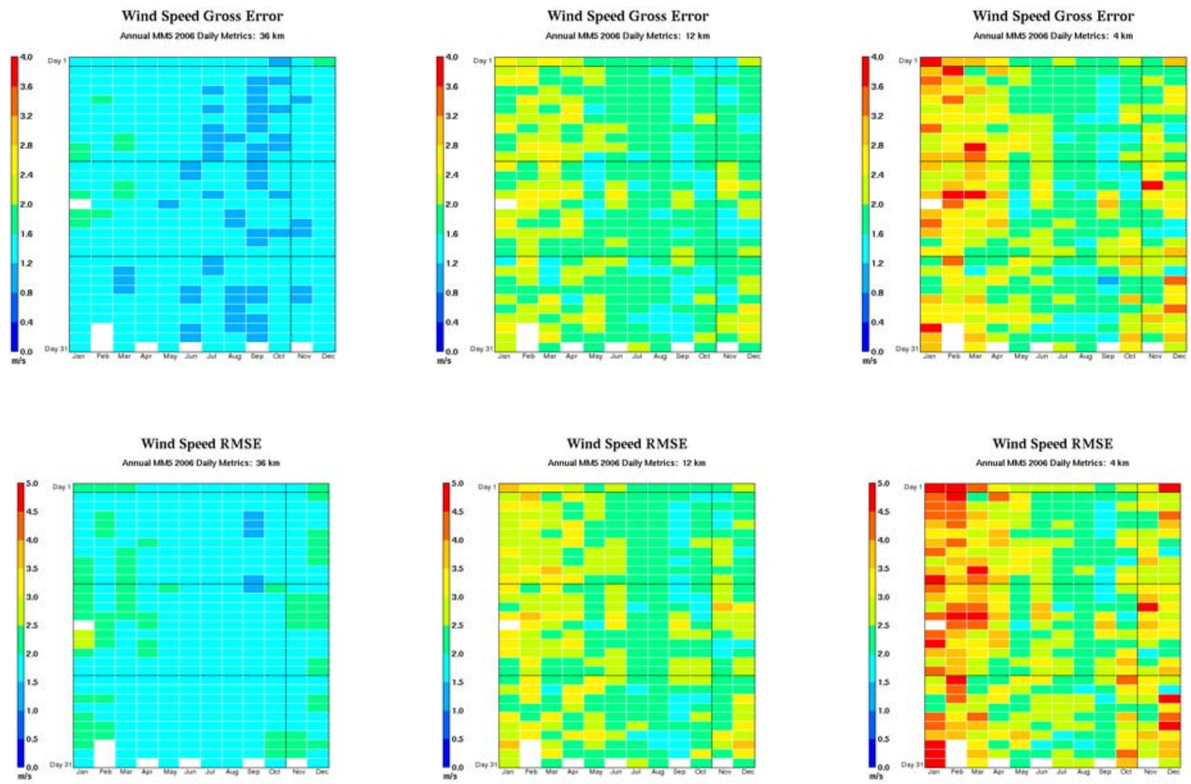
Appendix A

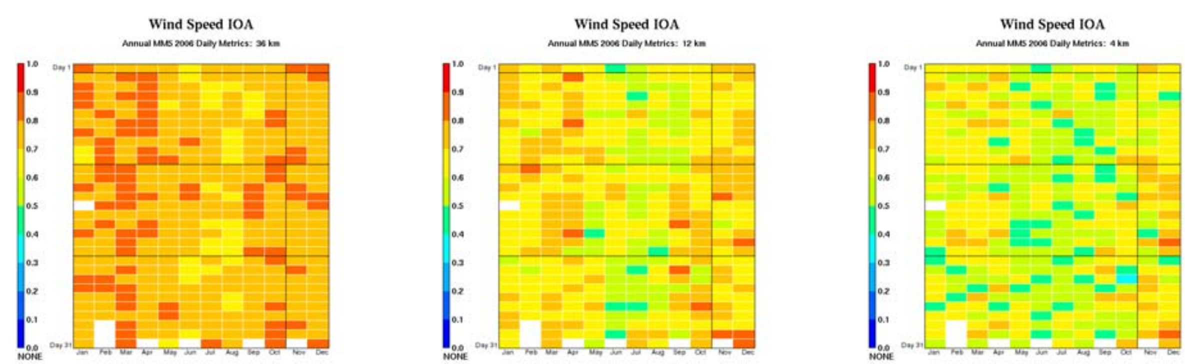
Comparison of 36km, 12km, and 4km Bakergrams



Statistical guidelines: Bias ≤ ±0.5 m/s, this coincides with the gray areas in the above plots.

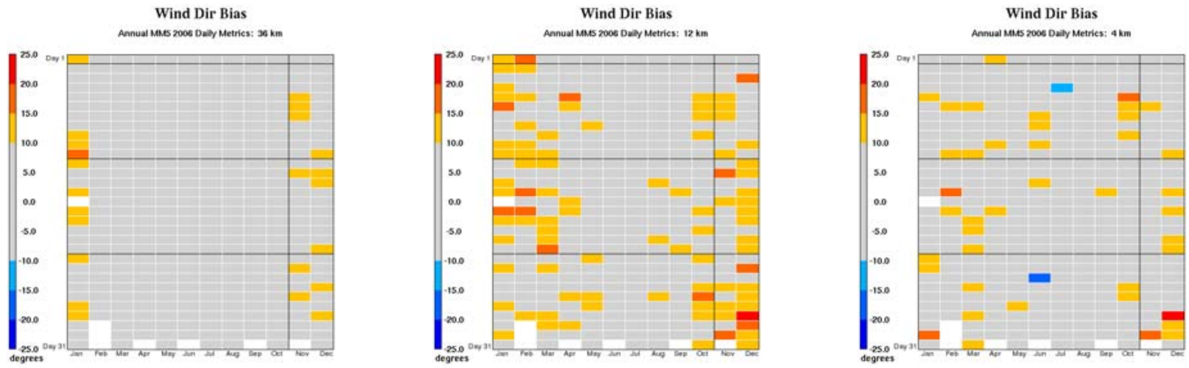


Statistical guidelines: RMSE ≤ 2m/s, this coincides with the light blue to dark blue areas in the above plots.

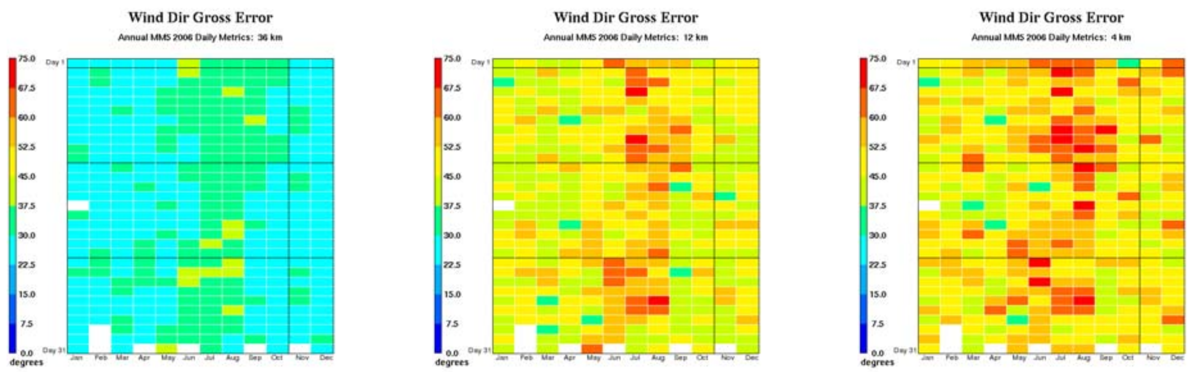


Statistical guidelines: IOA ≥ 0.6, this coincides with the yellow, orange and red areas in the above plots.

Figure A-1. Bakergrams of wind speed statistics for the 36km (left), 12km (middle) and 4km (right) runs.

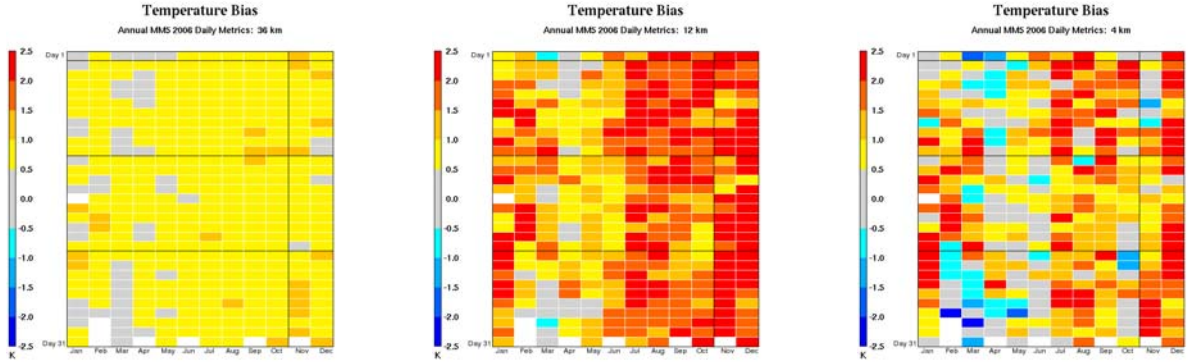


Statistical guidelines: Bias ≤ ±10 deg, this coincides with the gray areas in the above plots.

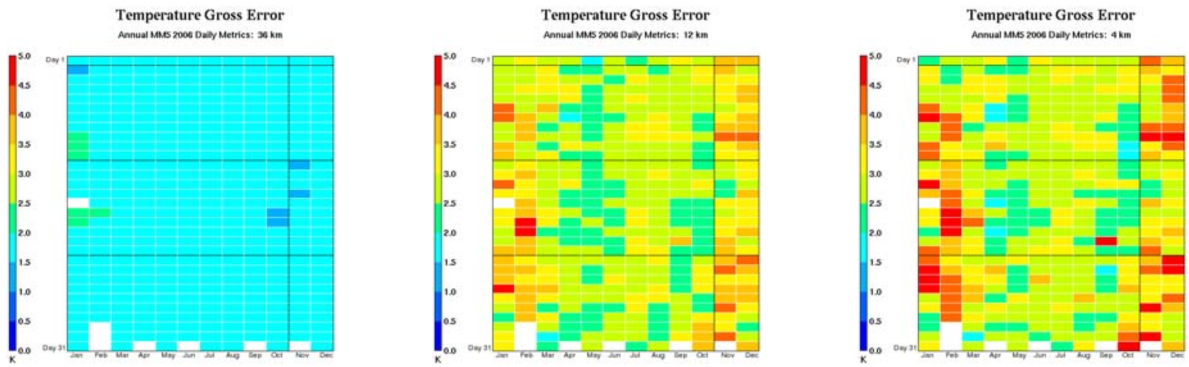


Statistical guidelines: Gross Error ≤ 30 deg, this coincides with the light blue to dark blue areas in the above plots.

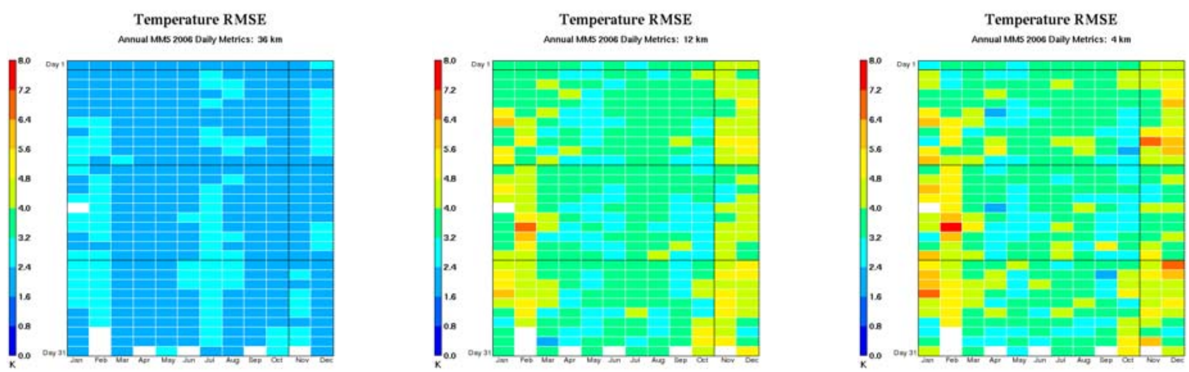
Figure A-2. Bakergrams of wind direction statistics for the 36km (left), 12km (middle) and 4km (right) runs.

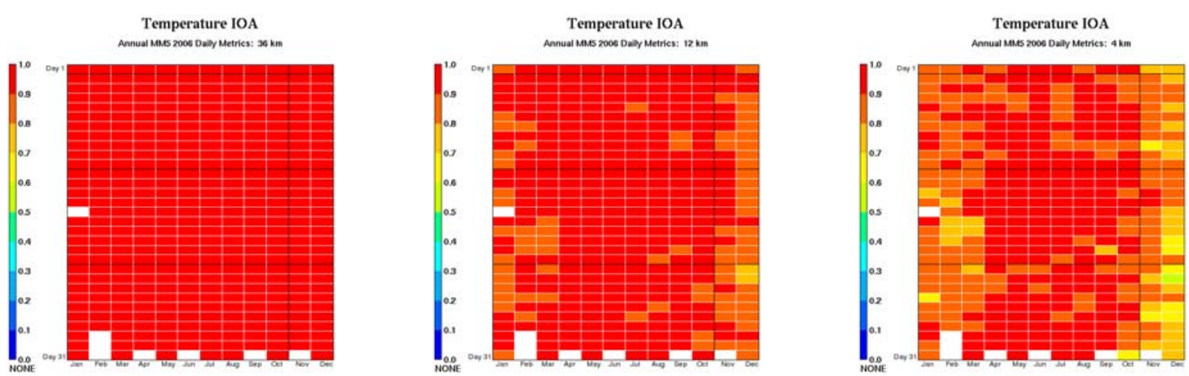


Statistical guidelines: Bias ≤ ±0.5K, this coincides with the gray areas in the above plots.



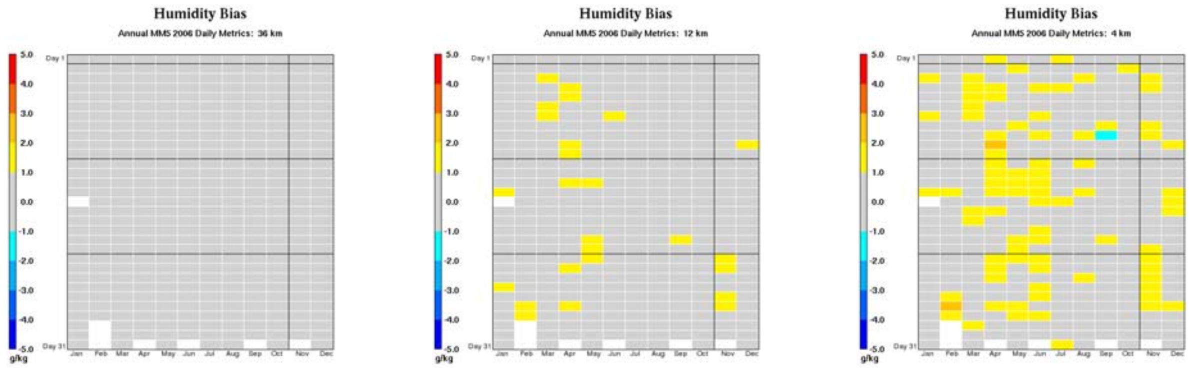
Statistical guidelines: Gross Error ≤ 2K, this coincides with the light blue to dark blue areas in the above plots.



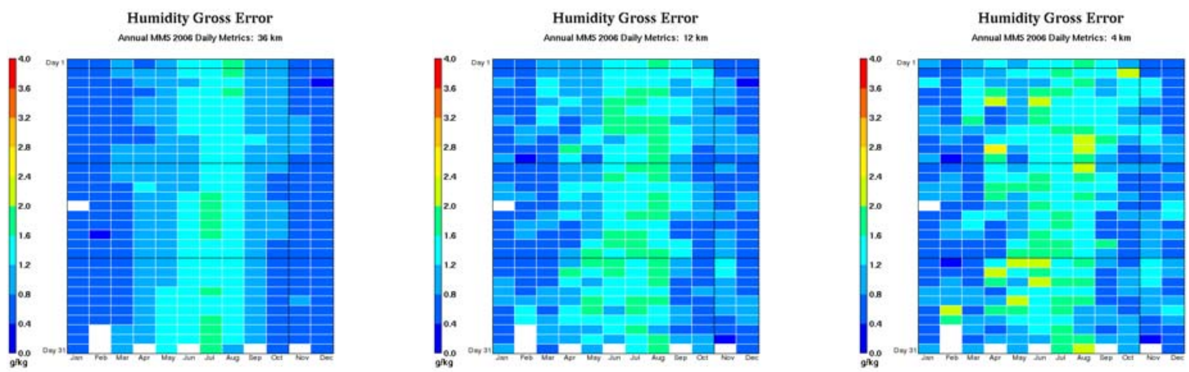


Statistical guidelines: IOA ≥ 0.8, this coincides with the dark orange and red areas in the above plots.

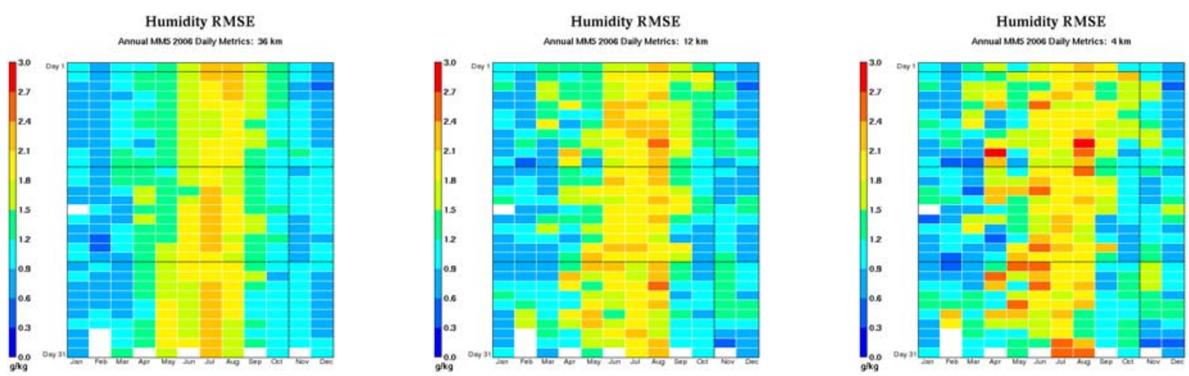
Figure A-3. Bakergrams of temperature statistics for the 36km (left), 12km (middle) and 4km (right) runs.

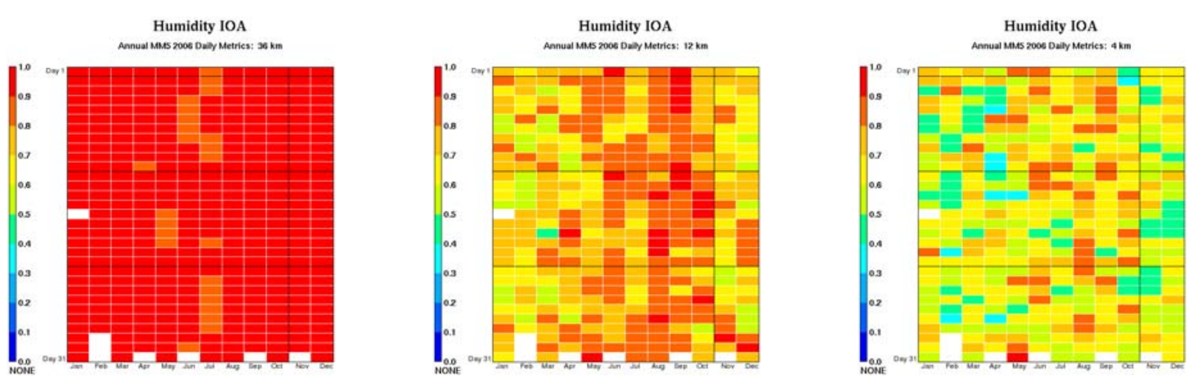


Statistical guidelines: Bias ≤ ±1.0 g/kg, this coincides with the gray areas in the above plots.



Statistical guidelines: Gross Error ≤ 2g/kg, this coincides with the aqua to dark blue areas in the above plots.





Statistical guidelines: IOA ≥ 0.6, this coincides with the yellow, orange and red areas in the above plots.

Figure A-4. Bakergrams of humidity statistics for the 36km (left), 12km (middle) and 4km (right) runs.

Appendix B

Daily Averaged Observation and Modeled Mixing Height Time Series

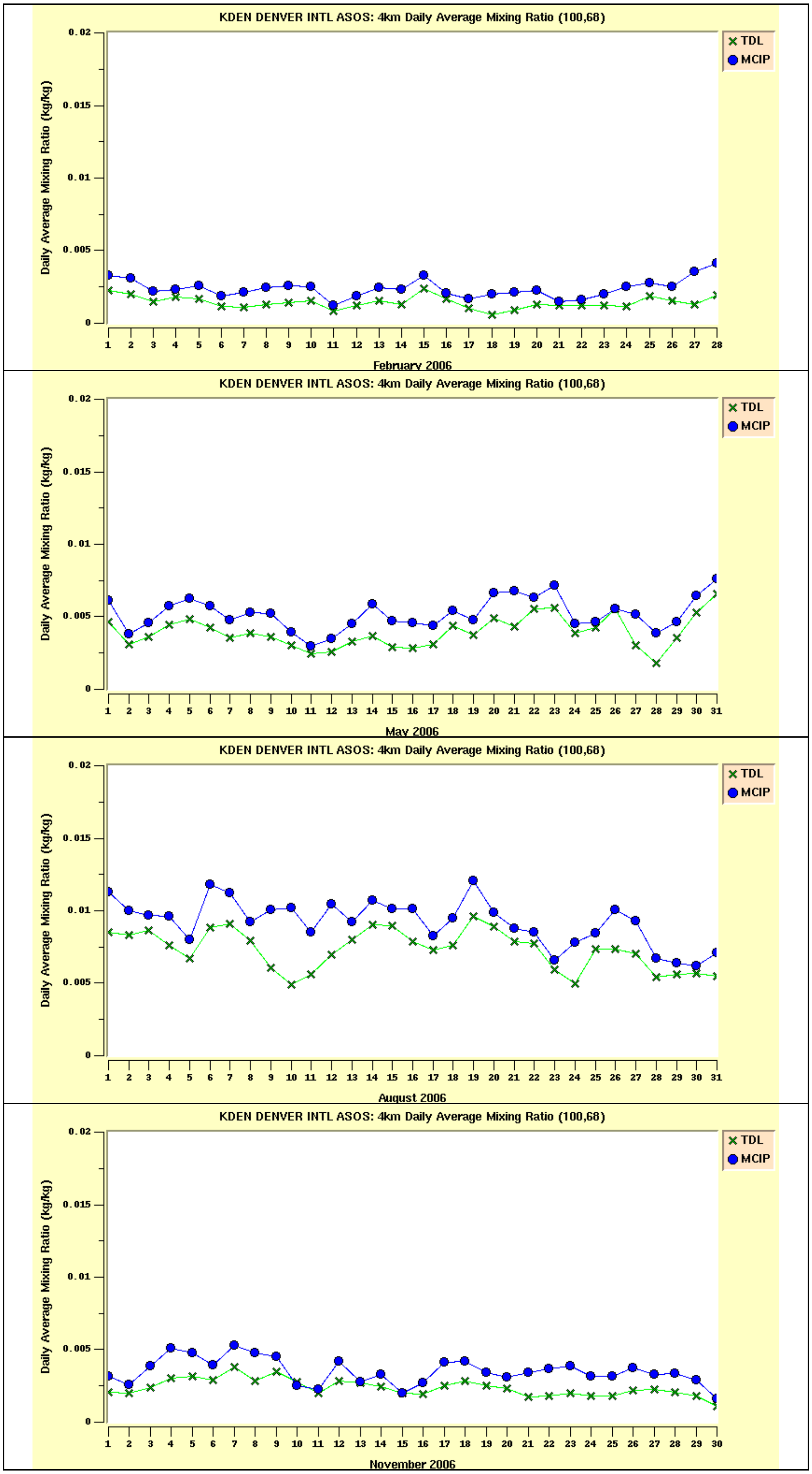


Figure B.1. Daily average observation and modeled mixing ratio at the Denver Intl. ASOS station.

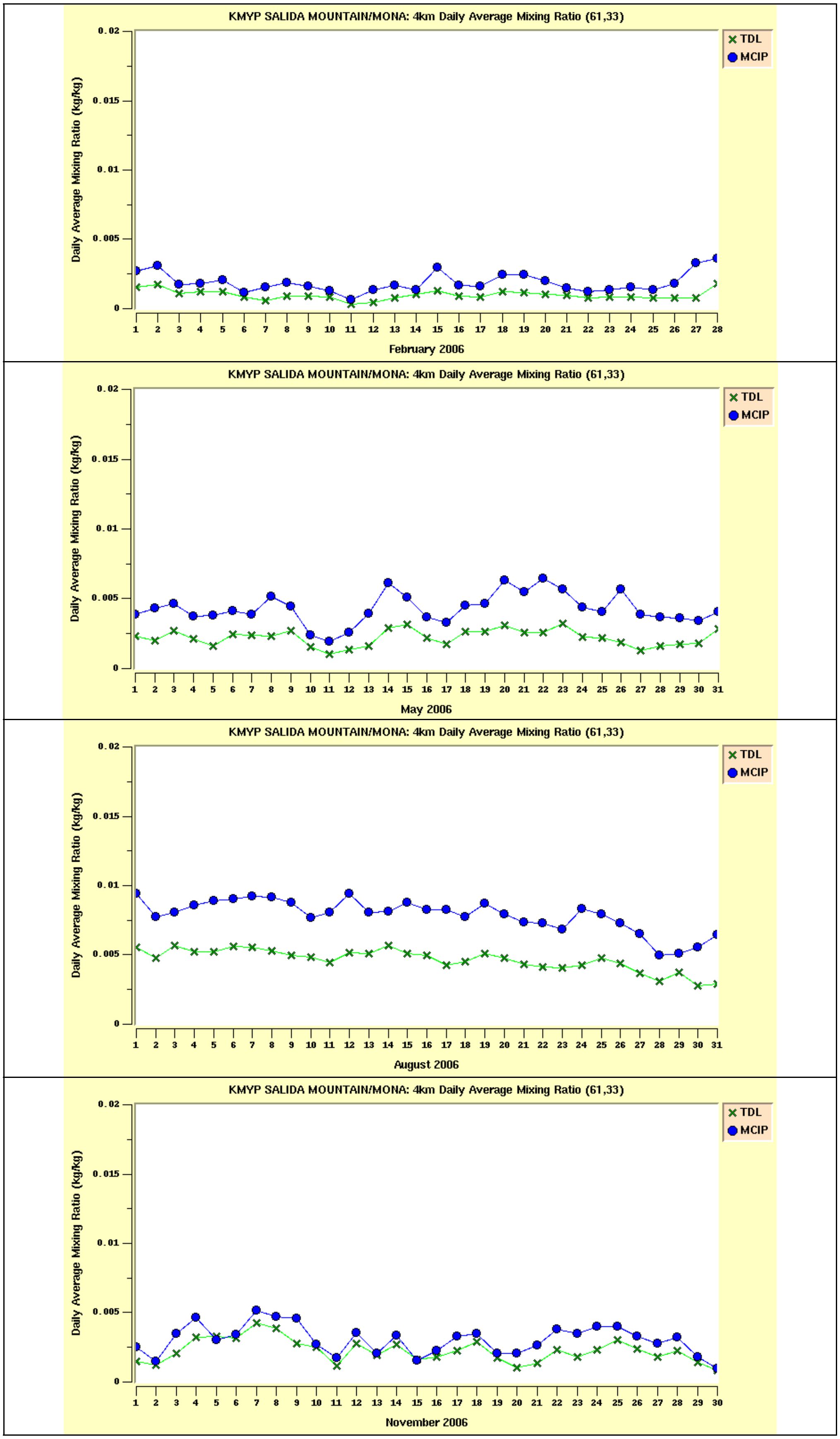


Figure B.2. Daily average observation and modeled mixing ratio at the Salida Mountain station.

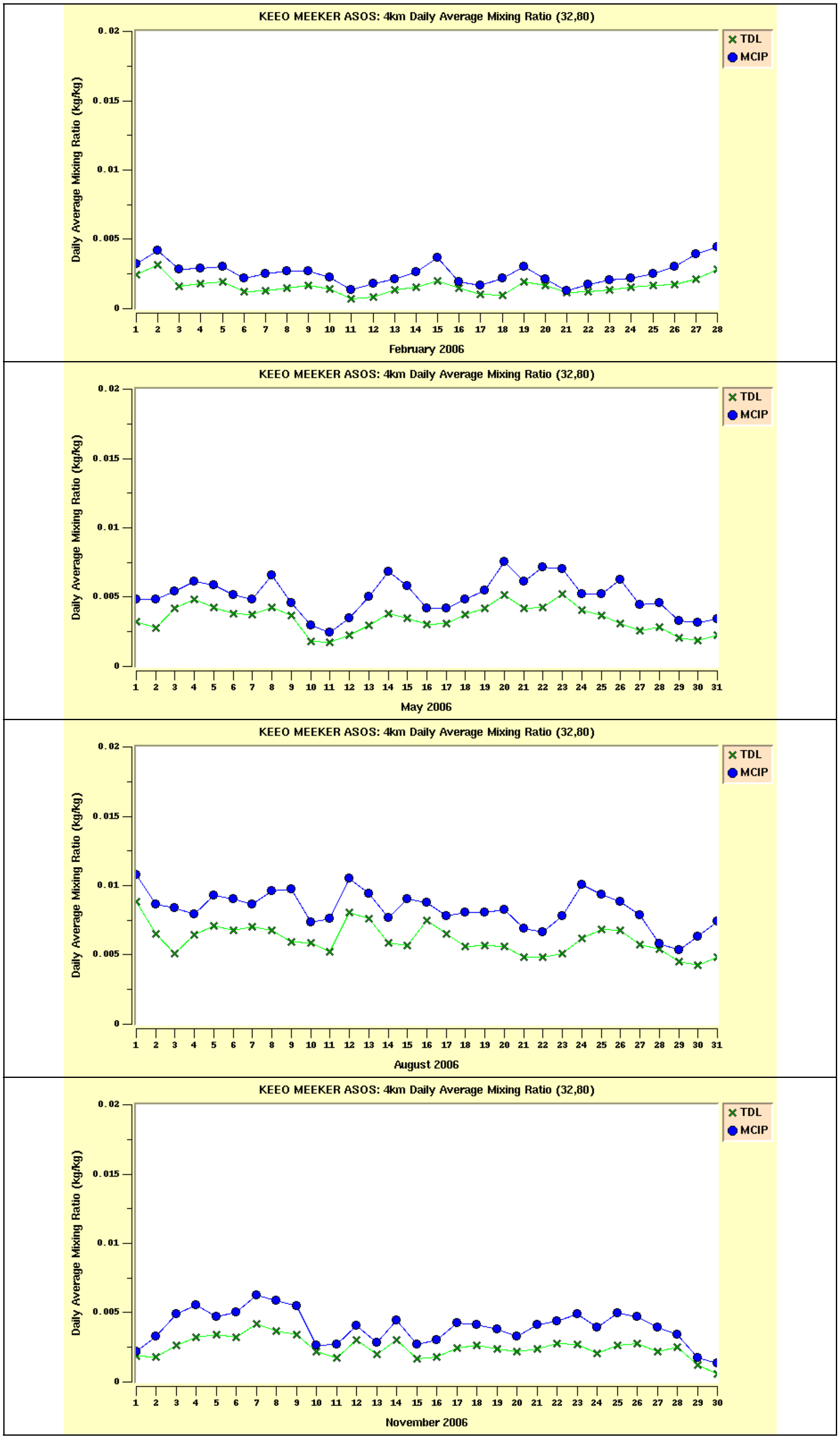


Figure B.3. Daily average observation and modeled mixing ratio at the Meeker ASOS station.

Appendix C

Daily Averaged Observation and Modeled Temperature Time Series

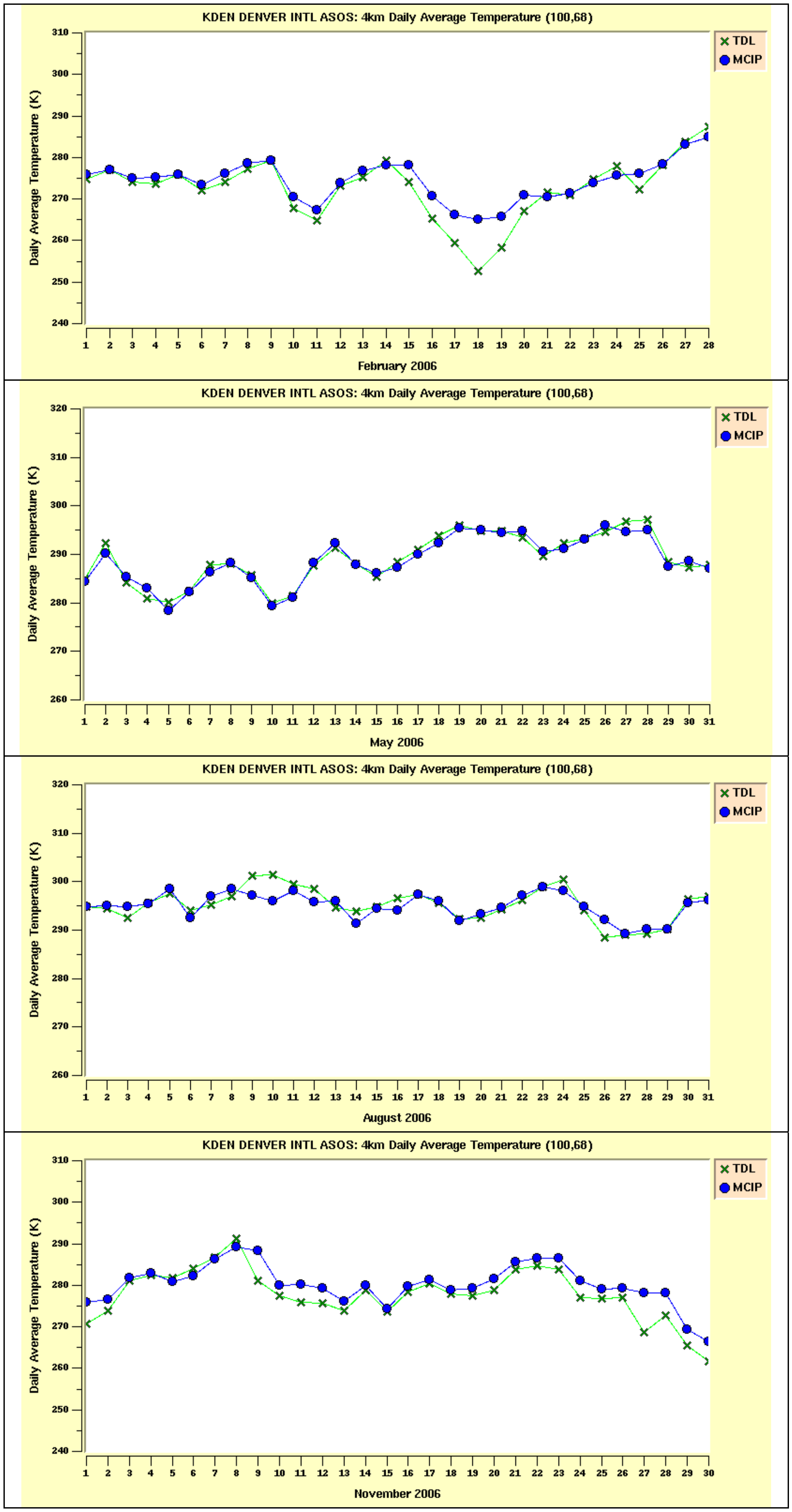


Figure C.1. Daily average observation and modeled temperature at Denver Intl. ASOS station.

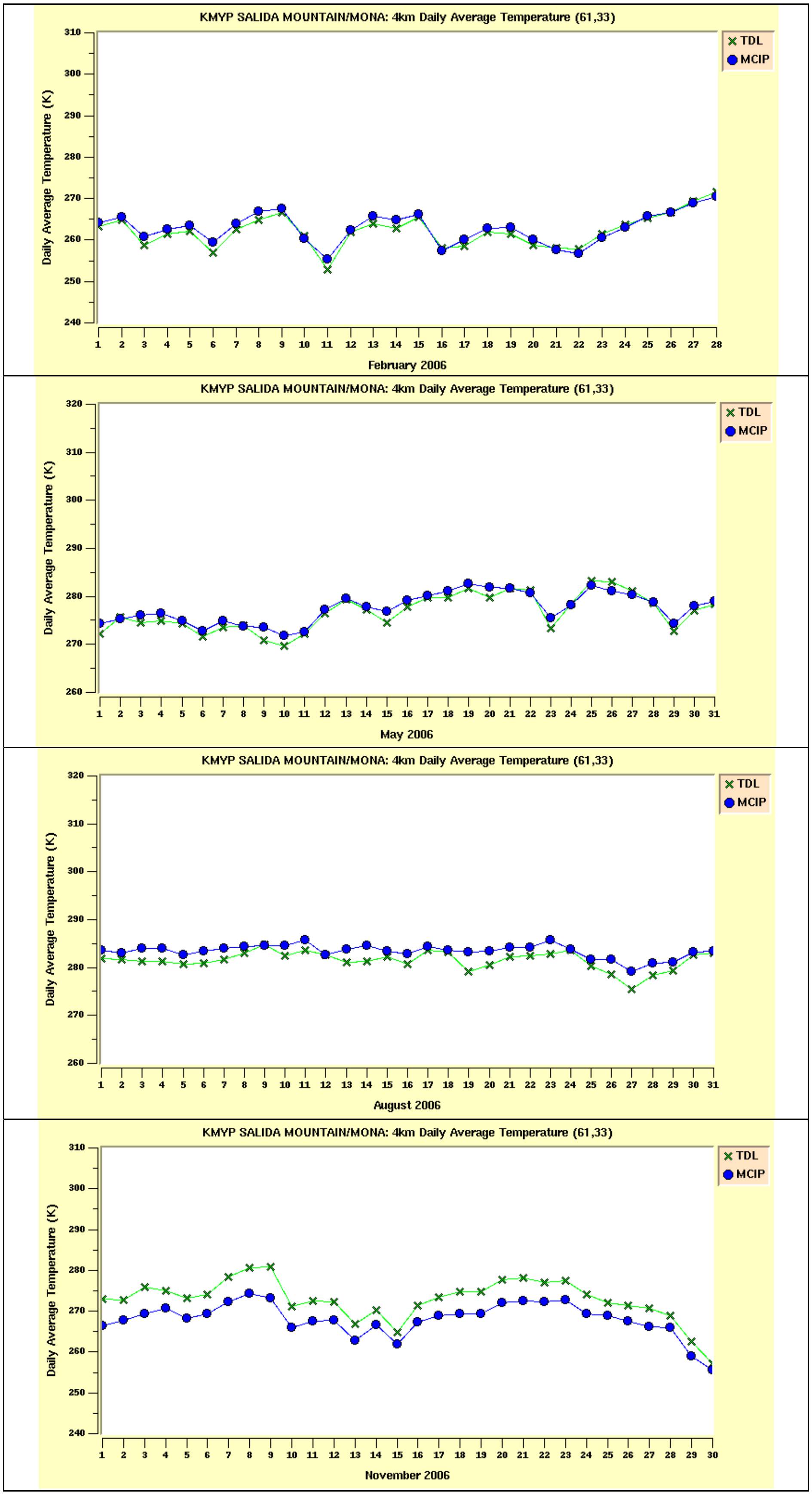


Figure C.2. Daily average observation and modeled temperature at the Salida Mountain station.

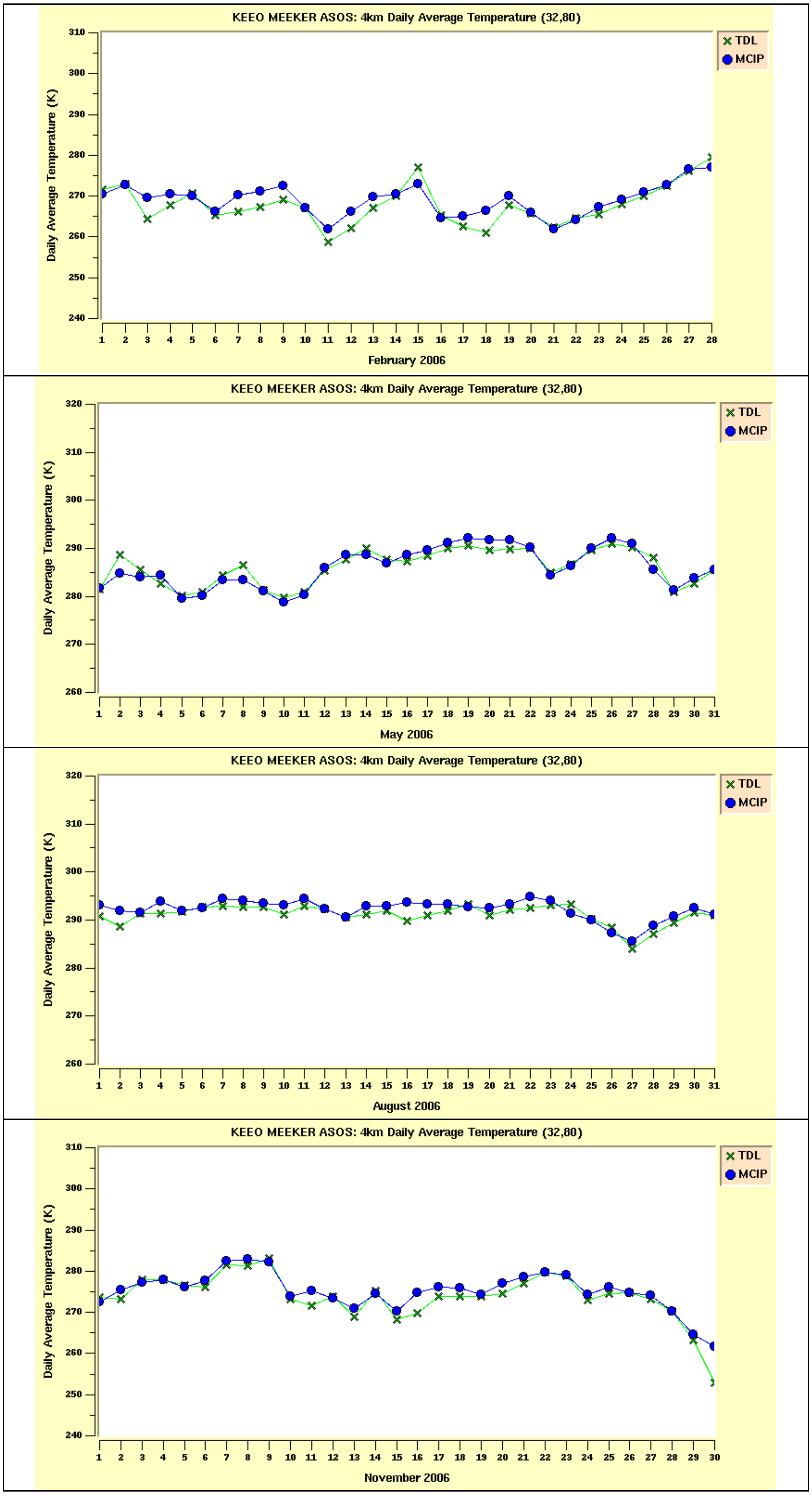


Figure C.3. Daily average observation and modeled temperature at the Meeker ASOS station.

Appendix D

Topographic Wind Plots

(These wind plot files are too large to be included in the electronic document.
The plots are included in printed copies of this report.)