Appendix D

Model Performance Evaluation of the 2005-2006 MM5 Meteorological Model Simulations Used for the Continental Divide-Creston CAMx Photochemical Grid Modeling

APPENDIX D – MODEL PERFORMANCE_EVALUATION_ OF_THE_2005-2006_MM5 SIMULATIONS

INTRODUCTION

For the Continental Divide-Creston (CD-C) oil and gas (O&G) development project Environmental Impact Statement (EIS), the Comprehensive Air-quality Model with extensions (CAMx; ENVIRON, 2009) photochemical grid model is being run for the 2005 and 2006 base case years. To provide a meteorological database for these CAMx simulations, the MM5 mesoscale meteorological model (Dudhia, 1993; Grell, Dudhia and Stauffer, 1994) was run for the 2005-2006 period. An overview of the MM5 modeling domain and model configuration is given in Section 4.4.1. The 2005 and 2006 MM5 runs were evaluated against observed surface and aloft meteorological data, with a focus on Southwest Wyoming (SWWY). The model performance evaluation addresses the following question: is the performance of the 2005-2006 MM5 run sufficiently good to allow CAMx to accurately characterize transport, chemistry, and removal processes and accurately simulate pollutant concentrations over SWWY and surrounding states?

To provide a reasonable meteorological characterization to CAMx, MM5 must represent with some fidelity the large-scale and mesoscale wind, temperature, humidity and precipitation fields. If errors in the meteorological fields are too large, the ability of the air quality model to replicate regional pollutant levels over the two-year base case period will be hampered and the predicted air quality and visibility impacts from future year growth and controls will be unreliable. Accurate simulation of winds is critical to model transport of pollutants from emissions sources to receptors within the domain. For visibility impact analysis, the moisture and condensate fields are particularly important as they impact PM chemical formation, removal, and light scattering efficiency. In addition, cloud and precipitation fields are a good integrated measure of the performance of the model since these are model-derived quantities and are not nudged to observations. Because of the model's coarse resolution of 36/12/4 km, the present runs cannot be expected to faithfully simulate the high frequency pattern or variability of the convective precipitation, but should reproduce the synoptic precipitation patterns.

In this evaluation, we focus on the model's simulation of near-surface wind, temperature, and humidity and precipitation. Annual MM5 runs generate a very large amount of data to be analyzed, so we evaluate the overall model performance by month, focusing on Southwest Wyoming monitors. In the Western Regional Air Partnership (WRAP) 2002 regional haze modeling annual run, the MM5 evaluation focused on model performance during sample winter, summer, and transitional months (i.e. January, July, April, and October) as these months were determined to have performance representative of their entire season (Kemball-Cook et al., 2004). In the 2005/2006 MM5 evaluation presented in this Appendix, we focus on months within the January-July period, since most high ozone events and many high nitrate events in SWWY occurred during these months in 2005-2006. To place the MM5 performance in context of other annual simulations, we compare the performance of the CD-C MM5 runs with other annual MM5 modeling efforts such as 2002 WRAP, VISTAS, CENRAP Regional Planning Organization (RPO) runs made for regional haze modeling. Finally, we provide an overview of the 2005/2006 MM5 model performance and discuss how the MM5 performance may be expected to affect the CAMx simulations.

APPENDIX D – MODEL PERFORMANCE_EVALUATION_ OF_THE_2005-2006_MM5 SIMULATIONS

The 2005 36/12/4 km MM5 model output used in the CD-C CAMx modeling was built off of 2005 36/12 km MM5 modeling that was originally performed to support an NO_2 PSD increment consumption analysis for the New Mexico Environment Department (NMED) that was funded by Western Refining (ENVIRON and Alpine, 2009) and subsequently used for CAMx modeling in the Four Corners Air Quality Task Force (FCAQTF) study (ENVIRON, 2009). Additional 2005 4 km MM5 modeling was performed under the Continental Divide-Creston (CD-C) EIS Project for SWWY using a nest down from the FCAQTF 12 km MM5 output. Similarly, 2006 36/12 km MM5 modeling was conducted using the same 36/12 km grid structure as in the FCAQTF and then one-way 4 km MM5 modeling conducted for SWWY.

MODEL CONFIGURATION

CUMULUS PARAMETERIZATION

The physics options used for the final MM5 simulations for 2005 and 2006 on the 4 km domain are listed in Table 4.2. The MM5 simulations for the 36/12 km grids were run with same options as for the 4 km domain, except that cumulus parameterization not used in the 12 km run from the PSD Increment Consumption/FCAQTF projects that was used for the CD-C 4 km boundary conditions. The 2006 CD-C 4 km run was performed before the 2005 run and no cumulus parameterization (CuP) was used in order to maintain consistency with the 12 km grid. The model performance evaluation of the initial 2006 4 km run showed that rainfall was overestimated in summer. Overstated model resolved convective rainfall can adversely influence wind fields and CAMx simulation of wet deposition, so a sensitivity test was carried out in order to improve MM5's performance in simulating summer rainfall. The 2005 CD-C 4 km run was subsequently made with the Kain-Fritsch II CuP in order to enhance the release of sub-grid scale convective instability and reduce excessive rainfall. Because this run showed better precipitation performance than the 2006 run, a second 2006 run was then made with Kain-Fritsch II CuP and with additional surface observation wind nudging within the 4 km domain. In the text and figures below, the original 2006 run that was not run with a CuP is referred to as the Old Run and the second run that was performed with the Kain-Fritsch CuP and additional observation nudging is called the New Run.

OBSERVATION NUDGING

Observation nudging to the National Center for Atmospheric Research (NCAR) ds472 airport surface wind data was performed for both the 2005 and 2006 runs; both runs were also nudged to the observed winds from the Jonah, Boulder, and Daniel industrial site monitors in Southwest Wyoming. For 2006, additional Wyoming industrial sites were used for surface wind observation nudging in the New Run (with CuP), some of which were not in operation during 2005. The additional stations are Simplot, OCI, Whitney Canyon, Riverton, Centennial, Rock Springs, Evanston, and Wamsutter. The locations of the ds472 and additional stations used for observation nudging as well as model performance evaluation are shown as red crosses in Figure D.1 and the additional Wyoming industrial sites are shown by the blue circles. For both 2005 and 2006, analysis nudging was performed for winds, temperature, and humidity above the boundary layer. MM5 default nudging coefficients were used for all observation and analysis nudging.

APPENDIX D – MODEL PERFORMANCE_EVALUATION_ OF_THE_2005-2006_MM5 SIMULATIONS

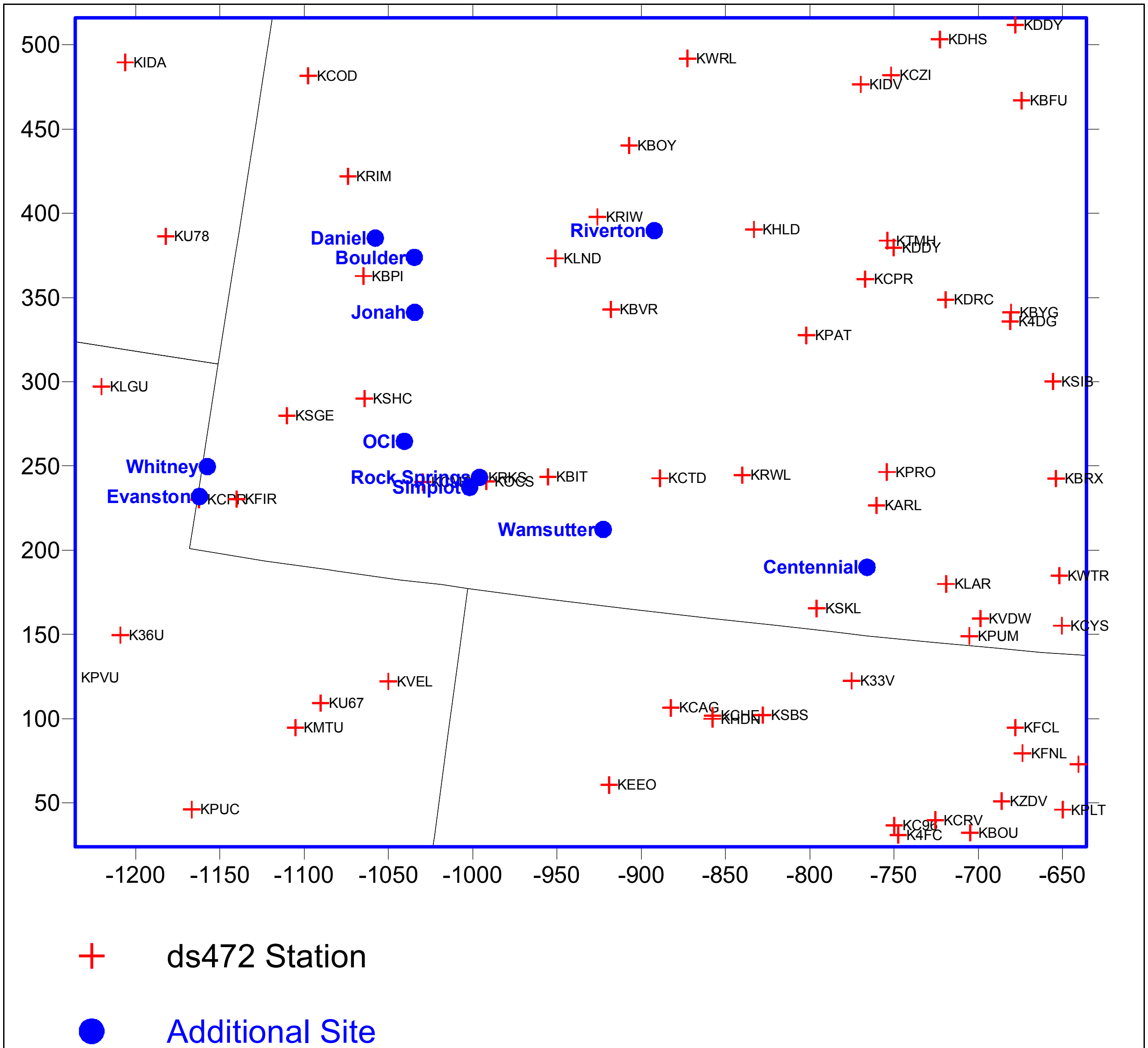


Figure D.1. 4 km Grid Meteorological Station Locations used in the Observation Nudging.

APPENDIX D – MODEL PERFORMANCE_EVALUATION_ OF_THE_2005-2006_MM5 SIMULATIONS

EVALUATION OF PERFORMANCE ACROSS THE 4 KM DOMAIN

As a starting point for the MM5 model performance evaluation, we examine overall surface performance across the 4 km domain during January and July of 2005 and 2006. Observed and modeled surface wind, temperature, humidity time series were averaged for all ds472 sites within the 4 km domain. January and July surface time series were found to be representative of winter and summer performance for individual stations within Wyoming and are presented in Figures D.2-D.9.

SURFACE WINDS

The 2005 and 2006 January surface wind time series are shown in Figures D.2 and D.3, respectively. Many of the main features of the observed wind speed time series are captured by the model, but there is an overall low wind speed bias that persists through most of the month in both years. The gross features of the observed wind direction time series are controlled by the large-scale flow following the progression of frontal systems through the region. Superimposed on the large-scale flow are more rapid wind shift changes that may be due to variability at smaller spatial scales, such as drainage flows in mountainous areas. MM5 does not reproduce some of the high frequency variability in wind direction, but wind direction performance is generally very good.

The July wind time series (Figures D.6 and D.7) are similar to January in that the performance for winds is generally good, but there is an overall low bias in wind speeds and the model is not able to simulate many of the abrupt changes in wind direction. In July, there are fewer large frontal systems transiting the 4 km domain and the observed winds are more affected by the diurnal cycle and by variability at local scales that are not well-resolved by the model. The observed wind direction time series therefore has many more high-frequency shifts in wind direction than in January and is harder fir the model to simulate.

SURFACE TEMPERATURE

The observed and modeled January temperature time series are shown in the upper panels of Figures D.4 (2005) and D.5 (2006). In both years, the model captures the low frequency variability in the observed temperatures quite well, but is less successful in reproducing the daily maximum and minimum temperatures. In July (Figures D.8 and D.9), the daily temperature peaks are well-simulated in both years, but night time temperature minima are not low enough-this is likely related to excessive surface humidity in the model, as discussed in the next section.

SURFACE HUMIDITY

The observed and modeled January water vapor concentration (humidity) time series are shown in the lower panels of Figures D.4 (2005) and D.5 (2006). In both years, the model reproduces the general trends in variability of the observed humidity, but has a high bias through most of the months. July is shown in Figures D.8 (2005) and D.9 (2006). In July, the observed humidity is higher, and there is more day-to-day humidity variation than in January. The model also shows an increase in overall humidity in July relative to January, but has a high bias in humidity throughout most of July during both 2005 and 2006. The high bias in humidity is most likely the result of excessive summer convective precipitation in the model (discussed below). The high bias in the surface humidity can also affect the surface temperature by causing incorrect partitioning of latent and surface heat fluxes.

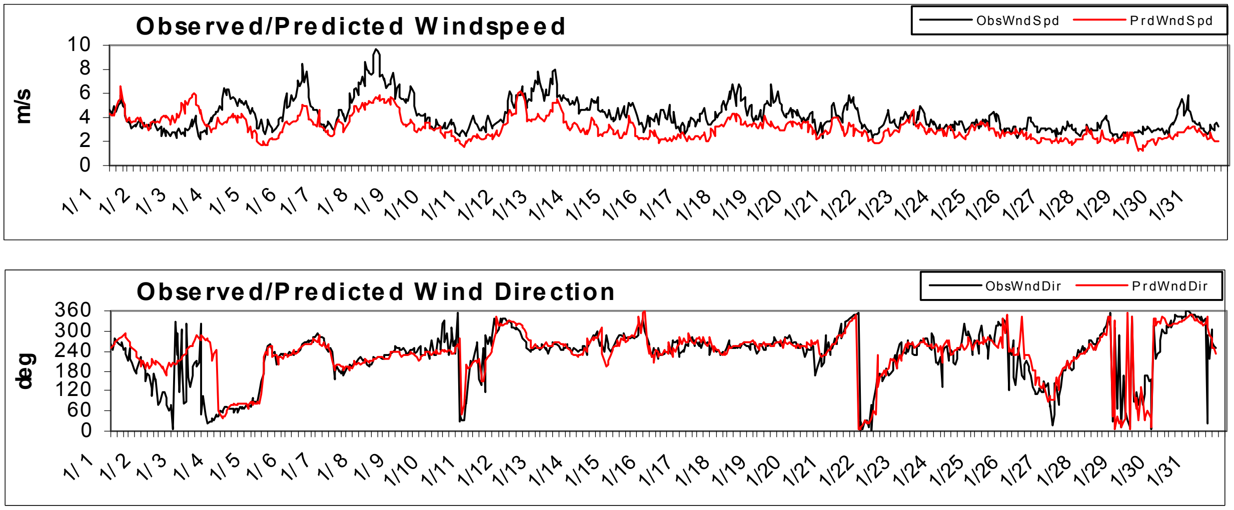


Figure D.2. Time series of observed (black) and MM5 (red) January 2005 near-surface wind speed (upper panel) and wind direction (lower panel) averaged over all monitoring sites in the 4 km grid.

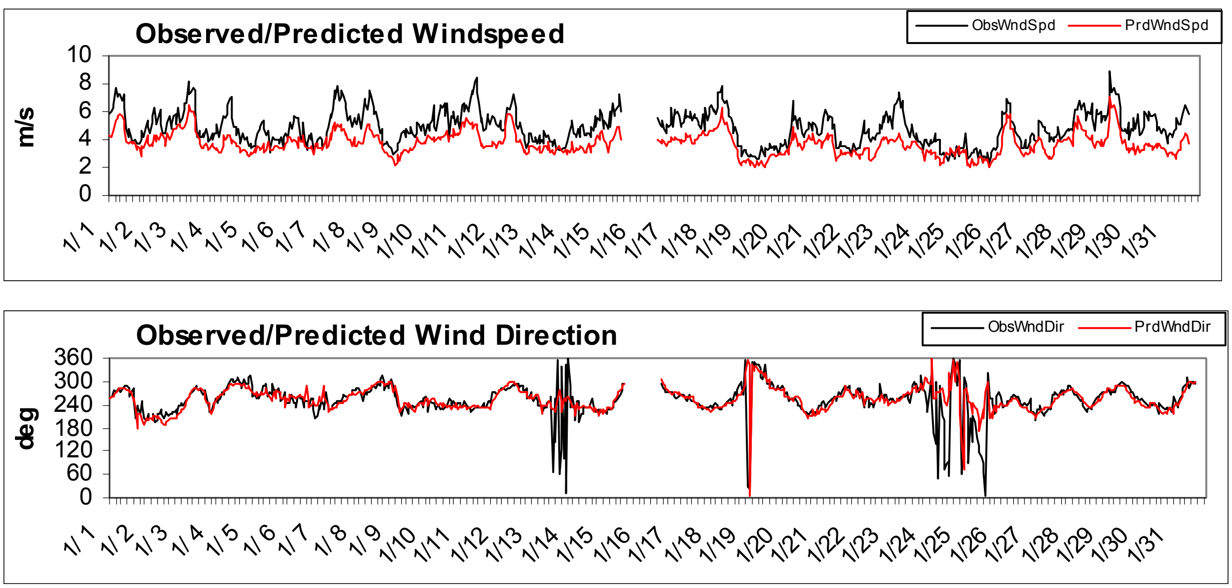


Figure D.3. Time series of observed (black) and MM5 (red) January 2006 near-surface wind speed (upper panel) and wind direction (lower panel) averaged over all monitoring sites in the 4 km grid.

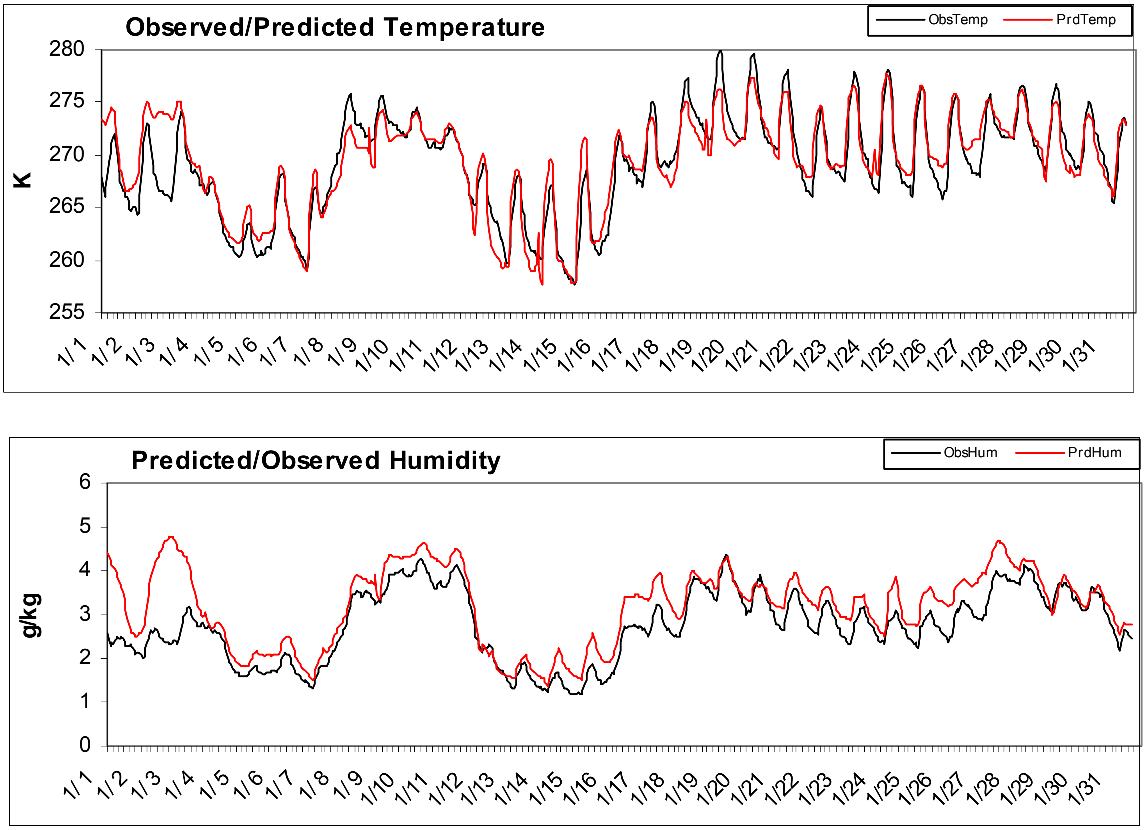
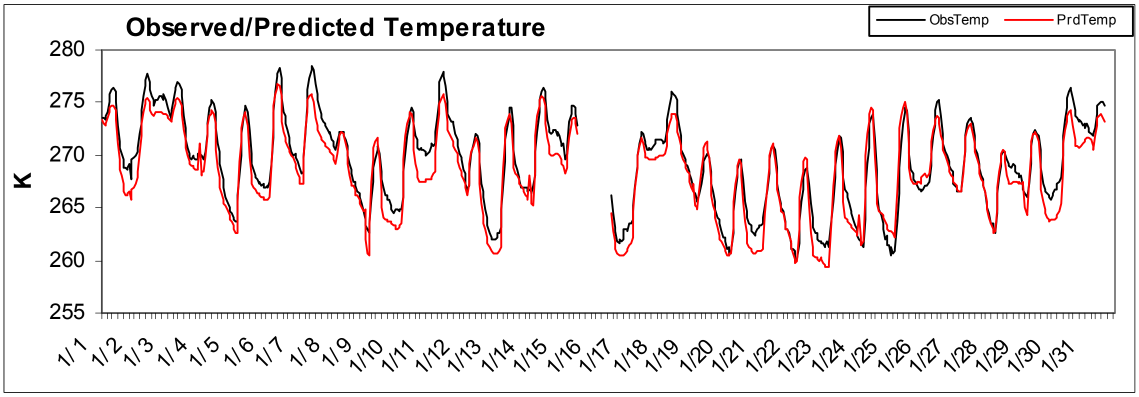


Figure D.4. Time series of observed (black) and MM5 (red) January 2005 near-surface temperature (upper panel) and humidity (lower panel) averaged over all monitoring sites in the 4 km grid.



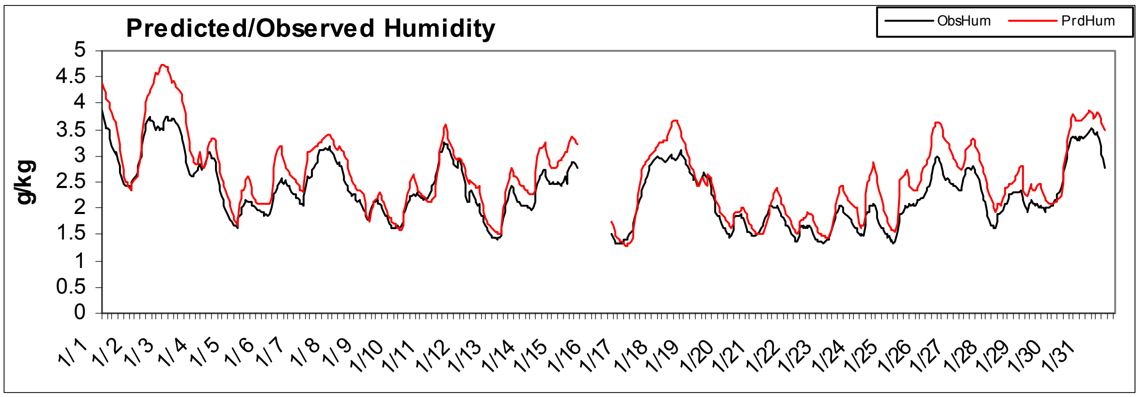


Figure D.5. Time series of observed (black) and MM5 (red) January 2006 near-surface wind speed (upper panel) and wind direction (lower panel) averaged over all monitoring sites in the 4 km grid.

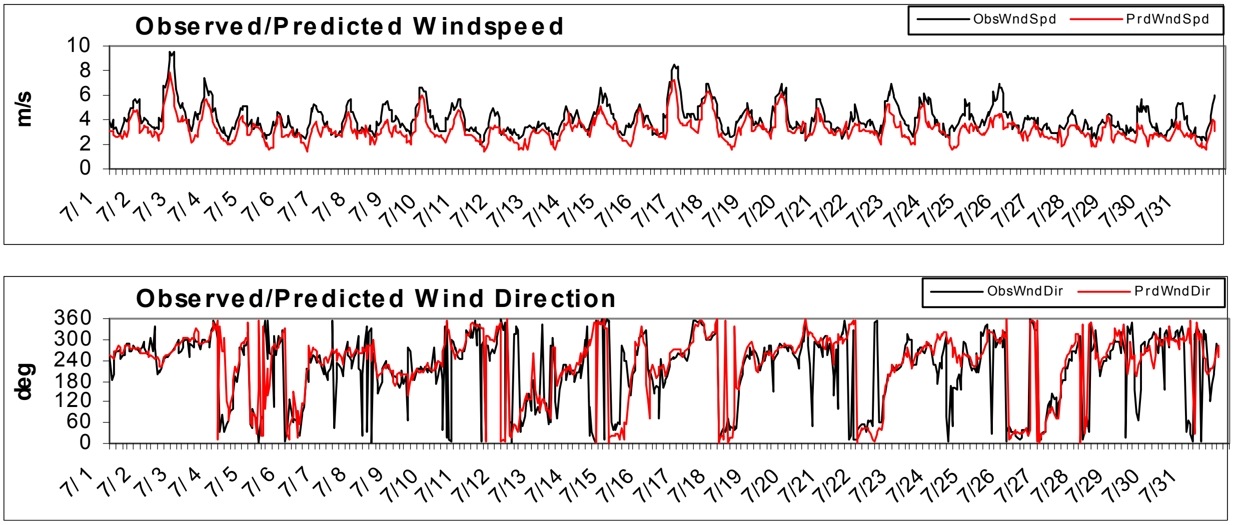


Figure D.6. Time series of observed (black) and MM5 (red) July 2005 near-surface wind speed (upper panel) and wind direction (lower panel) averaged over all monitoring sites in the 4 km grid.

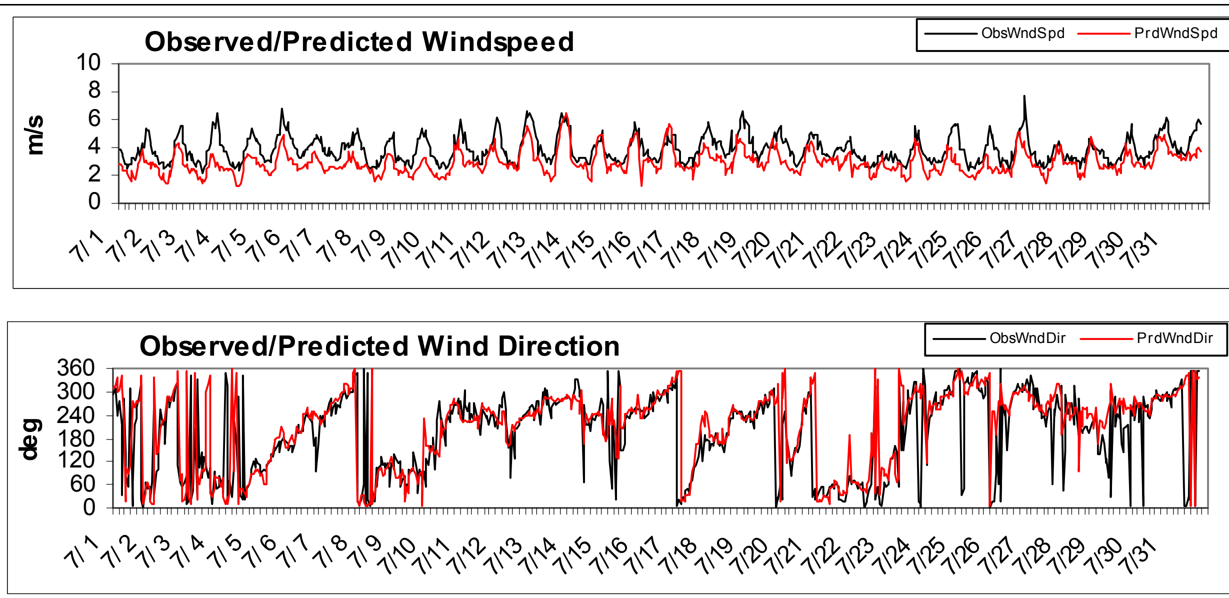


Figure D.7. Time series of observed (black) and MM5 (red) July 2006 near-surface wind speed (upper panel) and wind direction (lower panel) averaged over all monitoring sites in the 4 km grid.

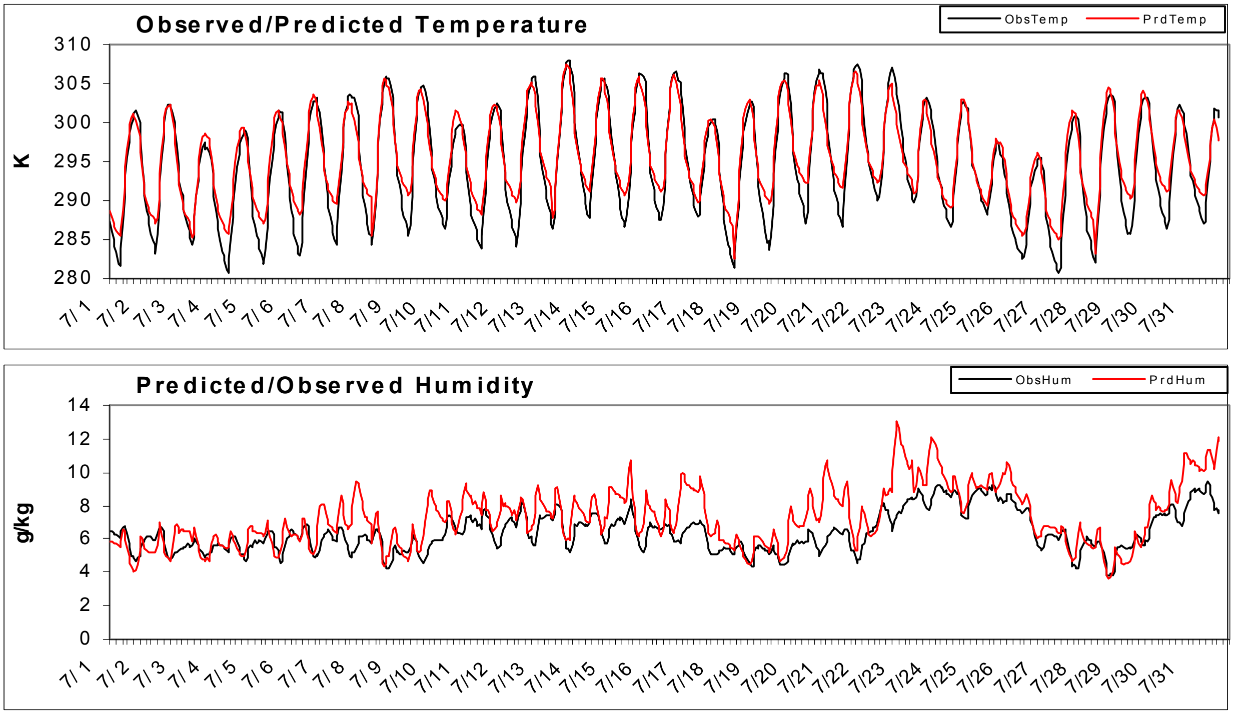


Figure D.8. Time series of observed (black) and MM5 (red) July 2005 near-surface temperature (upper panel) and humidity (lower panel) averaged over all monitoring sites in the 4 km grid.

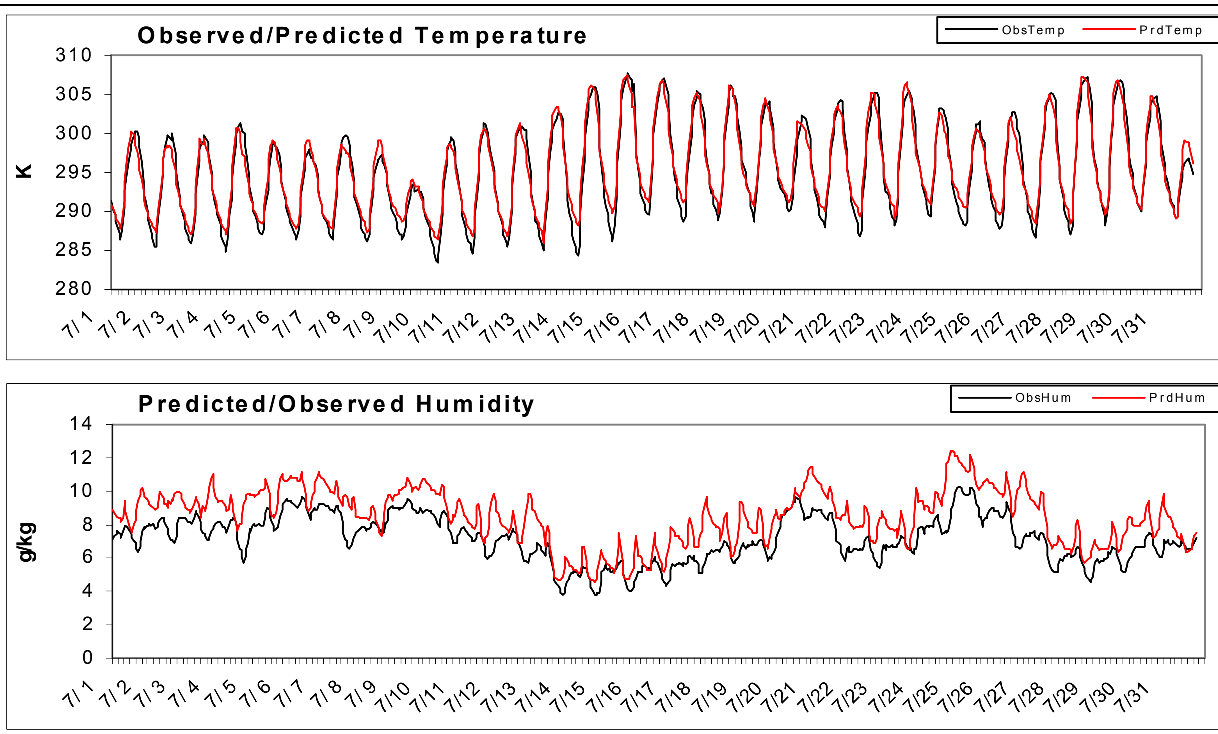


Figure D.9. Time series of observed (black) and MM5 (red) July 2006 near-surface wind speed (upper panel) and wind direction (lower panel) averaged over all monitoring sites in the 4 km grid.

APPENDIX D – MODEL PERFORMANCE_EVALUATION_ OF_THE_2005-2006_MM5 SIMULATIONS

SITE-SPECIFIC SURFACE WIND ROSE AND TIME SERIES ANALYSIS

The model performed reasonably well when performance is averaged across all monitoring sites in the 4 km domain; however, month-long averages taken over a large region can smooth over performance problems. We now turn to an examination of data for individual stations in Wyoming. For this phase of the evaluation, we choose sites within and outside Sublette County, and focus on the Wyoming state industrial site monitors in SWWY.

Wind roses are used to summarize station near-surface wind speed and direction performance over the course of a year. In a wind rose, the orientation and length of spokes indicates the frequency with which each wind direction occurs. The spokes show the direction from which wind blows toward the monitor, and the colored bands indicate the percentage of time the winds fall in a given speed range.

SUBLETTE COUNTY MONITORS

The 2005 wind rose for the Jonah monitor is shown in Figure D.10. The 4 km MM5 run shows good wind direction performance, but exhibits a low bias in simulating peak wind speed. The 4 km MM5 run shows clear improvement in both wind speed and direction over 12 km MM5 meteorological data used for the Moxa Arch CALMET modeling. In 2006, the Jonah wind rose shows that the 4 km MM5 run again captures the distribution of wind directions well, with the new CuP run doing a slightly better job than the old run with no CuP in simulating the highest wind speeds. The old run however, does a better job of simulating the frequency of winds out of the NNW.

The wind roses for the Daniel monitor for 2005 and 2006 Daniel 2005 are shown in Figures D.10 and D.11. The model correctly reproduces the dominant NW wind direction in 2005, although has a low bias in simulating peak wind speeds.

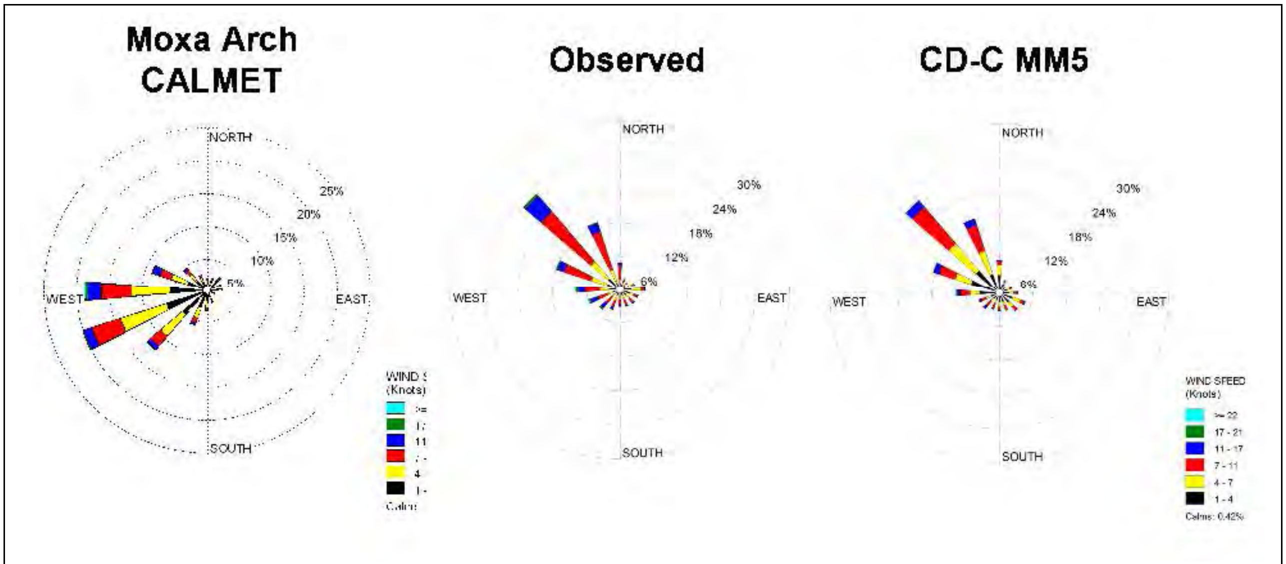


Figure D.10. Wind rose for 2005 near-surface winds at the Jonah monitor.

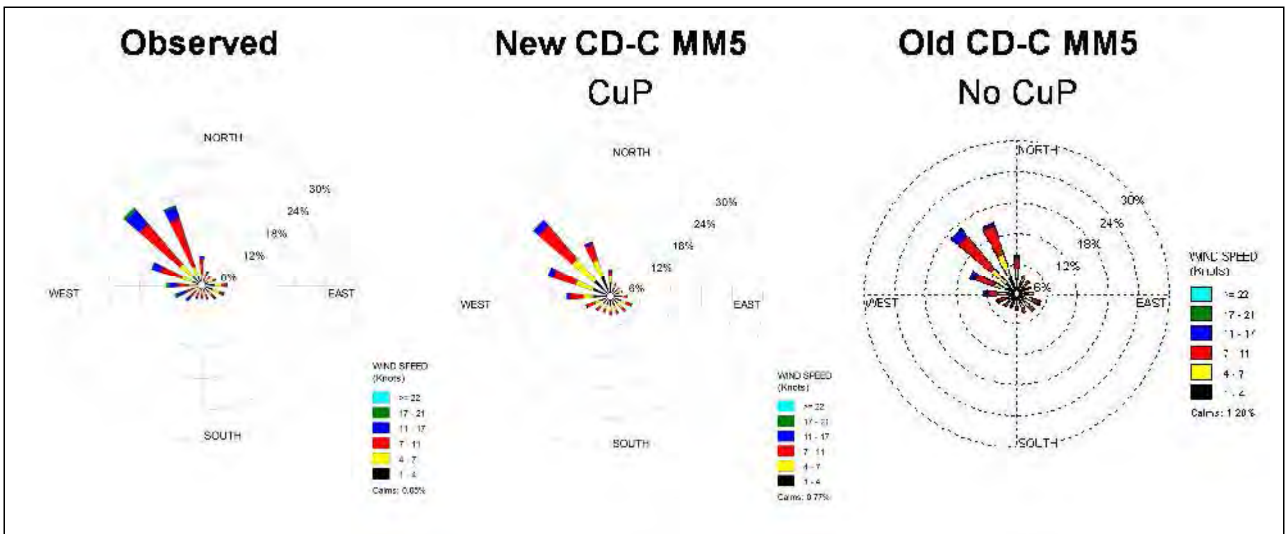


Figure D.11 Wind rose for 2006 near-surface winds at the Jonah monitor.

The model underestimates the frequency of southeasterly winds in 2005 but does a better job with this feature in both the old and new 2006 runs. The new (CuP) 2006 run shows clear improvement in its simulation of the NW winds that dominate the wind rose for the observed winds. However, the old run better reproduced the fact that the observed winds are strongly channeled in a particular direction, albeit with a bias in the direction, while the new run has winds that range more broadly around the NW quadrant of the compass.

Wind roses for the Boulder monitor are shown in Figures D.14 and D.15. In 2005, the model underestimates the frequency of easterly winds, with wind directions that cluster too tightly around W-NW. There is a small westerly directional bias and the modeled NW Winds have a low wind speed bias; the model understates the magnitude of the peak wind speed events. In 2006, the new (CuP) run shows some improvement in wind direction relative to the old (no CuP) run, with flow in the old run too strongly channeled in the NW direction. This problem is less pronounced in the new run. As in 2005, the frequency of NE winds is underestimated in 2006.

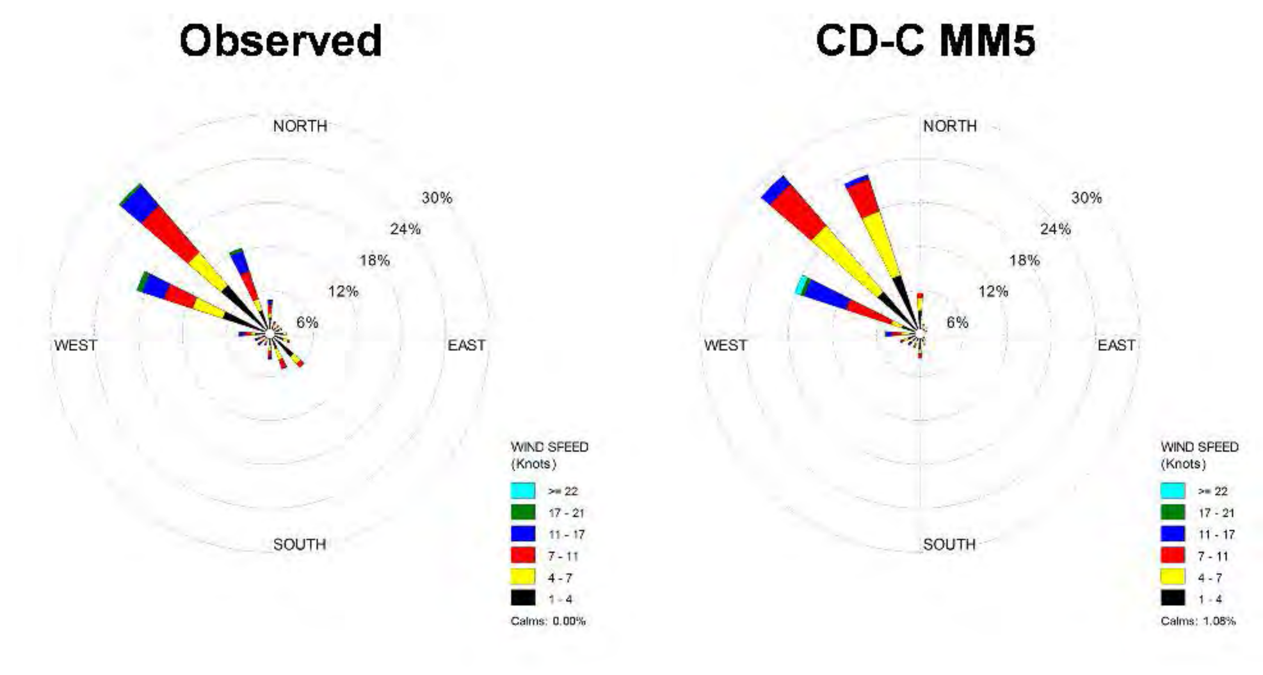


Figure D.12. Wind rose for 2005 near-surface winds at the Daniel monitor.

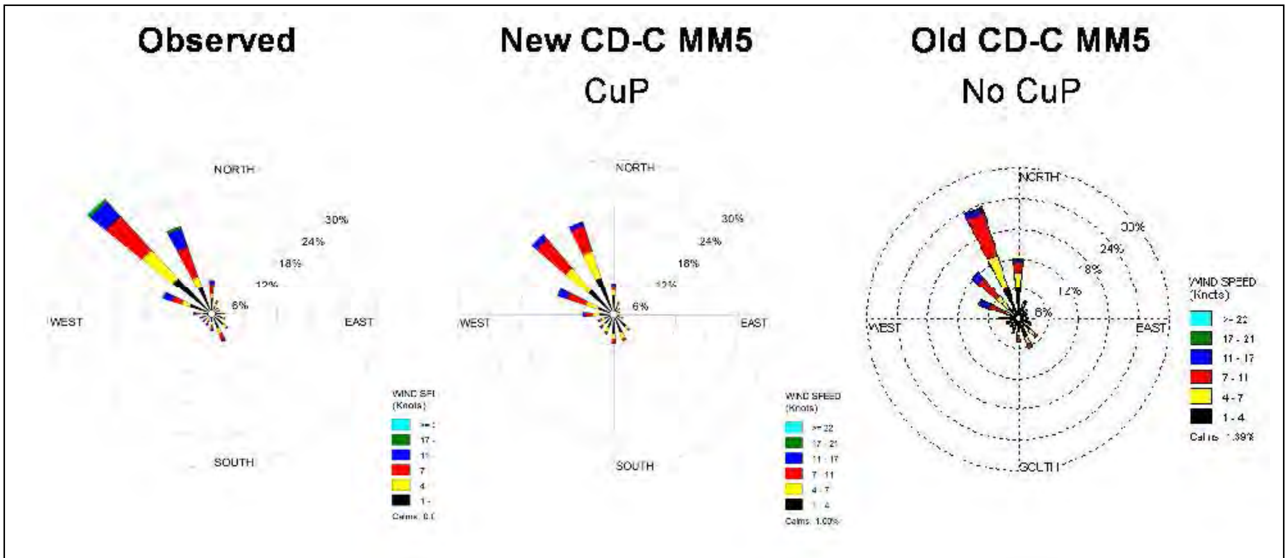


Figure D.13. Wind rose for 2006 near-surface winds at the Daniel monitor.

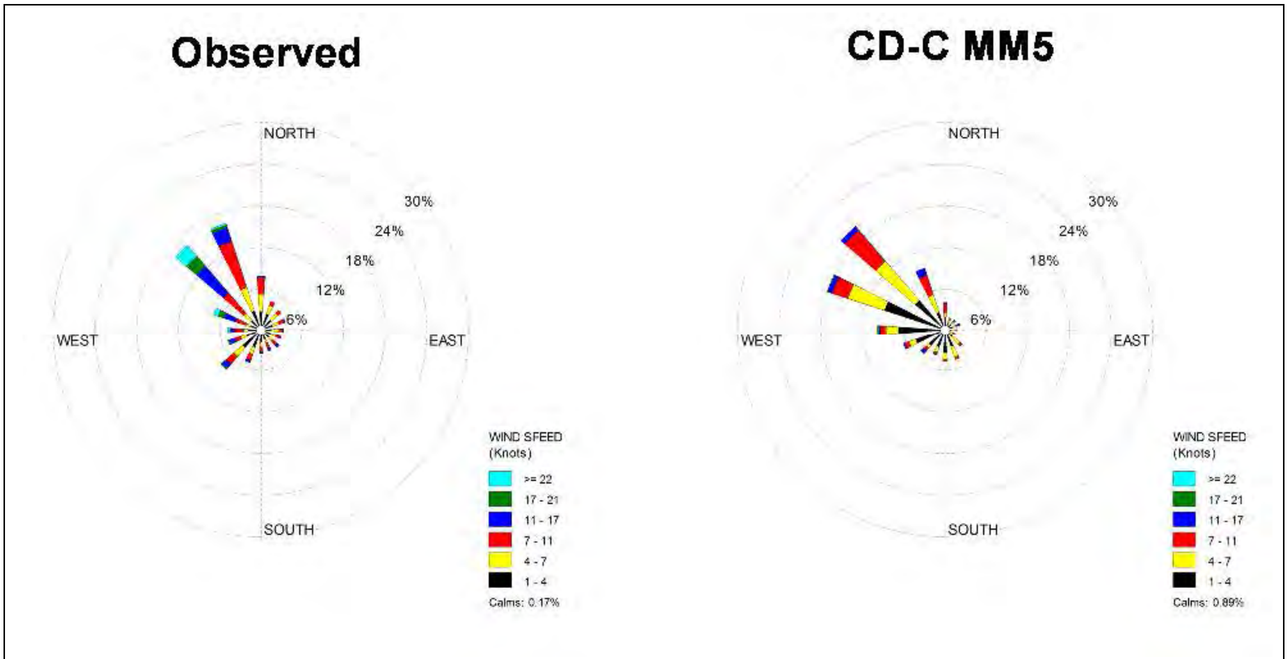


Figure D.14. Wind rose for 2005 near-surface winds at the Boulder monitor.

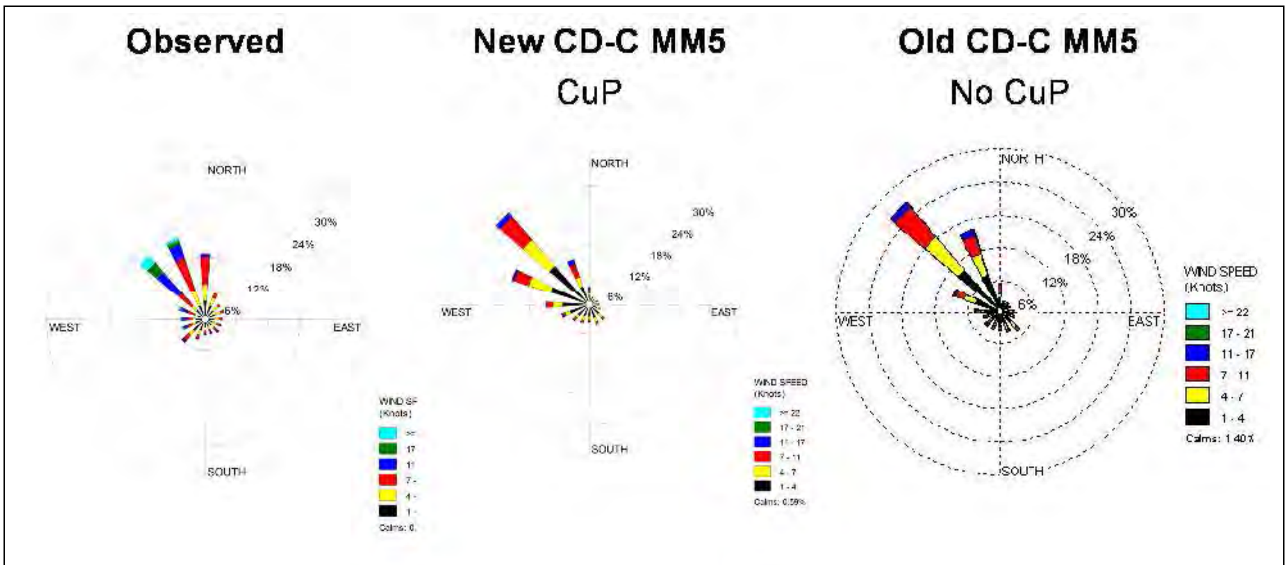


Figure D.15. Wind rose for 2006 near-surface winds at the Boulder monitor.

July wind speed and direction time series for the Sublette County monitors are shown in Figures D.16 and D.17, respectively. The wind speed time series show that the model does a reasonably good job of simulating the diurnal variability, but has a low wind speed bias and underestimates the daily peaks in wind speed. At all three of the monitors, the observed wind direction shows rapid shifts likely driven by local thermal and orographic circulations. This is an extremely challenging meteorological regime for the model to simulate, and the model misses many of these rapid wind shifts.

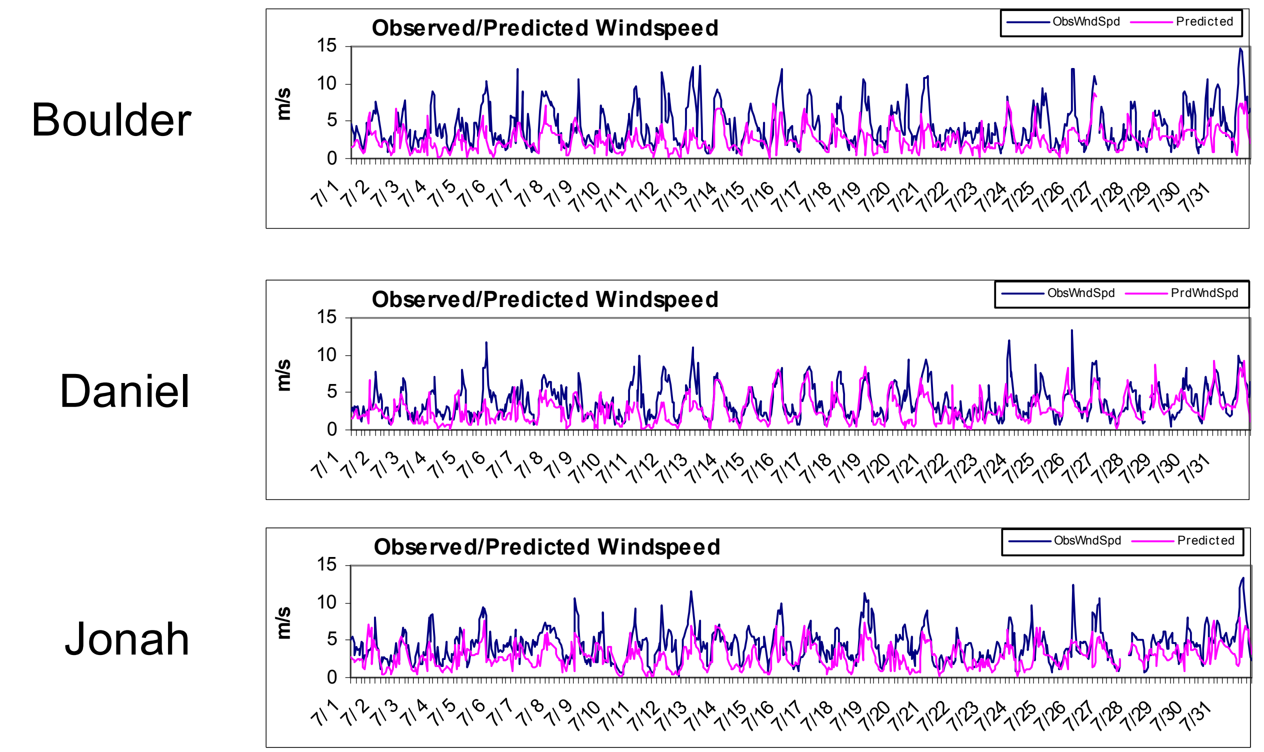


Figure D.16. Time series of observed (blue) and MM5 (pink) July 2006 near-surface wind speed at the Sublette County monitors.

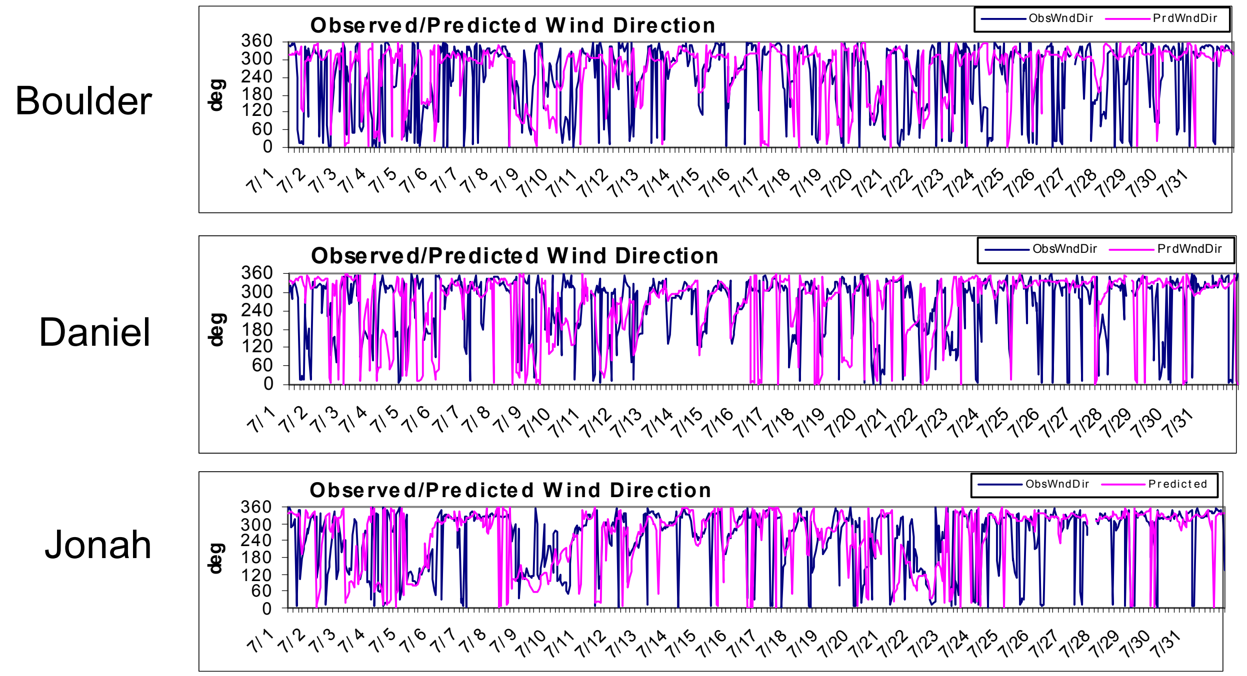


Figure D.17. Time series of observed (blue) and MM5 (pink) July 2006 near-surface wind direction at the Sublette County monitors.

WYOMING MONITORS OUTSIDE SUBLETTE COUNTY

During the original MM5 model performance evaluation reported during the CD-C study, the Wamsutter monitor was incorrectly placed by ~20 miles to the southwest of the actual location due to incorrect location in the file. The original incorrect location and the actual monitor location are shown in Figure D.18. The Wamsutter monitor came online in March 2006, so no data are available for evaluating 2005 model performance. The wind rose for Wamsutter is shown in Figure D.19. The wind direction performance is good, with the southwesterly wind direction frequency represented with reasonable fidelity. The model has a low wind speed bias, however.

The Simplot monitor observed wind rose (Figure D.20) indicates that the mean flow at this monitor is very strongly channeled with a predominantly westerly direction. The model does a fairly good job of reproducing the wind direction, although the flow is not as strongly channeled as the observed winds. There is a low wind speed bias in the modeled wind speeds.

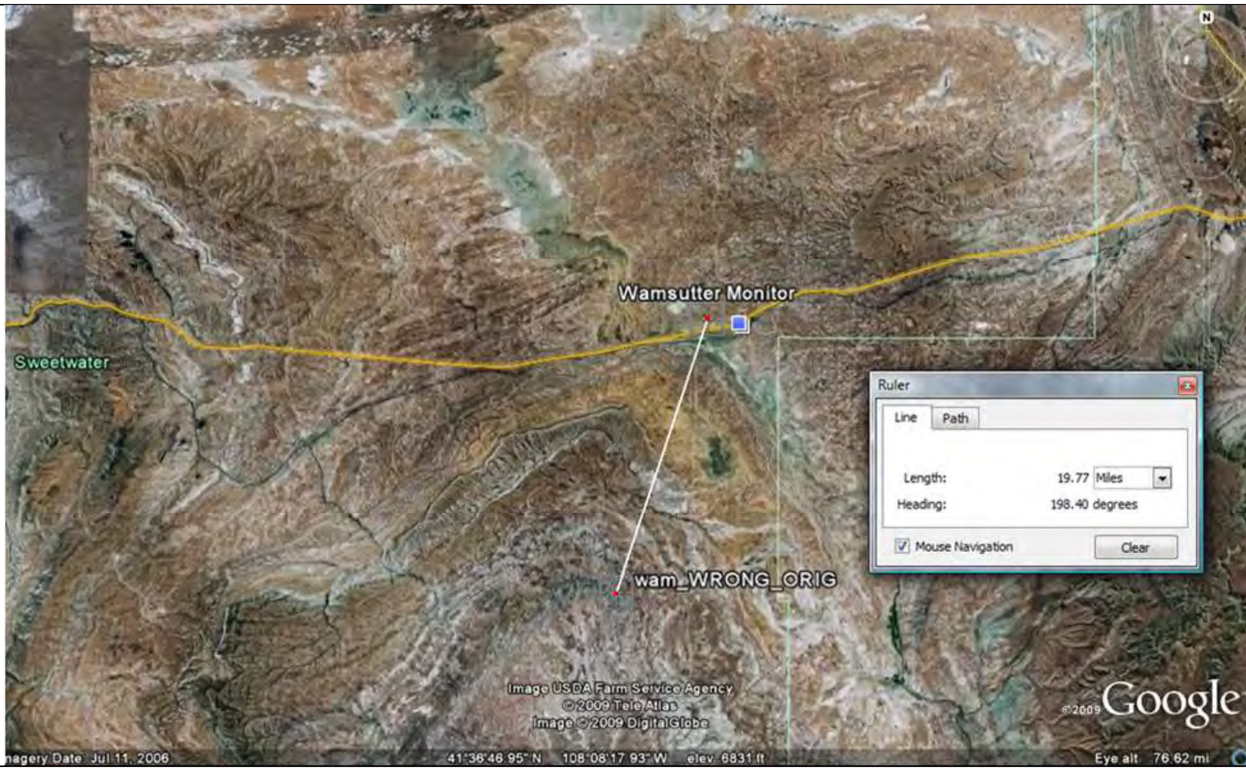


Figure D-18. Corrected Location of Wamsutter Monitor.

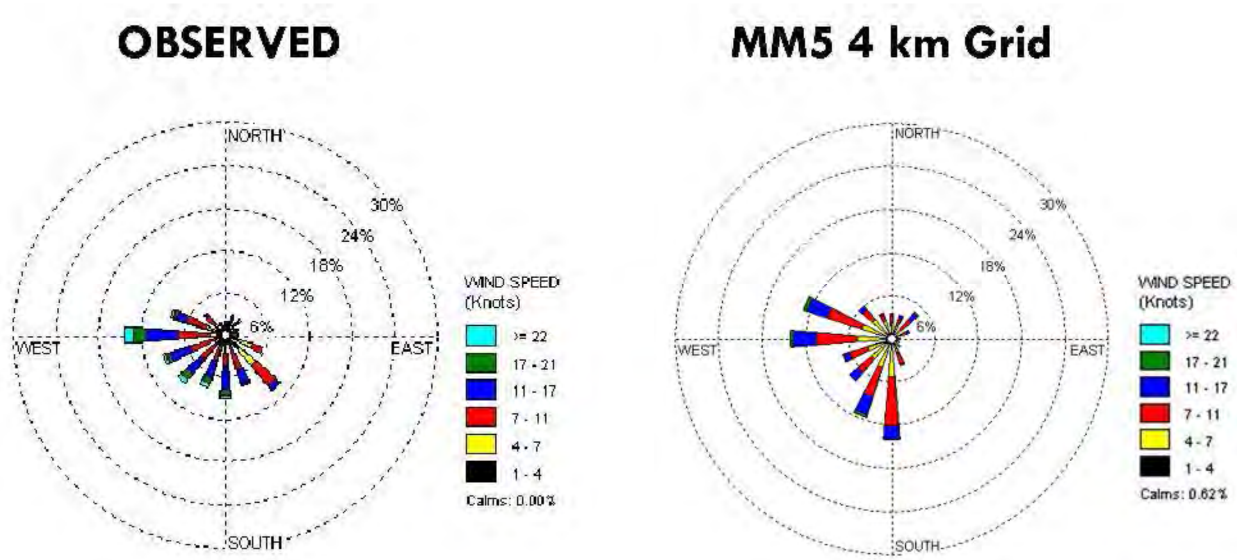


Figure D.19. Wind rose for 2006 near-surface winds at the Wamsutter monitor.

At the Riverton monitor, the observed flow is more evenly distributed in direction with NW winds occurring most frequently. The modeled winds at Riverton are also fairly evenly distributed in direction, but SW winds occur most often. As with the other stations, there is a low bias to the modeled wind speeds. Observed winds and model performance at the OCI monitor (Figure D.22), Evanston (Figure D.24) and the Rock Spring Monitors (Figure D.26) are similar to Riverton with a fairly even distribution of directions, with a westerly peak in direction and low bias to the modeled wind speed. At Centennial (Figure D.23), observed and modeled winds generally out of the west. Unlike the other stations, the model overestimates peak wind speeds for the NW direction at Centennial. At Whitney Canyon (Figure 25), the model does not reproduce the strong westerly direction preference seen in the observed winds, but instead distributes the winds more evenly.

July wind speed and direction time series for the Wamsutter, Simplot, and Riverton monitors are shown in Figures D.27 and D.28 respectively. The diurnal variation in the observed winds is captured by model, but the daily wind speed peaks are too low, resulting in a low wind speed bias. The wind direction time series show fewer sudden wind direction shifts than the Sublette County monitors, and the model performance is better at these non-Sublette County monitors.

Figures D.29 and D.30 show observed and modeled humidity time series for monitors inside and outside Sublette County, respectively. All of these monitors show a positive humidity bias during most of the month of July.

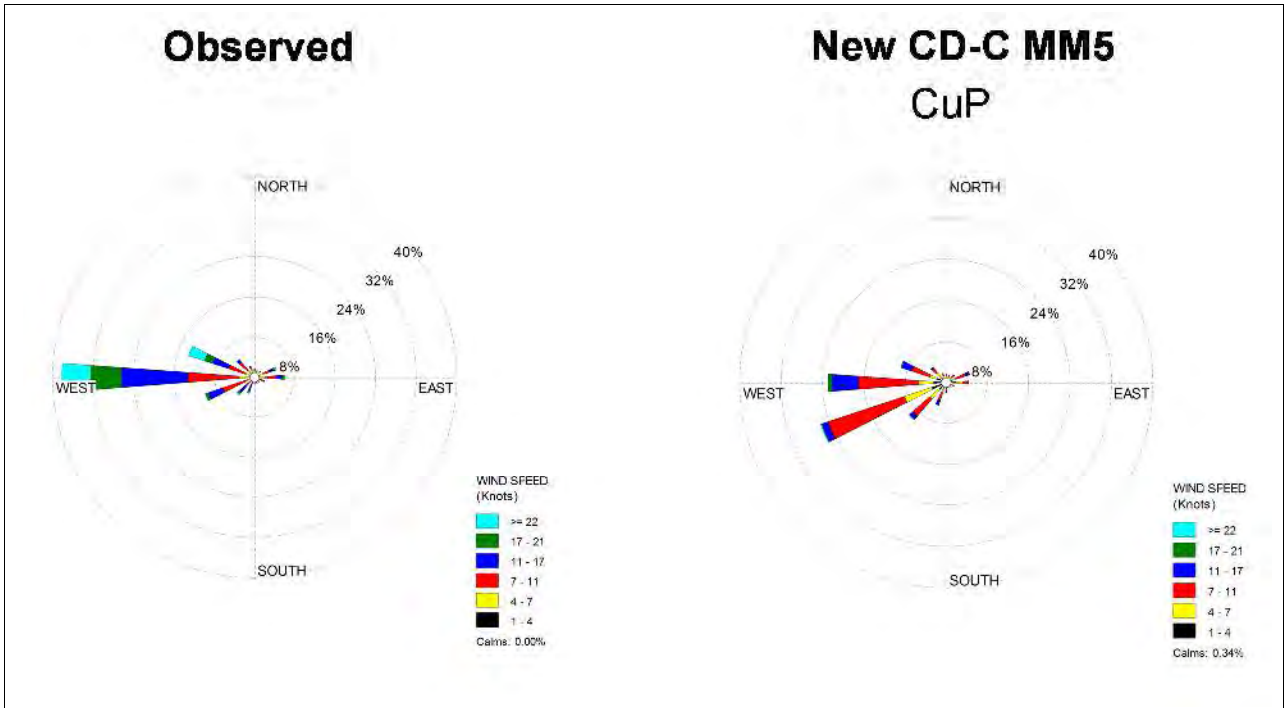


Figure D.20. Wind rose for 2006 near-surface winds at the Simplot monitor.

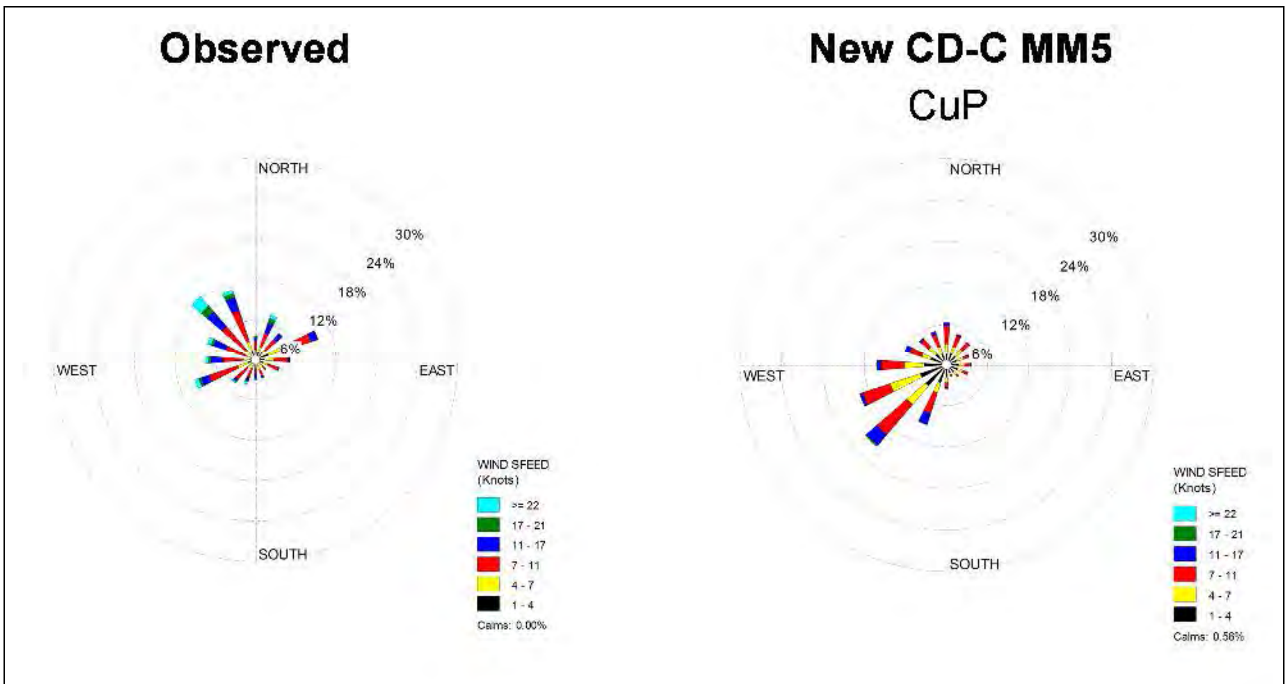


Figure D.21. Wind rose for 2006 near-surface winds at the Riverton monitor.

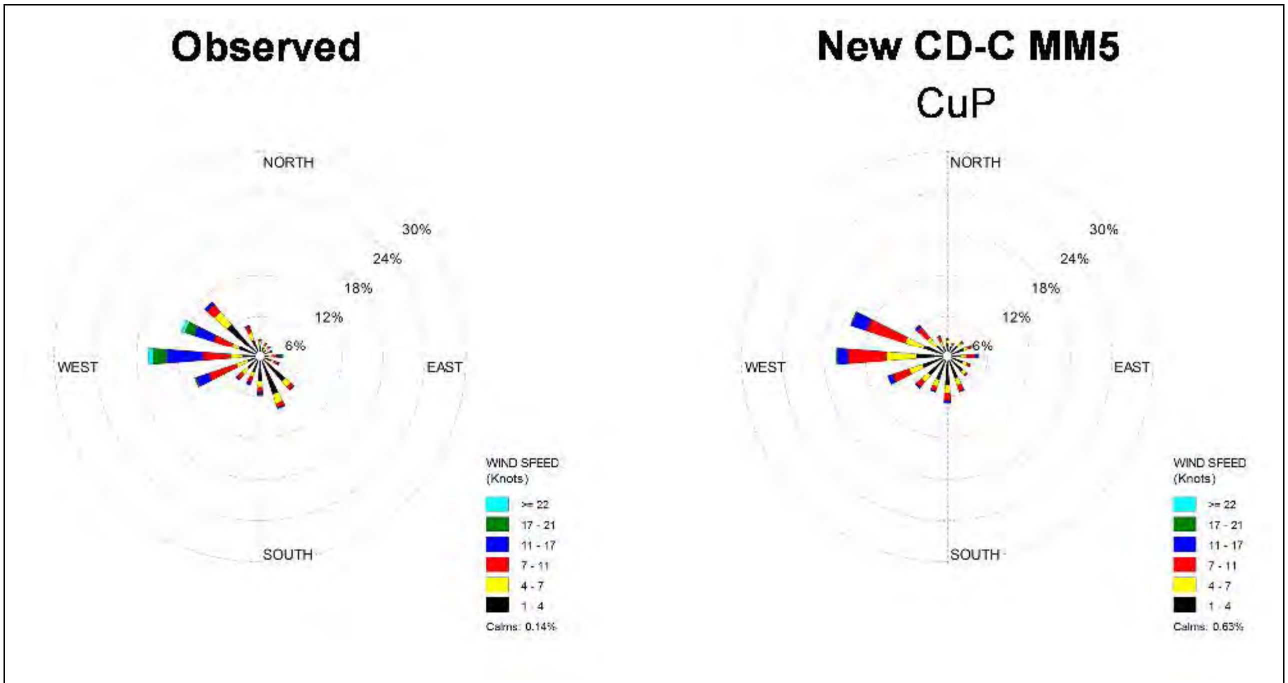


Figure D.22. Wind rose for 2006 near-surface winds at the OCI monitor.

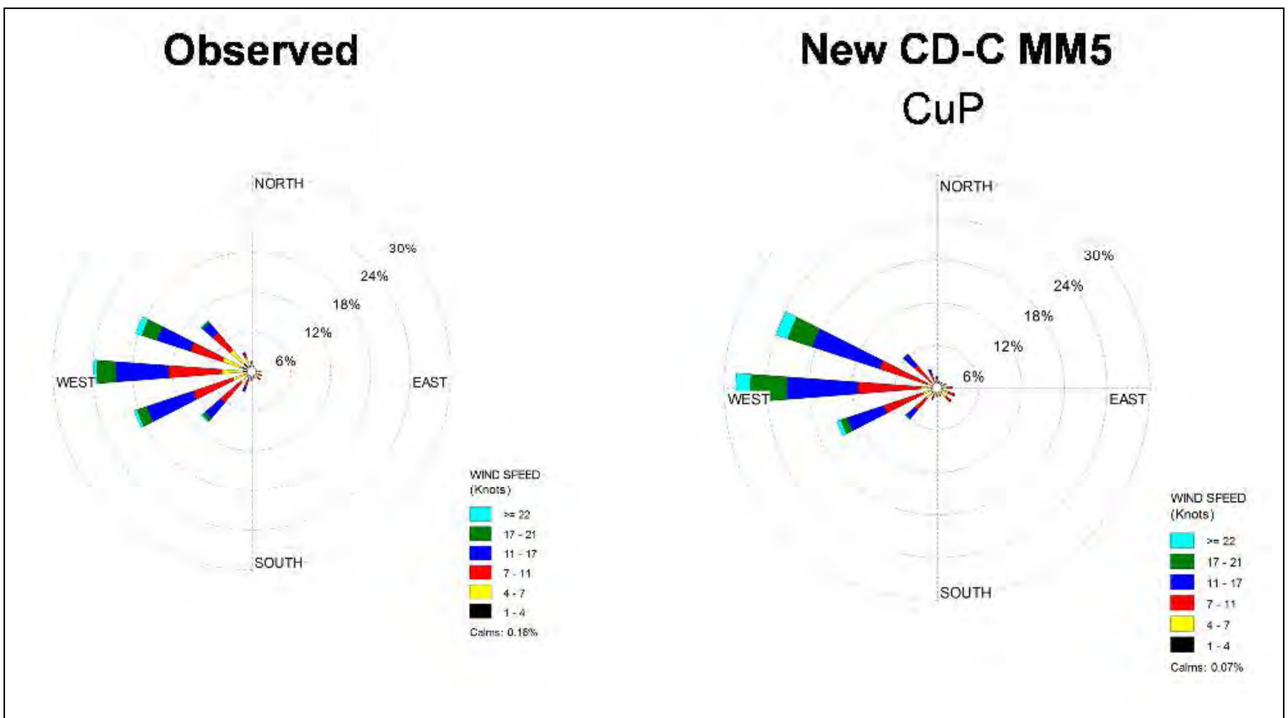


Figure D.23. Wind rose for 2006 near-surface winds at the Centennial monitor.

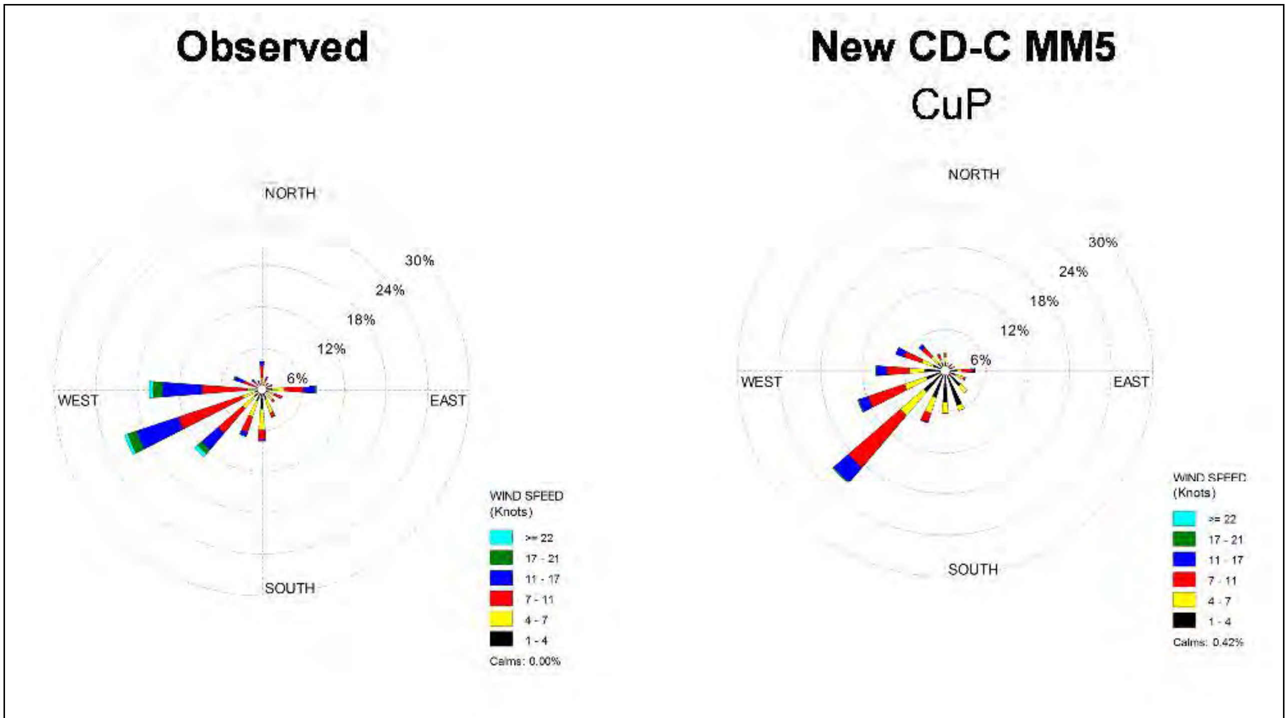


Figure D.24. Wind rose for 2006 near-surface winds at the Evanston monitor.

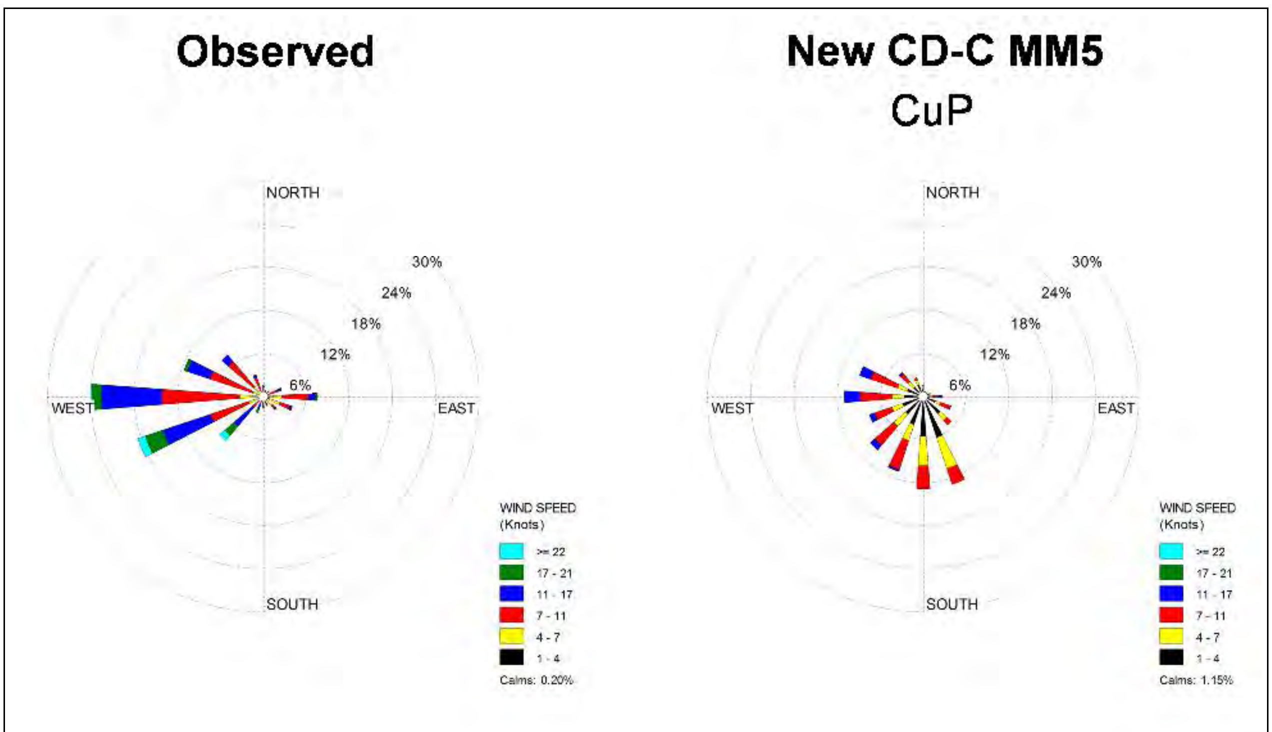


Figure D.25. Wind rose for 2006 near-surface winds at the Whitney Canyon monitor.

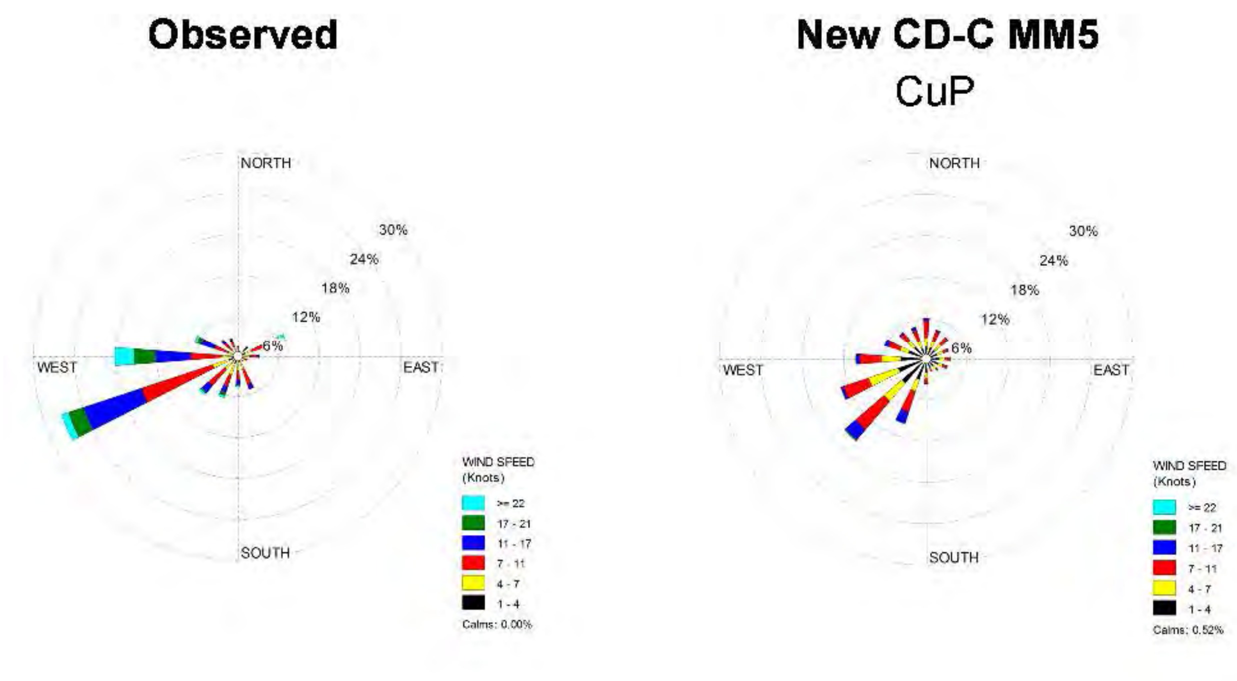


Figure D.26. Wind rose for 2006 near-surface winds at the Rock Springs monitor.

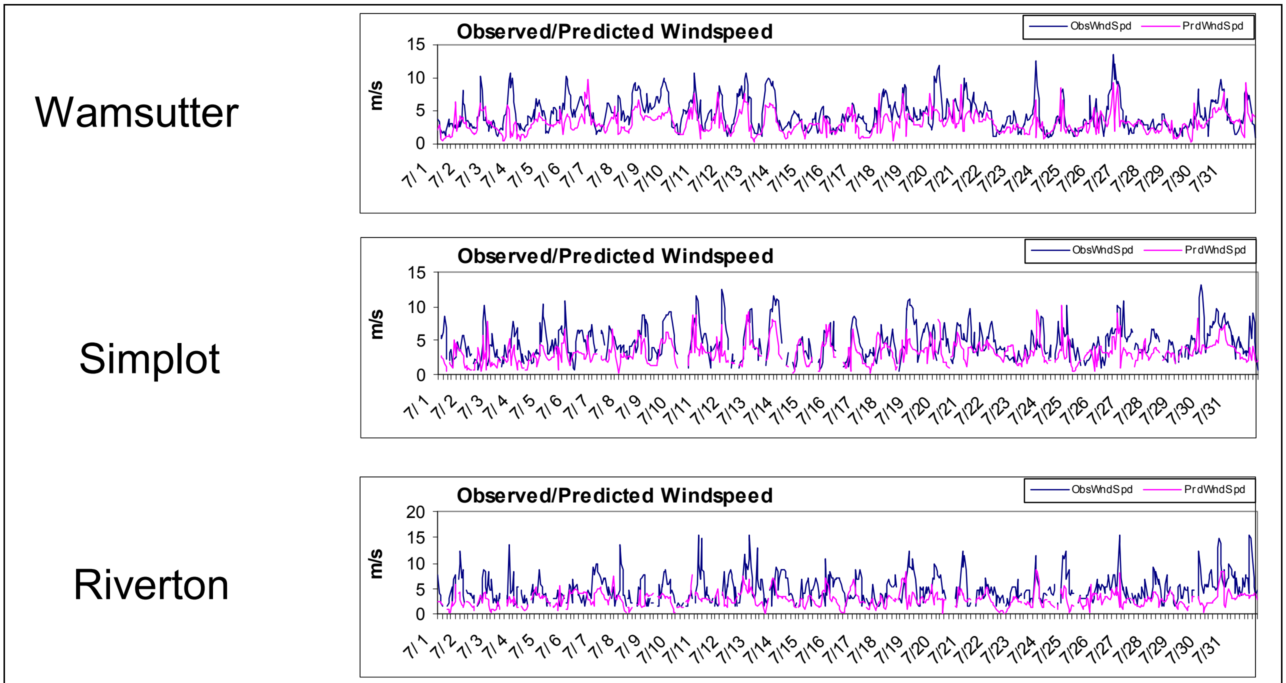


Figure D.27. Time series of observed (blue) and MM5 (pink) July 2006 near-surface wind speed at monitors outside Sublette County.

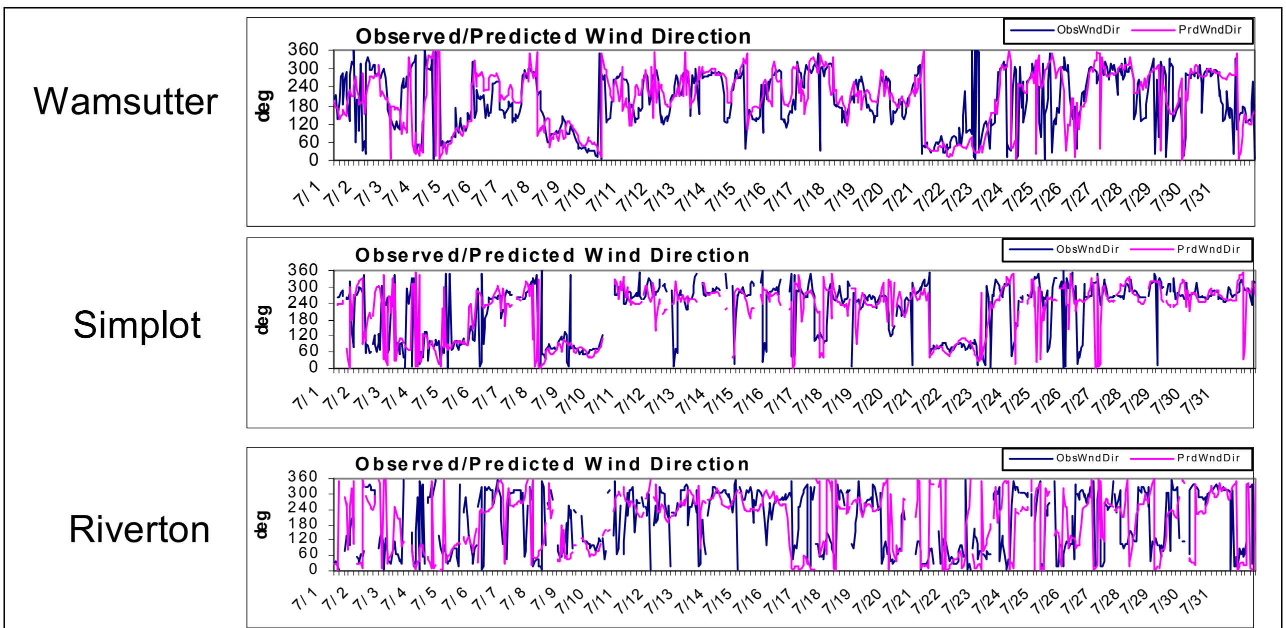
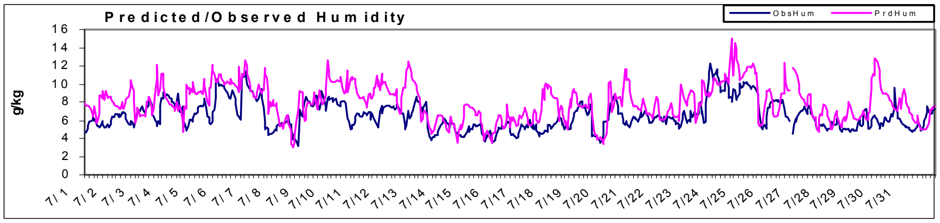
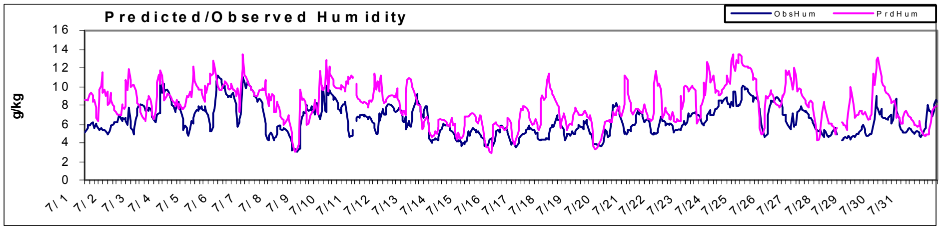


Figure D.28. Time series of observed (blue) and MM5 (pink) July 2006 near-surface wind direction at monitors outside Sublette County.

Boulder



Daniel



Jonah

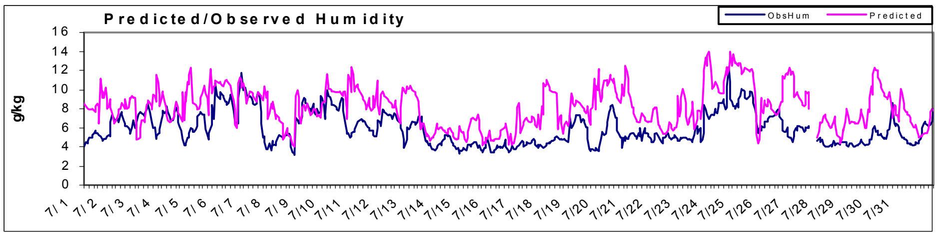
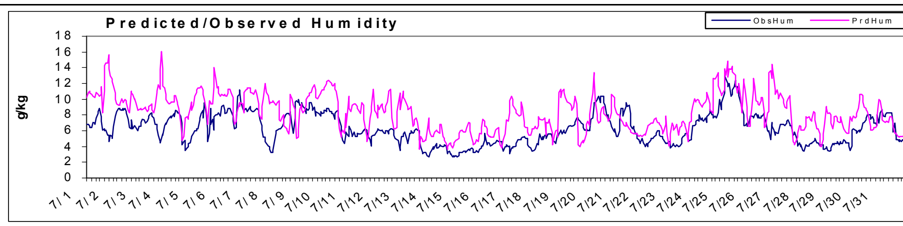
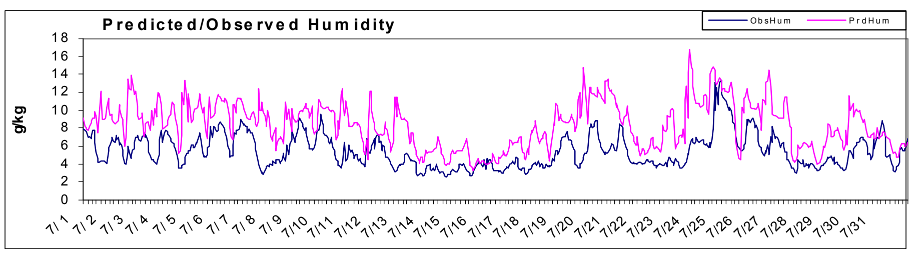


Figure D.29. Time series of observed (blue) and MM5 (pink) 2006 near-surface humidity at monitors in Sublette County.

Rock Springs



OCI



Riverton

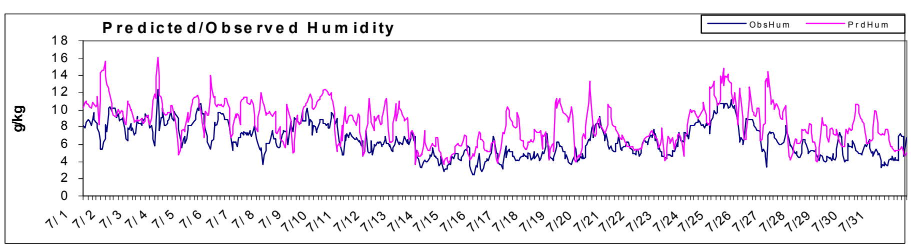


Figure D.30. Time series of observed (blue) and MM5 (pink) 2006 near-surface humidity at monitors outside Sublette County.

APPENDIX D – MODEL PERFORMANCE_EVALUATION_ OF_THE_2005-2006_MM5 SIMULATIONS

SUMMARY OF SURFACE PERFORMANCE

The overall model performance at monitors within southwestern Wyoming was good. The model does a good job of reproducing the large-scale features of the surface winds, temperatures and humidity at most monitors. The model has an overall low wind speed bias at all SW Wyoming sites, and an important part of the low wind speed bias is the model's underprediction of peak wind speeds. Wind direction variability was underestimated in the model. This problem was particularly pronounced at the Sublette County monitors, which are influenced by local-scale flows due to the complex topography that surrounds them. In winter, MM5 often misses the daytime transition from NW winds to SW/W winds seen in observations. At 4 km resolution, MM5 may be expected to have difficulty resolving local-scale drainage flows. Outside Sublette County, the winter wind direction performance was better. In summer, there are more rapid changes, in wind direction outside Sublette County due to the passage of meso- to local-scale convective events, and the model has more difficulty simulating these. The model showed an overall wet bias at the surface at all Wyoming industrial site monitors. Overall, MM5 generally handles large-scale features of the circulation well but has more difficulty simulating locally-driven circulations such as small-scale convective storms and flow in mountainous areas.

COMPARISON WITH 2002 RPO MM5 MODELING

In order to place the performance of the 2005/2006 36/12/4 km MM5 modeling in the context of other annual MM5 runs, we compare the 4 km MM5 model performance to that of the annual MM5 simulations of 2002 that were made by the CENRAP (Johnson, 2007), VISTAS (Olerud, 2003a,b), and WRAP (Kemball-Cook et al., 2004) Regional Planning Organizations (RPO) for regional haze modeling. These annual runs were made on a 36 km grid that is identical to the 36 km grid used for the 2005/2006 MM5 modeling. For the purposes of comparison with 2005/2006 MM5 modeling, only a sub-region of the 36 km MM5 run consisting of the states Wyoming, Montana and eastern Idaho was considered. We also compare the 2005/2006 4 km MM5 runs run to a 12 km 2002 annual run made by the WRAP and evaluated on the same sub-region as the 36 km RPO runs. The RPO runs share a common grid and projection, but use different column physics options, and differ from one another in their performance (see Kemball-Cook et al., 2004 and Johnson et al., 2006). The RPO runs were evaluated by region and by month against ds472 surface meteorological data and the results were averaged over the Wyoming-Montana-Idaho sub-region described above (Kemball-Cook et al., 2004). The CD-C results were averaged over the 4 km domain, as described in the preceding sections. Although the horizontal grid resolution and size of the averaging regions is different in the RPO and CD-C runs, we may draw a rough comparison among the annual runs to determine whether the CD-C run performs approximately as well as the RPO runs.

METSTAT SURFACE STATISTICAL ANALYSIS

In this section, we describe the benchmarks used in the comparison between the 2002 RPO and 2005/2006 MM5 runs as well as the graphical displays used to present the data.

Emery *et al.* (2001) have derived a set of daily performance benchmarks for typical meteorological model performance. These standards were based upon the evaluation of approximately 30 MM5 and RAMS meteorological simulations executed in support of air quality applications, as reported by Tesche *et al*. (2001). The purpose of these benchmarks was not necessarily to give a passing or failing grade to any one particular meteorological model application, but rather to put its results into context and to allow the identification of potential problems in the MM5 fields. For example, expectations for meteorological model performance for a domain located in the Rocky Mountains might be different than for a Central U.S. domain with simpler topography. The statistical performance benchmarks developed by Emery and co-workers (2001) are given in Table D.1.

Table D.1 Statistical benchmarks for evaluating meteorological model performance.

	Wind Speed	Wind Direction	Temperature	Humidity
RMSE	≤ 2 m/s			
Mean Bias	≤ ±0.5 m/s	≤ ±10°	≤ ±0.5 K	≤ ±1 g/kg
Gross Error		≤ 30°	≤ 2 K	≤ 2 g/kg

In order to summarize model performance, we will show soccer plots on which are displayed average performance statistics for each region over the entire episode. Definitions for the statistical model performance metrics are given in Table A.4 of Appendix A. Soccer plots are shown for wind speed root mean square error (RMSE) versus wind direction error, wind speed bias versus wind speed RMSE, temperature bias versus temperature error, and humidity bias versus humidity error. In each plot, a solid blue line indicates the benchmark. A data point that falls inside the box represents a model run that meets the performance benchmark. Perfect model performance is indicated by a data point at (0,0). The closer a data point is to the origin, the better the model's performance.

January Soccer Plots

In the soccer plot for wind direction error and wind speed RMSE for January (Figure D.31) is representative of winter performance during other months (not shown), the 2005 MM5 run is within the benchmark for wind speed RMSE but not wind direction error; the 2006 MM5 run is outside the benchmark for both bias and error, with performance similar to that seen in the CENRAP and VISTAS runs. The WRAP 36 km and 12 km runs had the best performance of all runs, and were within the benchmark for both RMSE and wind direction error. The 2006 new run wind performance was similar to the performance of the old 2006 run, and the 2006 MM5 run performance was comparable to or better than the RPO runs, except for the WRAP 2002 12 km run for wind direction error. The wind bias soccer plot (Figure D.32) shows that the both the 2005 and 2006 MM5 runs and the WRAP 2002 12 km run underestimate wind speeds; the 2005/2006 MM5 and WRAP 2002 MM5 performance are comparable. Performance degrades slightly going from the old to the new 2006 run. Wind bias data was not readily available for the 36 km RPO runs.

The January temperature soccer plot is shown in Figure D.33. The 2005 MM5 4 km run is within the bias benchmark, as is the VISTAS 2002 36 km run. All of the other runs are outside the bias benchmark, and exhibit a cold bias. The old and new 2006 MM5 runs lie outside benchmark for both bias and error but perform better than the WRAP and CENRAP 2002 MM5 runs for bias and have the best performance of any run for temperature error. For humidity (Figure D.34), the performance of all model runs was similar, all models falling with the benchmarks for both bias and error and all model runs showing a wet bias.

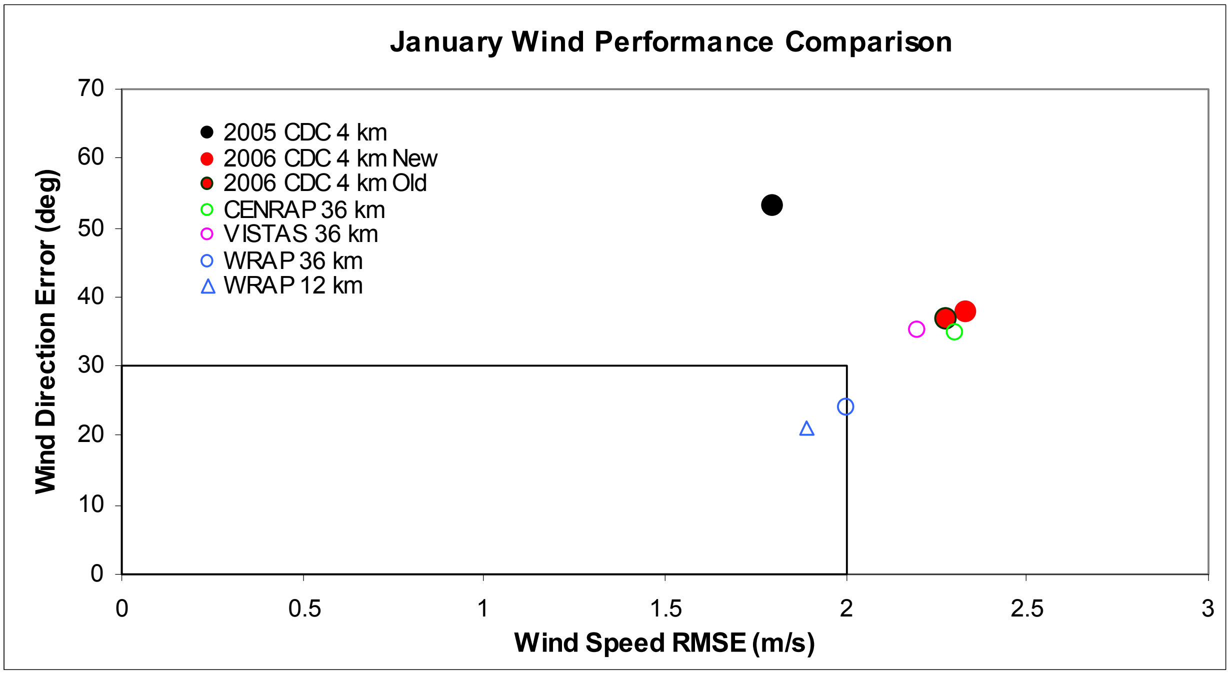


Figure D.31. January wind speed and direction performance soccer plot.

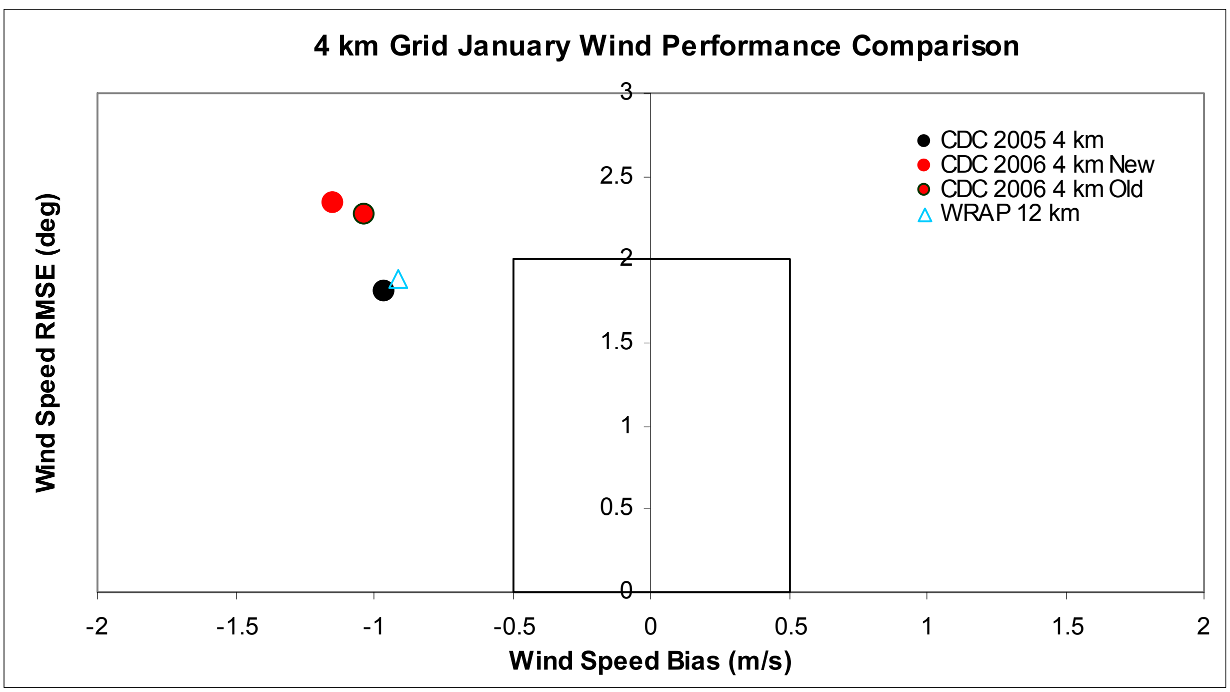


Figure D.32. January wind speed bias and RMSE performance soccer plot.

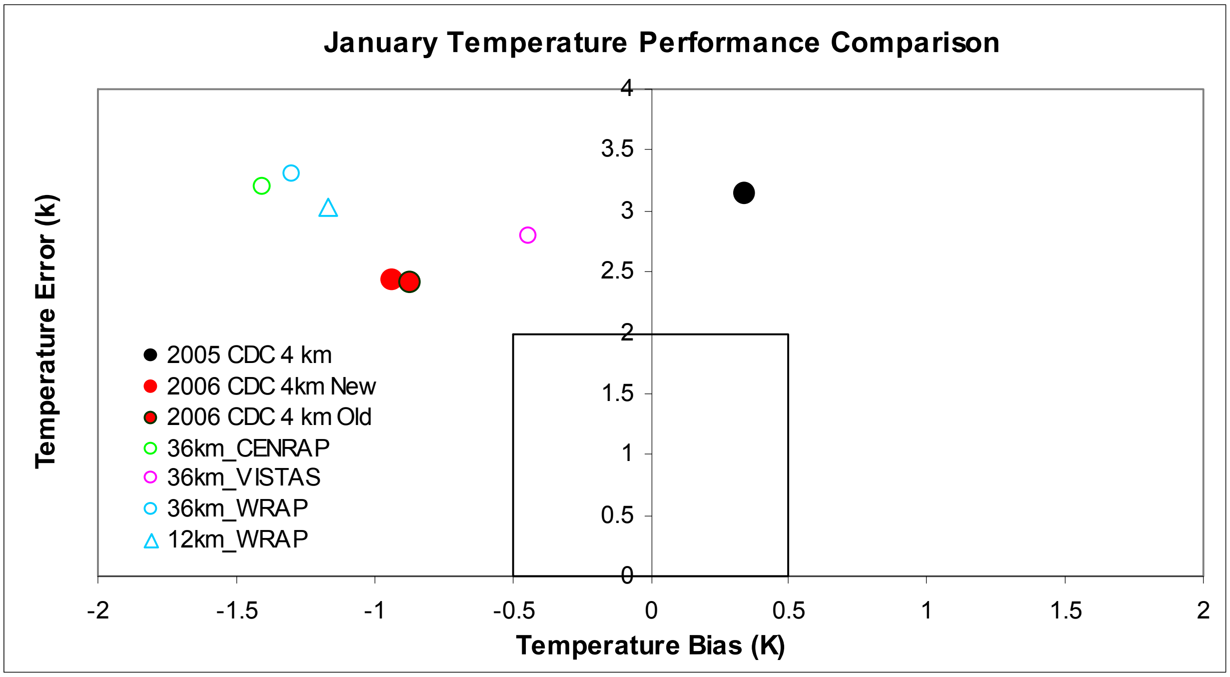


Figure D.33. January temperature performance soccer plot.

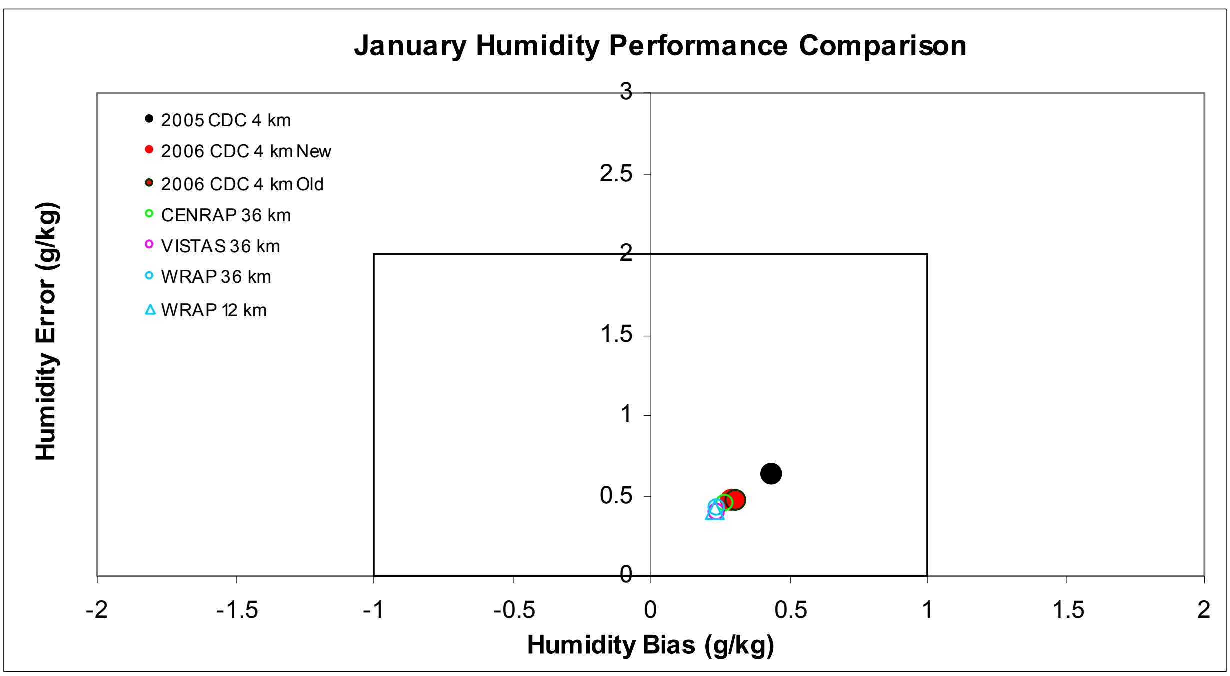


Figure D.34. January humidity performance soccer plot.

JULY SOCCER PLOTS

Figures D.35 and D.36 are the soccer plots for winds for the month of July. Results are similar to January, with the 2005/2006 MM5 and CENRAP and VISTAS 2002 MM5 simulations showing similar performance for wind speed RMSE and direction and the WRAP 36 km and 12 km MM5 runs the only simulations to fall within the performance benchmark. Both the 2005/2006 MM5 and WRAP 2002 12 km MM5 runs show a low bias in wind speed and have similar bias performance. Bias performance degrades slightly in going from the old to the new 2006 run.

For temperature (Figure D.37), the 2006 MM5 4 km runs fall within the bias benchmark and are close to the benchmark for error, but the 2005 MM5 run lies well outside the benchmark for both bias and error. The 2005 and 2006 MM5 runs performance is generally comparable to that of the RPO runs for error; while the 2005 MM5 run is comparable to the VISTAS run, it does not perform as well as the WRAP and CENRAP MM5 runs for bias.

All runs except the 2006 MM5 runs lie within the benchmarks for humidity (Figure D.38). The 2005 MM5 4 km run lies within bias and error benchmarks, while the 2006 runs meet the humidity error benchmark but not the bias benchmark. All of the MM5 simulations have a wet bias, which is most pronounced in the 2006 MM5 simulation and is larger than in January due to the increased prevalence of convective rainfall during summer. Turning on the CuP in the new 2006 MM5 run did little to ameliorate this wet bias.

Overall, the soccer plot analysis shows that the 2005/2006 MM5 runs are comparable in performance to the RPO annual simulations of 2002. Low wind speed bias and wet bias were common to all of these MM5 simulations.

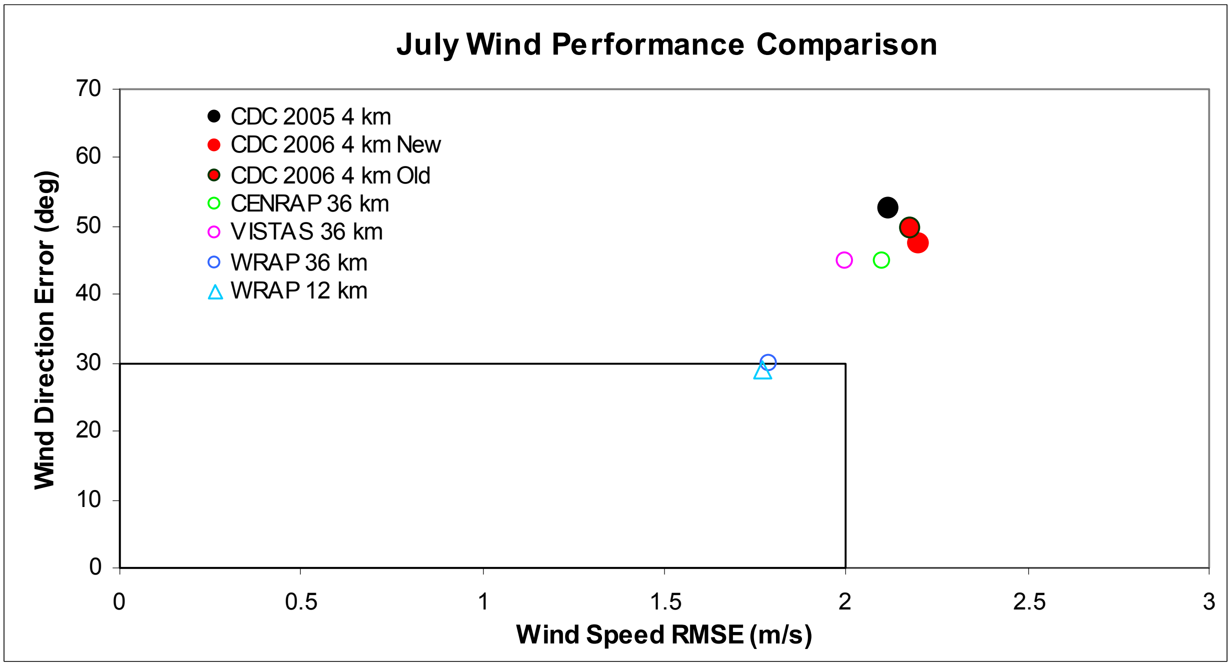


Figure D.35. July wind speed and direction performance soccer plot.

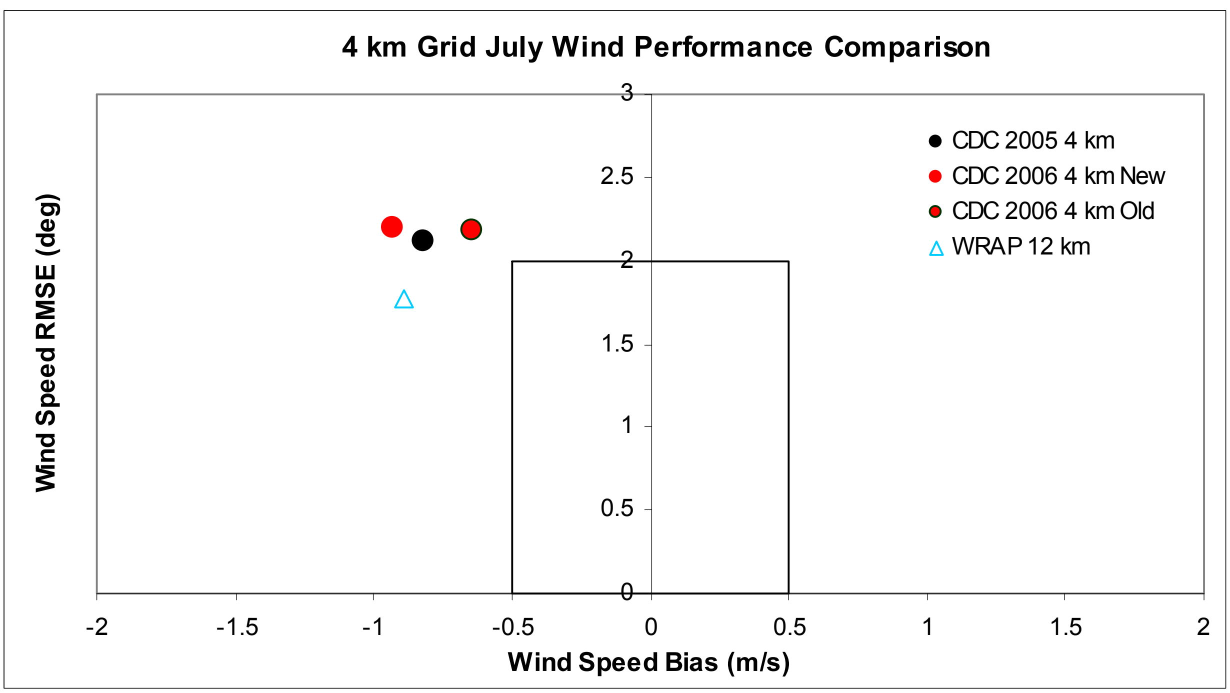


Figure D.36. July wind speed bias and RMSE performance soccer plot.

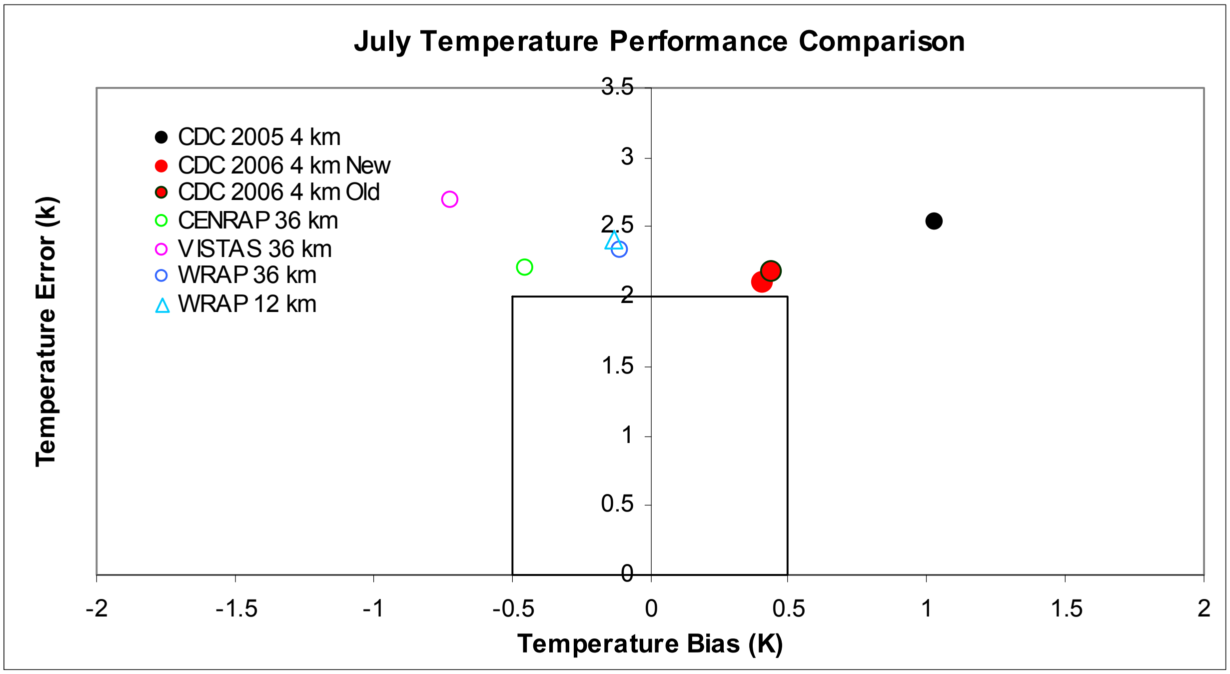


Figure D.37. July temperature performance soccer plot.

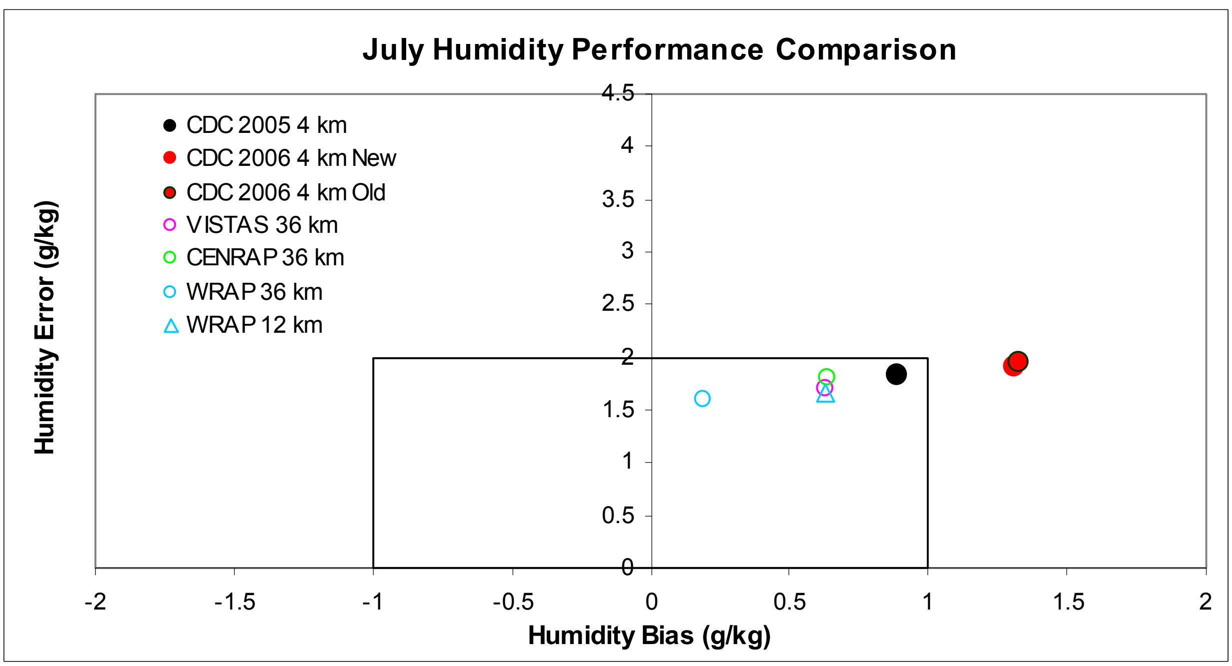


Figure D.38. July humidity performance soccer plot.

PRECIPITATION EVALUATION

In this section, we evaluate the 2005 and 2006 MM5 simulation performance in simulating precipitation over the 12 km and 4 km grid domains. The total MM5 precipitation was calculated for each hour of the run. The total precipitation is equal to the sum of the resolved, grid-scale rainfall and the sub-grid-scale convective rainfall which is calculated by the cumulus parameterization. The sum of the hourly precipitation amounts in each grid cell was taken over a month to obtain a monthly precipitation total for each grid cell. The monthly model precipitation totals were then compared with monthly precipitation totals from the Climate Prediction Center (CPC) gridded precipitation analysis and the National Weather Service New Precipitation Analysis (NPA).

The CPC gridded precipitation amount dataset is available from the National Weather Service's Climate Prediction Center at http://www.cpc.ncep.noaa.gov/products/precip/realtime/retro.html. The CPC daily precipitation amounts are derived from rain gauge data from the River Forecast Center, and are gridded on a latitude-longitude mesh that covers the U.S. mainland at a resolution of 0.25°x 0.25° (about 25 km x 25 km for Wyoming in the present modeling domain). The gridded precipitation fields are ramped down to zero immediately offshore of the Continental U.S. The CPC dataset was interpolated to the 12 km MM5 Lambert conformal grid for the analysis presented below.

The advantage of the CPC precipitation data set is that it is a gridded field with reasonably high resolution that can be used to qualitatively evaluate model performance over land. However, this CPC product has a relatively coarse resolution compared to that of the 12 km or 4 km grid, and features such as intense localized precipitation from thunderstorms will be smoothed out in the CPC fields so that its maxima will be less intense and its rainfall will be distributed over a wider area than in the real world or on the 12/4 km MM5 grids. This CPC product can be most effectively used as a screening tool to determine whether there was any rainfall in a given area on a particular day, rather than to compare specific rainfall amounts and we use it here to evaluate the 12 km MM5 rainfall because its resolution is most similar to this grid.

For evaluating the model precipitation fields on the 4 km grid, we use the National Weather Service New Precipitation Analysis (NPA). The NPA data set is also derived from the River Forecast gauge data, has a resolution of 4 km, and has been gridded to the MM5 model's Lambert conformal projection. The data are available at: http://www.srh.noaa.gov/rfcshare/precip_analysis_new.php. The 2005/2006 MM5 precipitation evaluation focuses on February, April, and July, which are winter, spring, and summer months with high ozone/nitrate over southwest Wyoming during 2005-6.

Figures D.39 and D.40 show the observed and modeled 2005 precipitation on the 12 km and 4 km domains, respectively. On the 12 km grid, the observed large-scale features are well-simulated by the model. Most of the rainfall during February is generated by synoptic-scale (~1000 km) weather systems that are well-resolved by MM5. The increased resolution of the 4 km grid enhances the orographic rainfall. For example, precipitation totals are larger over the Wind River Range in Wyoming on the 4 km grid (>100 mm) than on the 12 km grid (<50 mm).

On both grids, MM5 replicates the overall pattern well, but tends to overestimate rainfall maxima, especially in Northern Colorado.

In February, 2006, the overall rainfall pattern is reproduced well by the model on the 12 km grid (Figure D.41). On the 4 km grid (Figure D.42), rainfall is generally overpredicted on the 4 km grid. On the 4 km grid, there is a region of high precipitation lying along the Wind River Range where the maximum is greater than 160 mm, while the observed totals are lower. It is worth bearing in mind that mountainous regions are less well-sampled by the rain gauge network than lower-lying areas, which introduces a bias toward underestimating the actual precipitation by failing to capture the orographically enhanced precipitation in the high terrain features. The use of the CuP has only a minor impact on the precipitation field, since most precipitation is resolved at grid-scale in February.

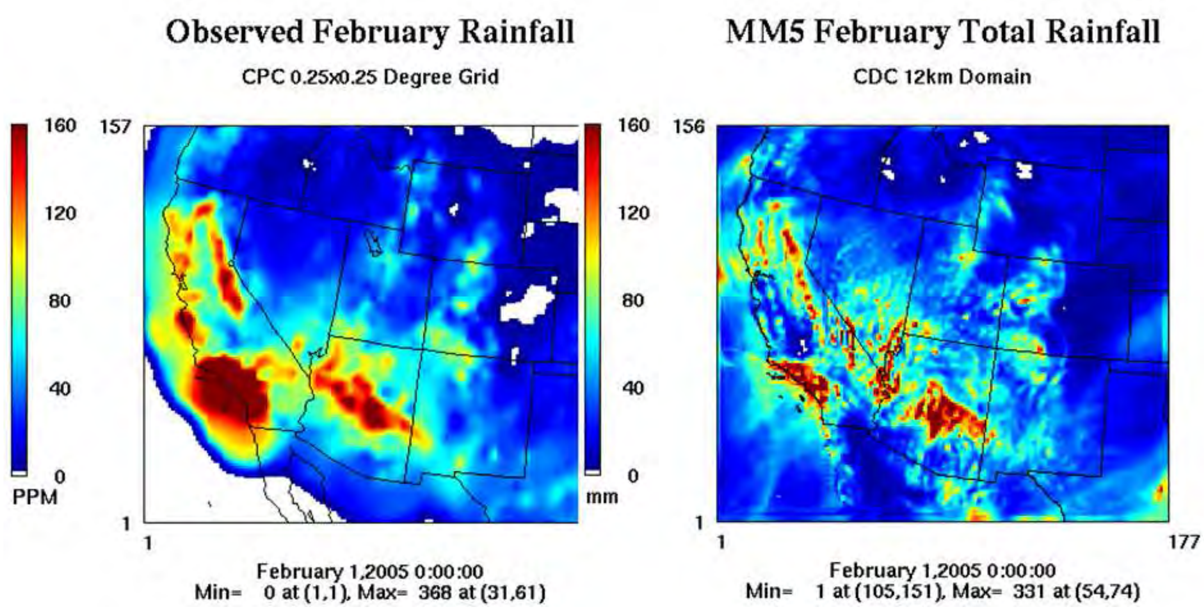


Figure D.39. February, 2005 precipitation in 12 km MM5 domain.

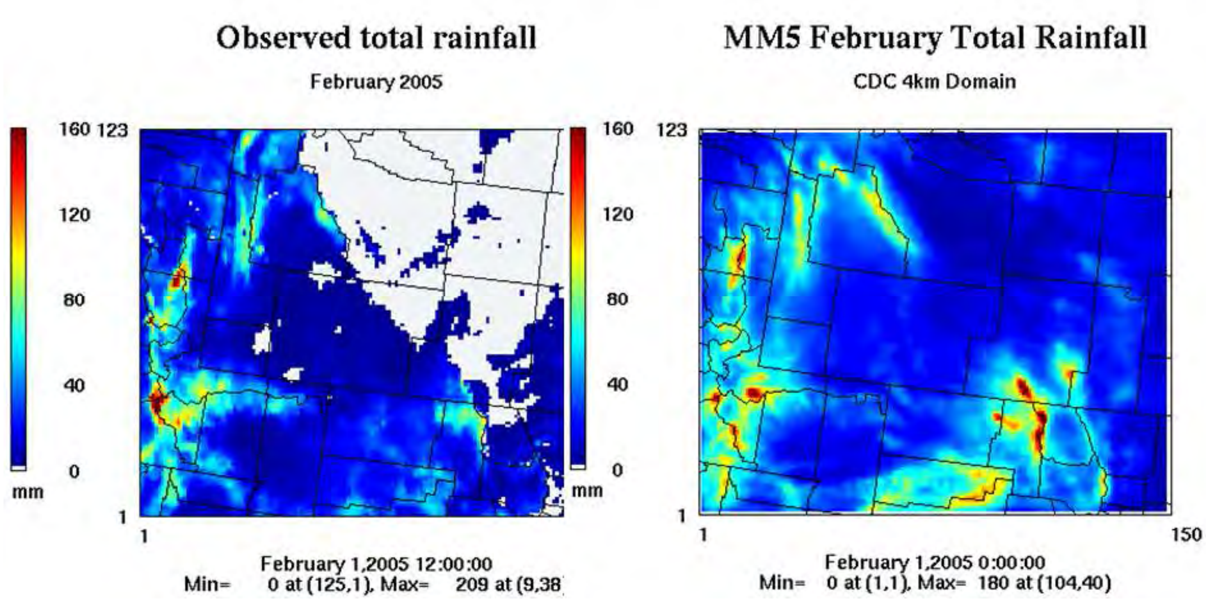


Figure D.40. February, 2005 precipitation in 4 km MM5 domain.

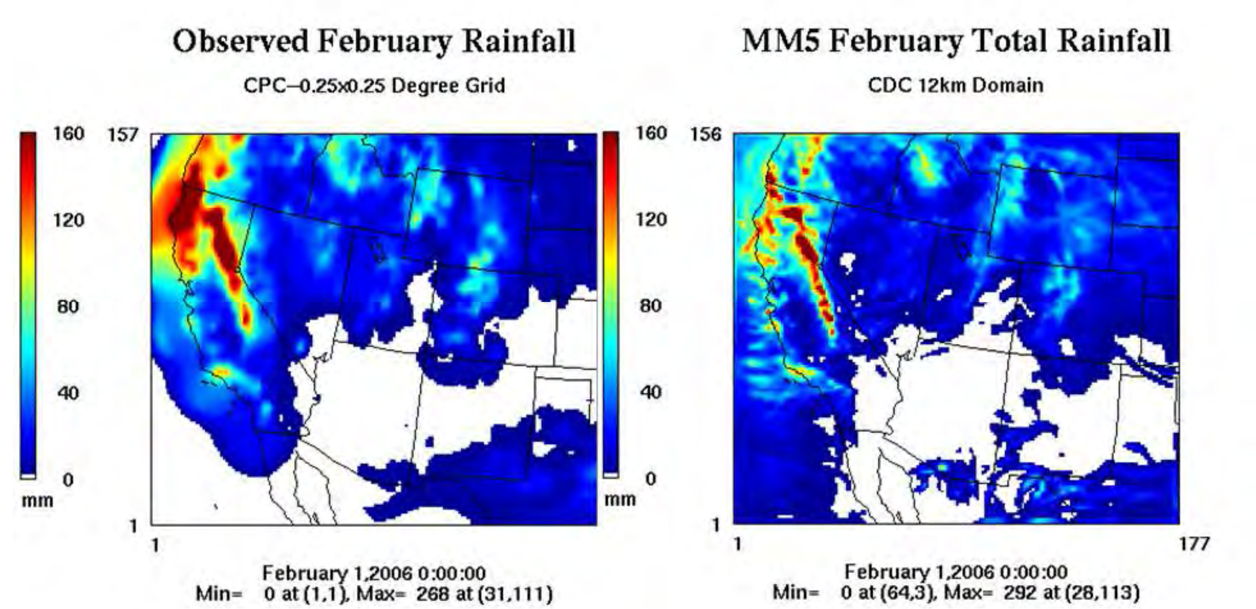


Figure D.41. February, 2006 precipitation in 12 km MM5 domain.

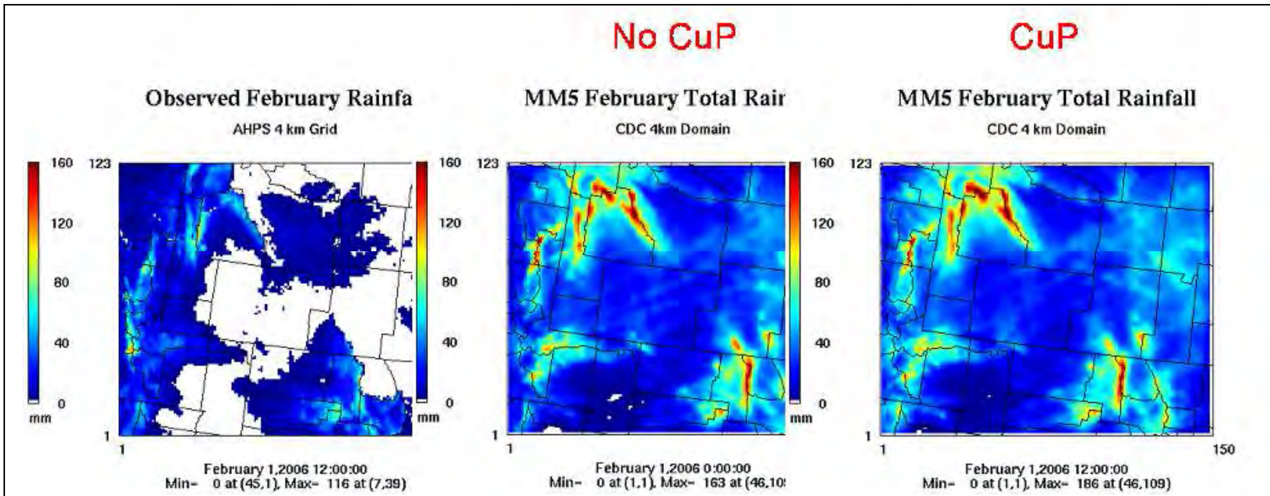


Figure D.42. February, 2006 precipitation in 4 km MM5 domain.

April marks a transition between the synoptic-scale storms of winter and the convective storms of summer. On the 12km grid, MM5 picks up the main features in the observed April 2005 precipitation (Figure D.43), but shows areas of overestimated precipitation. Comparison of the 4 km modeled precipitation with the NWS data set (Figure D.44) shows that the modeled maxima are much higher than the observed maxima. We may expect CAMx to overestimate wet deposition on the 4 km grid during April. In April, precipitation performance is better on the 12 km grid than on the 4 km grid. MM5 performance in 2006 is similar to 2005 (Figures D.45 and D.46), with better performance on the 12 km grid than the 4 km grid. Use of the CuP tends to exaggerate the precipitation overprediction, and does not improve performance in April.

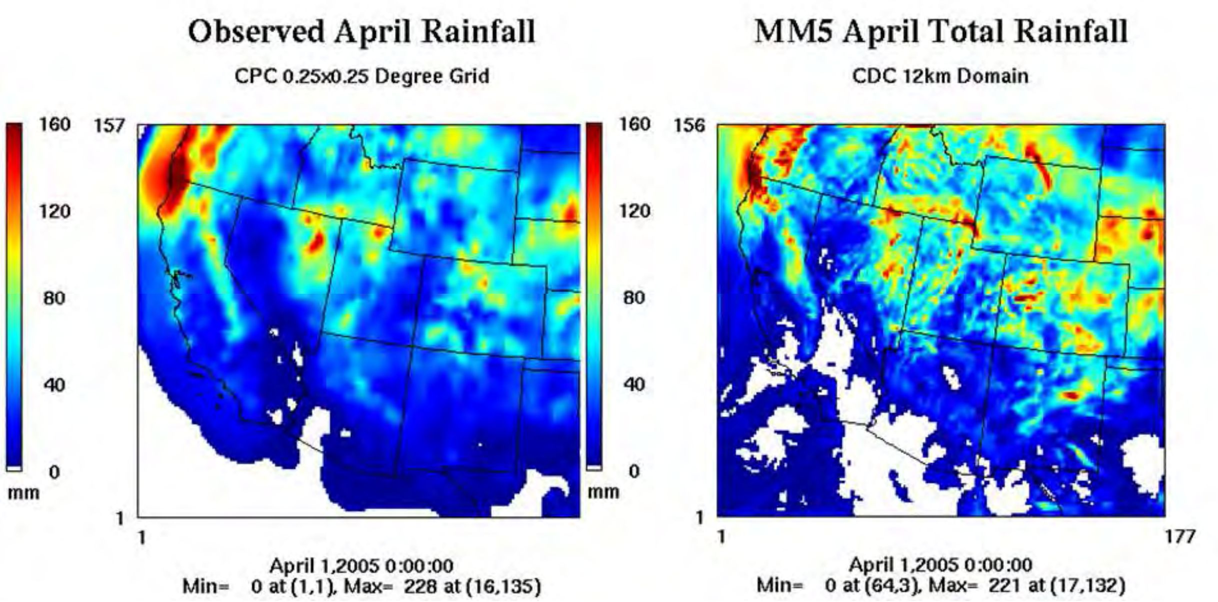


Figure D.43. April, 2005 precipitation in 12 km MM5 domain.

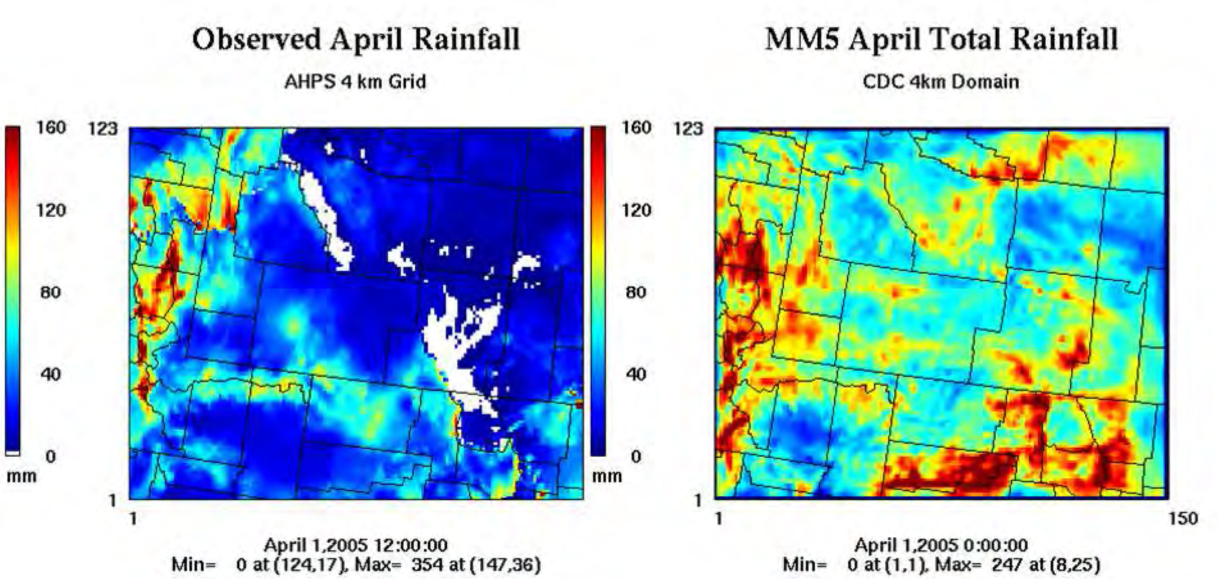


Figure D.44. April, 2005 precipitation in 4 km MM5 domain.

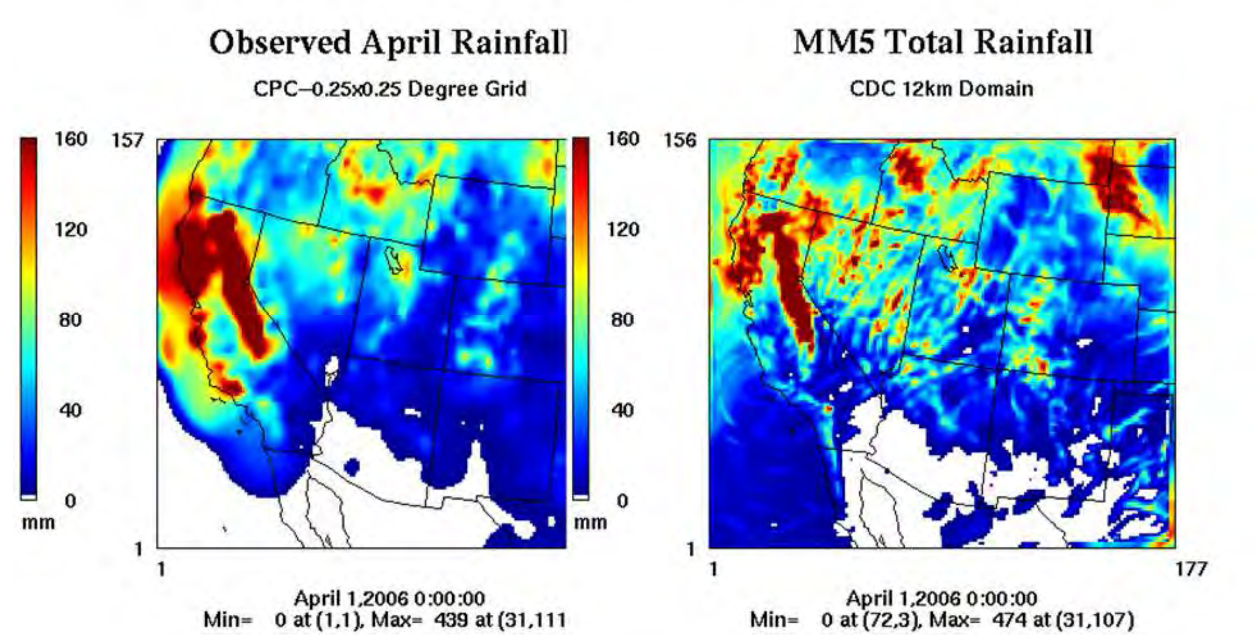


Figure D.45. April, 2006 precipitation in 12 km MM5 domain.

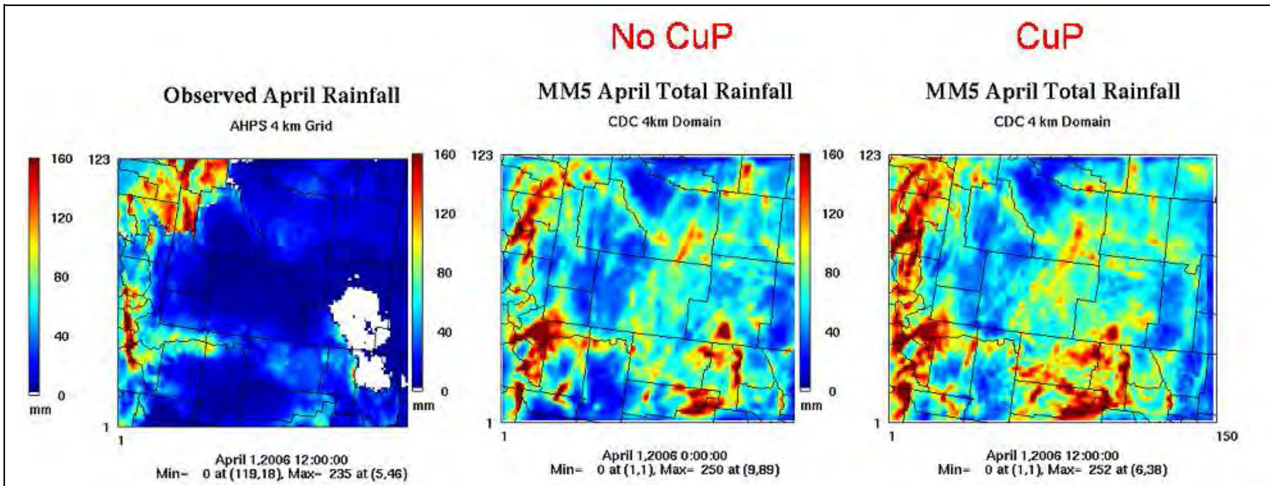


Figure D.46. April, 2006 precipitation in 4 km MM5 domain.

In July, most rainfall is produced by convective storms that are not well-resolved by MM5, even at 4 km grid size. The observed precipitation distribution is relatively smooth and is difficult to compare to modeled pattern, which is spottier due to localized nature of convective storms. Rainfall is overestimated on the 12 km grid and the modeled maxima are misplaced (Figures D.47 and D49); the overall pattern of rainfall is not nearly as well-reproduced in July as in January. Summer rainfall is greatly overestimated on the 4 km grid in both 2005 (Figure D.48) and 2006 (Figure D.50) regardless of whether or not a CuP is used. The overestimate is more pervasive in 2006 than in 2005 despite use of cumulus parameterization in new 2006 run. This pronounced summer rainfall overprediction in the west was seen in the RPO 2002 annual runs, and is typical of MM5. Excessive rainfall will cause wet deposition of soluble species to be overestimated.

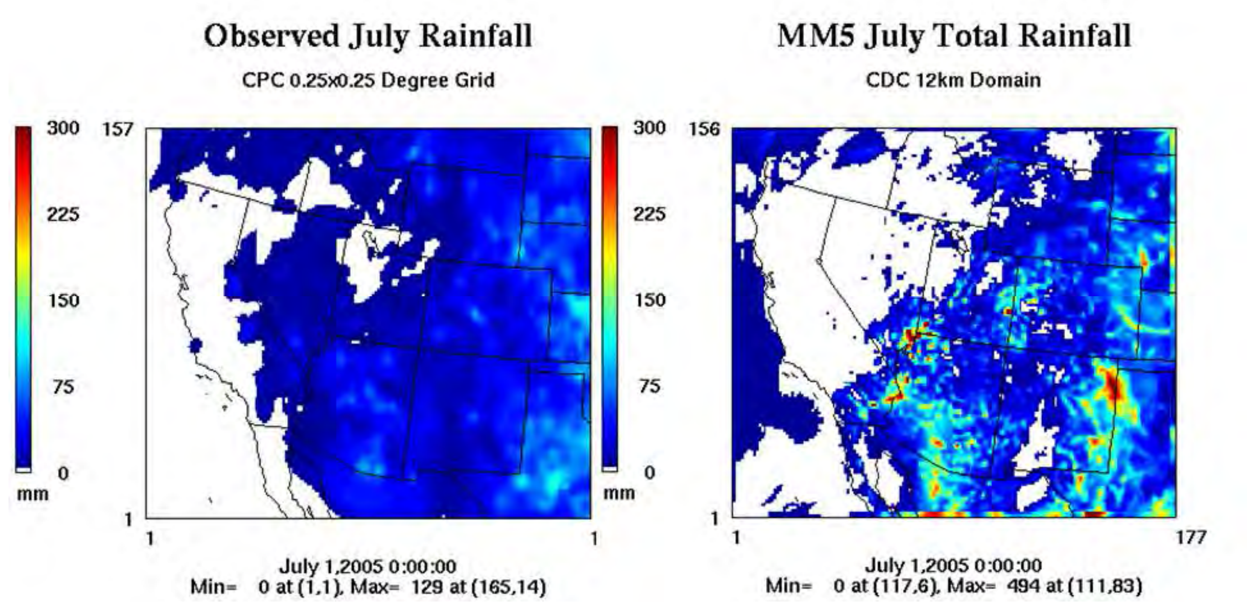


Figure D.47. July, 2005 precipitation in 12 km MM5 domain.

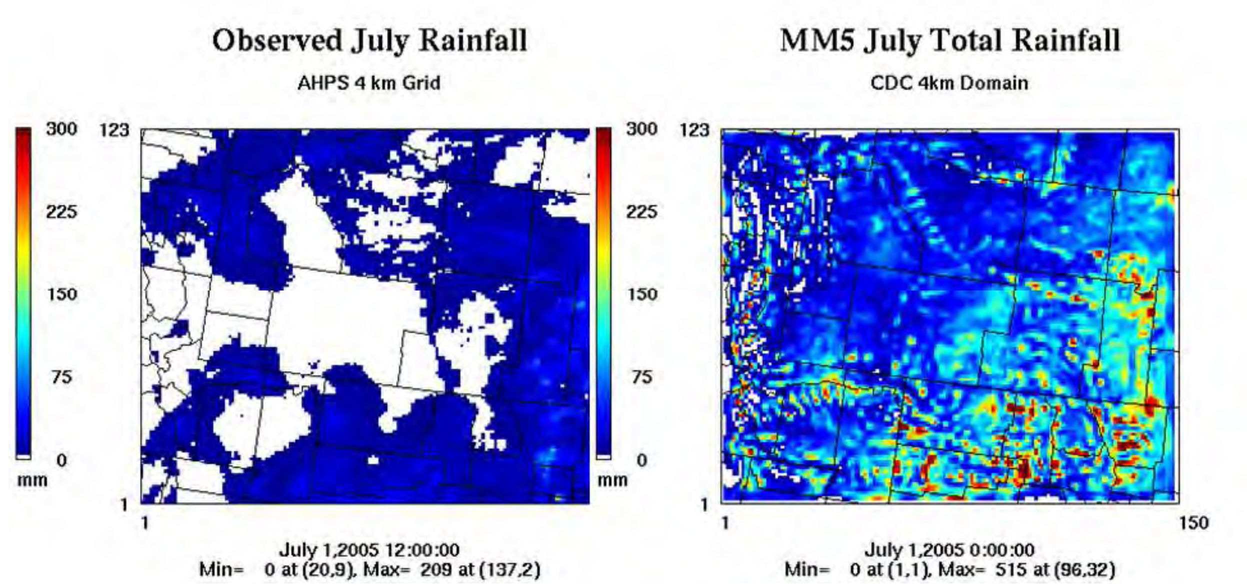


Figure D.48. July, 2005 precipitation in 4 km MM5 domain.

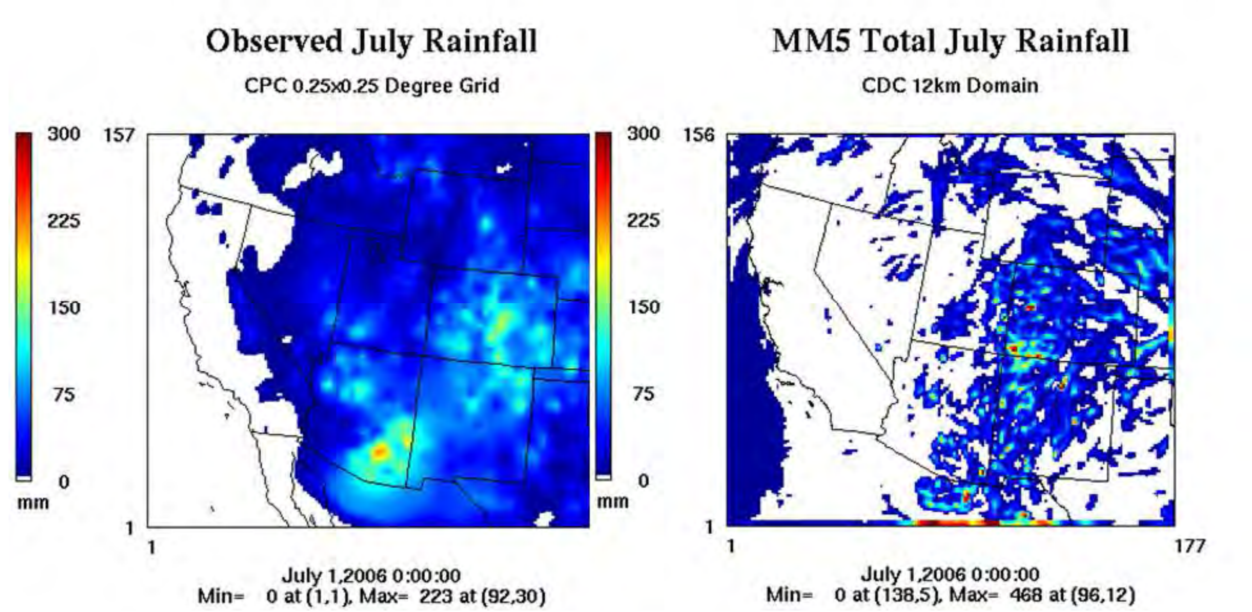


Figure D.49. July, 2006 precipitation in 12 km MM5 domain.

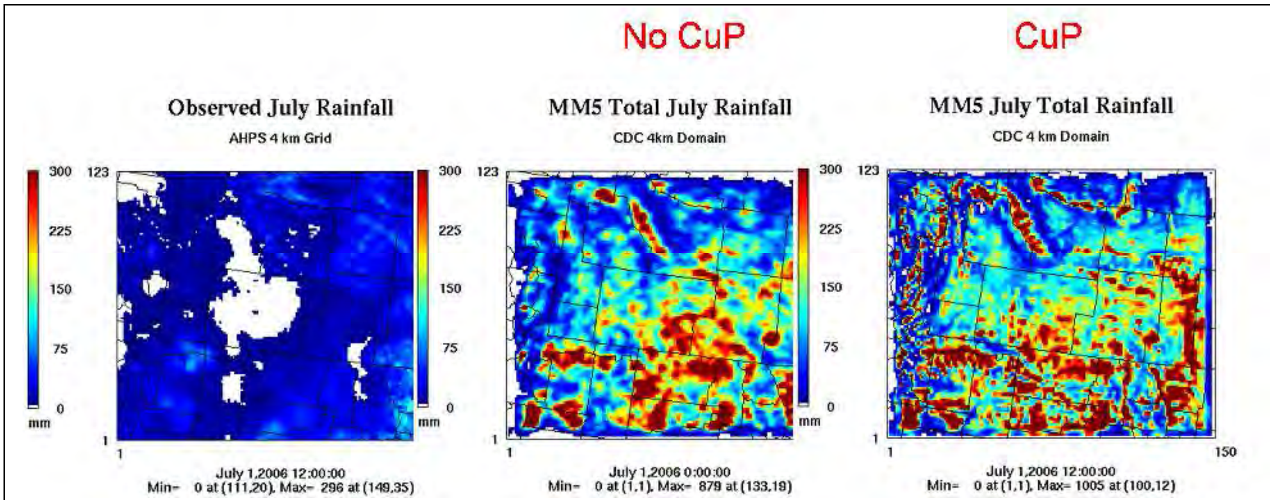


Figure D.50. July, 2006 precipitation in 4 km MM5 domain.

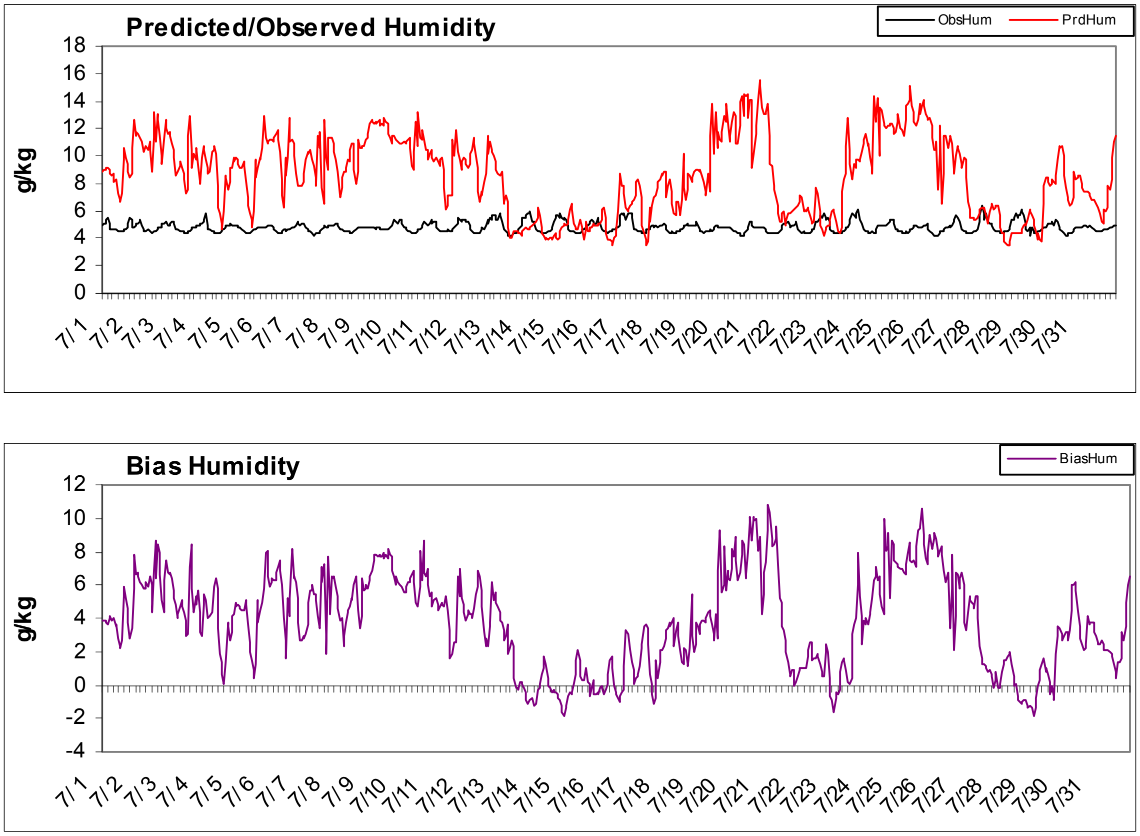


Figure D.51. Time series of observed (black) and MM5 (red) January 2005 near-surface temperature (upper panel) and humidity bias (lower panel) at the Wamsutter monitor.

SUMMARY OF PRECIPITATION PERFORMANCE

In winter, the 2005 and 2006 MM5 runs show considerable skill in reproducing the observed precipitation field. In spring and summer, rainfall is overestimated over much of Wyoming on the 12 km and 4 km grids. The overestimate is due to excessive convective rainfall; this problem was noted in the RPO runs as well. Although the 2006 simulation was run both with cumulus parameterization turned on and off (no CuP was used in the original 2006 run), the overestimate of precipitation remains, and worsened in July.

OVERALL SUMMARY OF MM5 MODEL PERFORMANCE

The overall performance of the 2005/2006 MM5 simulations was generally good and was comparable to the RPO 2002 MM5 annual run performance. Simulation of surface winds was reasonably consistent with observed winds, with a persistent low wind speed bias and generally good wind direction except during times of rapid shifts in the observed winds. Precipitation performance was very good during winter, but rainfall was overestimated during spring and summer, which is typical of MM5 and which will likely cause CAMx to overestimate the deposition of soluble species. The modeled surface humidity has a corresponding wet bias, which grows more pronounced during the summer.

Because of the overall good performance and the fact that the 2005/2006 MM5 run performance was comparable to that of similar annual modeling efforts, we conclude that the MM5 runs for 2005 and 2006 may be used to supply the meteorological input database for the CAMx air quality modeling in the CD-C impact analysis. The new 2006 run with CuP will be used both for consistency with 2005 and because of the slight improvement in surface wind performance. No significant improvement was noted in the precipitation fields due to the use of the CuP, however.

REFERENCES

Dudhia, J., 1993. "A Non-hydrostatic Version of the Penn State/NCAR Mesoscale Model: Validation Tests and Simulation of an Atlantic Cyclone and Cold Front", Mon. Wea. Rev., Vol. 121. pp. 1493-1513.

ENVIRON and Alpine. 2009. Four Corners Prevention of Significant Deterioration (PSD) Consumption Study. ENVIRON International Corporation, Novato, CA and Alpine Geophysics, LLC, Arvada, CO. April 17.

ENVIRON. 2009. Air Quality Modeling Study for the Four Corners Region. ENVIRON International Corporation, Novato, CA. June 30.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994. "A Description of the Fifth Generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note, NCAR TN-398-STR, 138 pp.

Johnson, M. 2007. Meteorological Model Performance Evaluation of an Annual 2002 MM5 (Version 3.6.3) Simulation. Iowa Department of natural Resources, Air Quality Bureau. November. (http://www.iowadnr.gov/air/prof/progdev/modeling.html).

Johnson, J., Y. Jia, C. Emery, R. Morris, Z. Wang and G. Tonnesen. 2006. Comparison of CENRAP 36 km and 12 km MM5 Model Runs for 2002. Prepared for CENRAP Modeling Work Group. May 23. (http://pah.cert.ucr.edu/aqm/cenrap/ppt_files/CENRAP_2002_36km_vs_12km_MM5_May22_2006.ppt).

Kemball-Cook, S., Y. Jia, C. Emery, R. Morris, Z. Wang and G. Tonnesen. 2004. Comparison of CENRAP, VISTAS and WRAP 36 km MM5 Model Runs for 2002, Task 3: Meteorological Gatekeeper Report. (http://pah.cert.ucr.edu/aqm/cenrap/ppt_files/CENRAP_VISTAS_WRAP_2002_36km_MM5_eval.ppt). December 14.

Olerud, D. 2003a. “Evaluation Methodologies for Meteorological Modeling in Support of VISTAS (Visibility Improvement – State and Tribal Association): Task 1 Deliverables” (Draft) Baron Advanced Meteorological Systems, LLC, Research Triangle Park, NC. (available at: http://www.baronams.com/projects/VISTAS/#reports). April 16.

Olerud, D. 2003b. “Protocol for Annual MM5 Modeling of VISTAS (Visibility Improvement – State and Tribal Association): Task 7c Deliverable.” Baron Advanced Meteorological Systems, LLC, Research Triangle Park, NC. (available at: http://www.baronams.com/projects/VISTAS/#reports). March 27.