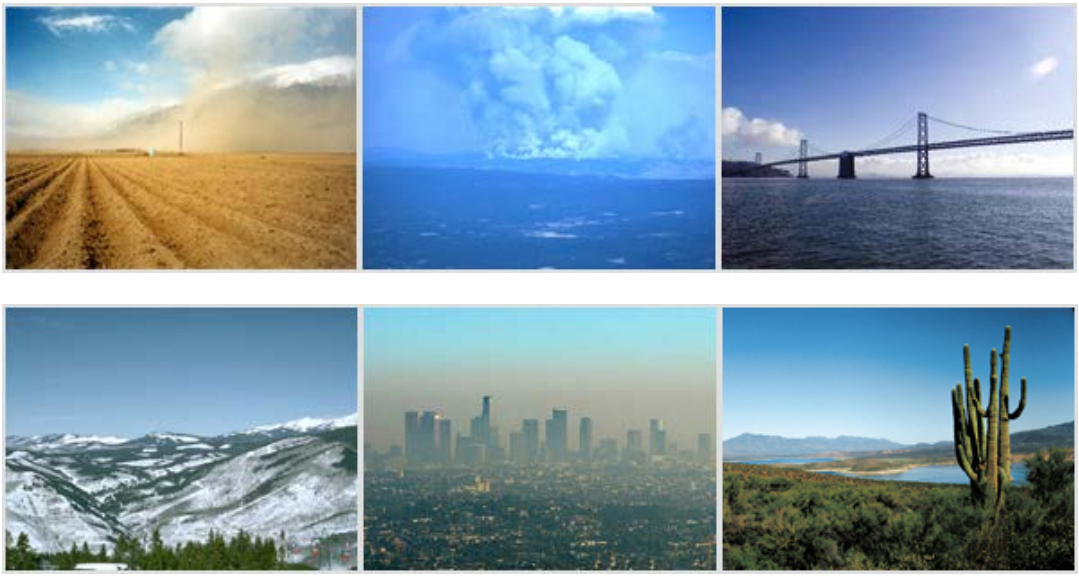


Western Regional Air Partnership (WRAP) West-wide Jump Start Air Quality Modeling Study (WestJumpAQMS)

WRF Application/Evaluation

Prepared for:
Tom Moore
Western Regional Air Partnership
c/o CIRA, Colorado State University
1375 Campus Delivery
Fort Collins, CO 80523-1375

Prepared by:
ENVIRON International Corporation
773 San Marin Drive, Suite 2115
Novato, California, 94945
P-415-899-0700
F-415-899-0707

Alpine Geophysics, LLC
University of North Carolina

February 29, 2012
0627372A

Table of Contents

Page

EXECUTIVE SUMMARY ES-1

1 INTRODUCTION 1

1.1 METEOROLOGICAL MODELING 1-1
1.2 WESTJUMPAQMS WRF METEOROLOGICAL MODELING 1-2

2 METHODOLOGY 2-1

2.1 MODEL SELECTION AND APPLICATION 2-1
2.2 EVALUATION APPROACH 2-2

3 WRF MODEL PERFORMANCE EVALUATION RESULTS 3-1

3.1 QUANTITATIVE MODEL EVALUATION RESULTS 3-1
3.1.1 Temperature Bias and Error 3-5
3.1.2 Mixing Ratio Bias and Error 3-8
3.1.3 Wind Direction and Wind Speed Performance 3-9
3.2 QUALITATIVE MONTHLY PRECIPITATION ANALYSIS 3-46
3.3 SUMMARY OF MODEL PERFORMANCE EVALUATION 3-46

4 COMPARISON WITH OTHER ANNUAL MM5 SIMULATIONS 4-1

4.1 COMPARISON TO OTHER ANNUAL 36 KM SIMULATIONS 4-1
4.2 COMPARISON TO OTHER 12 KM ANNUAL SIMULATIONS 4-3
4.3 SUMMARY OF INTERCOMPARISON OF MODEL PERFORMANCE EVALUATION RESULTS 4-4

Appendices

Appendix A. WRF 36, 12 and 4 km Model Performance for the four Impact Assessment Domains (IADs)

Tables

Table 2-1. Physics options used in the WestJumpAQMS WRF Version 3.3.1 simulation of the 2008 calendar year. 2-3
Table 2-2. Vertical layer definition for WRF simulations. 2-4
Table 3-1. Temperature Bias (K) for 2008 WRF by Month and by State and Region in the 36 km Domain. 3-13
Table 3-2. Temperature Bias (K) for 2008 WRF by Month and by State in the 12 km Domain. 3-15
Table 3-3. Temperature Bias (K) for 2008 WRF by Month and by State in the 4 km Domain. 3-16
Table 3-4. Temperature Error (K) for 2008 WRF by Month and by State in the 36 km Domain. 3-17
Table 3-5. Temperature Error (K) for 2007 WRF by Month and by State in the 12 km Domain. 3-19

Table 3-6. Temperature Error (K) for 2007 WRF by Month and by State in the 4 km..... 3-20
Table 3-7. Mixing Ratio Bias (g/kg) for 2008 WRF by Month and by State and Region in the 36 km Domain..... 3-21
Table 3-8. Mixing Ratio Bias (g/kg) for 2008 WRF by Month and by State and Region in the 12 km Domain..... 3-23
Table 3-9. Mixing Ratio Bias (g/kg) for 2008 WRF by Month in the 4 km Domain..... 3-24
Table 3-10. Mixing Ratio Error (g/kg) for 2008 WRF by Month and by State and Region in the 36 km Domain..... 3-25
Table 3-11. Mixing Ratio Error (g/kg) for 2008 WRF by Month and by State and Region in the 12 km Domain..... 3-27
Table 3-12. Mixing Ratio Error (g/kg) for 2008 WRF by Month in the 4 km Domain..... 3-28
Table 3-13. Wind Direction Bias (deg.) for 2008 WRF by Month and by State and Region in the 36 km Domain..... 3-29
Table 3-14. Wind Direction Bias (deg.) for 2008 WRF by Month and by State and Region in the 12 km Domain..... 3-31
Table 3-15. Wind Direction Bias (deg.) for 2008 WRF by Month in the 4 km Domain..... 3-32
Table 3-16. Wind Direction Error (deg.) for 2008 WRF by Month and by State and Region in the 36 km Domain..... 3-33
Table 3-17. Wind Direction Error (deg.) for 2008 WRF by Month and by State and Region in the 12 km Domain..... 3-35
Table 3-18. Wind Direction Error (deg.) for 2008 WRF by Month in the 4 km Domain..... 3-36
Table 3-19. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 36 km Domain..... 3-37
Table 3-20. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 12 km Domain..... 3-39
Table 3-21. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 4 km Domain..... 3-40
Table 4-1. Temperature Bias (°K) for 36 km Annual MM5 and WRF Simulations..... 4-5
Table 4-2. Temperature Error (°K) for 36 km Annual MM5 Simulations..... 4-5
Table 4-3. Mixing Ratio Bias (g/kg) for 36 km Annual MM5 Simulations..... 4-6
Table 4-4. Mixing Ratio Error (g/kg) for 36 km Annual MM5 Simulations..... 4-6
Table 4-5. Temperature Bias (°K) model performance evaluation (MPE) results by state for 12 km annual MM5 and WRF simulations. MPE results that are within the benchmark of ±1.0 °K are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008"..... 4-7
Table 4-6. emperature Error (°K) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of 3.0 °K are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008"..... 4-9
Table 4-7. Mixing ratio bias (g/kg) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of +1.0 g/kg are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008"..... 4-11
Table 4-8. Mixing Ratio Error (g/kg) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of 2.0 g/kg are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008"..... 4-13

Figures

Figure 2-1. 36 km CONUS 12 km WESTUS and 4 km IMWD processing domain that air quality modeling inputs will be developed for (note that actual 4 km air quality domains will be subsets of the 4 km IMWD). 2-5
Figure 2-2. 36/12/4 km WRF meteorological modeling domains. 2-6
Figure 2-3. Locations of MADIS surface meteorological modeling sites with the WRF 36 km CONUS modeling domain. 2-7
Figure 2-4. Locations of MADIS surface meteorological modeling sites with the WRF 12 km WESTUS modeling domain. 2-8
Figure 2-5. Locations of MADIS surface meteorological modeling sites with the WRF 4 km IMWS modeling domain. 2-9
Figure 3-1a. Regional Planning Organization (RPO) Boundaries 3-2
Figure 3-2b. Locations of the 4 km Detailed Source Apportionment Domains (DSAD). 3-3
Figure 3-3c. Locations of the 4 km Impact Assessment Domains (IAD). 3-4
Figure 3-4: Monthly Temperature Bias and Error Soccerplot by Month for All Stations in the 36 km domain (top left), 12 km domain (top right) and 4 km domain (bottom). 3-42
Figure 3-5: Monthly Mixing Ratio Bias and Error Soccerplot by Month for All Stations in the 36 km domain (top left), 12 km domain (top right) and 4 km domain (bottom). 3-43
Figure 3-6: Monthly Wind Direction Bias and Error Soccerplot by Month for All Stations in the 36 km domain (top left), 12 km domain (top right) and 4 km domain (bottom). 3-44
Figure 3-7: Wind Speed Bias and RMSE Soccerplot by Month for All Stations in the 36 km domain (top left), 12 km domain (top right) and 4 km domain (bottom). 3-45
Figure 3-8. CPC Analyzed Precipitation for January 2008 over the 36 km Domain. 3-48
Figure 3-9. WRF Estimated Precipitation for January 2008 over the 36 km Domain. 3-48
Figure 3-10. CPC Analyzed Precipitation for February 2008 over the 36 km Domain. 3-49
Figure 3-11. WRF Estimated Precipitation for February 2008 over the 36 km Domain. 3-49
Figure 3-12. CPC Analyzed Precipitation for March 2008 over the 36 km Domain. 3-50
Figure 3-13. WRF Estimated Precipitation for March 2008 over the 36 km Domain. 3-50
Figure 3-14. CPC Analyzed Precipitation for April 2008 over the 36 km Domain. 3-51
Figure 3-15. WRF Estimated Precipitation for April 2008 over the 36 km Domain. 3-51
Figure 3-16. CPC Analyzed Precipitation for May 2008 over the 36 km Domain. 3-52
Figure 3-17. WRF Estimated Precipitation for May 2008 over the 36 km Domain. 3-52
Figure 3-18. CPC Analyzed Precipitation for June 2008 over the 36 km Domain. 3-53
Figure 3-19. WRF Estimated Precipitation for June 2008 over the 36 km Domain. 3-53
Figure 3-20. CPC Analyzed Precipitation for July 2008 over the 36 km Domain. 3-54
Figure 3-21. WRF Estimated Precipitation for July 2008 over the 36 km Domain. 3-54
Figure 3-22. CPC Analyzed Precipitation for August 2008 over the 36 km Domain. 3-55
Figure 3-23. WRF Estimated Precipitation for August 2008 over the 36 km Domain. 3-55
Figure 3-24. CPC Analyzed Precipitation for September 2008 over the 36 km Domain. 3-56
Figure 3-25. WRF Estimated Precipitation for September 2008 over the 36 km Domain. 3-56
Figure 3-26. CPC Analyzed Precipitation for October 2008 over the 36 km Domain. 3-57
Figure 3-27. WRF Estimated Precipitation for October 2008 over the 36 km Domain. 3-57
Figure 3-28. CPC Analyzed Precipitation for November 2008 over the 36 km Domain. 3-58
Figure 3-29. WRF Estimated Precipitation for November 2008 over the 36 km Domain. 3-58
Figure 3-30. CPC Analyzed Precipitation for December 2008 over the 36 km Domain. 3-59

Figure 3-31. WRF Estimated Precipitation for December 2008 over the 36 km Domain. 3-59
Figure 3-32. CPC Analyzed Precipitation for January 2008 over the 12 km Domain. 3-60
Figure 3-33. WRF Estimated Precipitation for January 2008 over the 12 km Domain. 3-60
Figure 3-34. CPC Analyzed Precipitation for February 2008 over the 12 km Domain. 3-61
Figure 3-35. WRF Estimated Precipitation for February 2008 over the 12 km Domain. 3-61
Figure 3-36. CPC Analyzed Precipitation for March 2008 over the 12 km Domain. 3-62
Figure 3-37. WRF Estimated Precipitation for March 2008 over the 12 km Domain. 3-62
Figure 3-38. CPC Analyzed Precipitation for April 2008 over the 12 km Domain. 3-63
Figure 3-39. WRF Estimated Precipitation for April 2008 over the 12 km Domain. 3-63
Figure 3-40. CPC Analyzed Precipitation for May 2008 over the 12 km Domain. 3-64
Figure 3-41. WFF Estimated Precipitation for May 2008 over the 12 km Domain. 3-64
Figure 3-42. CPC Analyzed Precipitation for June 2008 over the 12 km Domain. 3-65
Figure 3-43. WRF Estimated Precipitation for June 2008 over the 12 km Domain. 3-65
Figure 3-44. CPC Analyzed Precipitation for July 2008 over the 12 km Domain. 3-66
Figure 3-45. WRF Estimated Precipitation for July 2008 over the 12 km Domain. 3-66
Figure 3-46. CPC Analyzed Precipitation for August 2008 over the 12 km Domain. 3-67
Figure 3-47. WRF Estimated Precipitation for August 2008 over the 12 km Domain. 3-67
Figure 3-48. CPC Analyzed Precipitation for September 2008 over the 12 km Domain. 3-68
Figure 3-49. WRF Estimated Precipitation for September 2008 over the 12 km Domain. 3-68
Figure 3-50. CPC Analyzed Precipitation for October 2008 over the 12 km Domain. 3-69
Figure 3-51. WRF Estimated Precipitation for October 2008 over the 12 km Domain. 3-69
Figure 3-52. CPC Analyzed Precipitation for November 2008 over the 12 km Domain. 3-70
Figure 3-53. WRF Estimated Precipitation for November 2008 over the 12 km Domain. 3-70
Figure 3-54. CPC Analyzed Precipitation for December 2008 over the 12 km Domain. 3-71
Figure 3-55. WRF Estimated Precipitation for December 2008 over the 12 km Domain. 3-71
Figure 3-56. CPC Analyzed Precipitation for January 2008 over the 4 km Domain. 3-72
Figure 3-57. WRF Estimated Precipitation for January 2008 over the 4 km Domain. 3-72
Figure 3-58. CPC Analyzed Precipitation for February 2008 over the 4 km Domain. 3-73
Figure 3-59. WRF Estimated Precipitation for February 2008 over the 4 km Domain. 3-73
Figure 3-60. CPC Analyzed Precipitation for March 2008 over the 4 km Domain. 3-74
Figure 3-61. WRF Estimated Precipitation for March 2008 over the 4 km Domain. 3-74
Figure 3-62. CPC Analyzed Precipitation for April 2008 over the 4 km Domain. 3-75
Figure 3-63. WRF Estimated Precipitation for April 2008 over the 4 km Domain. 3-75
Figure 3-64. CPC Analyzed Precipitation for May 2008 over the 4 km Domain. 3-76
Figure 3-65. WFF Estimated Precipitation for May 2008 over the 4 km Domain. 3-76
Figure 3-66. CPC Analyzed Precipitation for June 2008 over the 4 km Domain. 3-77
Figure 3-67. WRF Estimated Precipitation for June 2008 over the 4 km Domain. 3-77
Figure 3-68. CPC Analyzed Precipitation for July 2008 over the 4 km Domain. 3-78
Figure 3-69. WRF Estimated Precipitation for July 2008 over the 4 km Domain. 3-78
Figure 3-70. CPC Analyzed Precipitation for August 2008 over the 4 km Domain. 3-79
Figure 3-71. WRF Estimated Precipitation for August 2008 over the 4 km Domain. 3-79
Figure 3-72. CPC Analyzed Precipitation for September 2008 over the 4 km Domain. 3-80
Figure 3-73. WRF Estimated Precipitation for September 2008 over the 4 km Domain. 3-80
Figure 3-74. CPC Analyzed Precipitation for October 2008 over the 4 km Domain. 3-81
Figure 3-75. WRF Estimated Precipitation for October 2008 over the 4 km Domain. 3-81

Figure 3-76. CPC Analyzed Precipitation for November 2008 over the 4 km Domain. 3-82
Figure 3-77. WRF Estimated Precipitation for November 2008 over the 4 km Domain. 3-82
Figure 3-78. CPC Analyzed Precipitation for December 2008 over the 4 km Domain..... 3-83
Figure 3-79. WRF Estimated Precipitation for December 2008 over the 4 km Domain..... 3-83

EXECUTIVE SUMMARY

The Western Regional Air Partnership (WRAP) is conducting the West-wide Jump Start Air Quality Modeling Study (WestJumpAQMS) to develop a regional photochemical grid model (PGM) modeling platform for the western states. The PGM modeling platform will be used to address issues related to ozone, fine particulate matter ($PM_{2.5}$) and visibility. The WestJumpAQMS is setting up the CAMx[1] and CMAQ[2] PGMs for the 2008 calendar year using grid resolutions of 36, 12 and 4 km. Meteorological data are key inputs for PGM modeling. These data include wind speed and direction, temperature, water vapor concentrations (mixing ratio), sunlight intensity, clouds and precipitation, and vertical mixing. For PGMs such meteorological inputs are generated using prognostic meteorological models that solve the fundamental (primitive) equations of the atmosphere. For the WestJumpAQMS study the Weather Research Forecast (WRF[3] Version 3.3.1) Advanced Research WRF (WRF-ARW) was applied for the 2008 calendar year on a 36 km continental U.S. (CONUS), 12 km western U.S. (WESTUS) and 4 km Intermountain West Domain (IMWD) modeling domains.

The WestJumpAQMS 2008 WRF 36/12/4 km simulation was run in 5-day segments using multiprocessing with 8 nodes per run segment. Because of the size of the WRF 4 km IMWD, the 2008 annual WRF simulation took approximately 25,000 processing hours (~100 computing days) to complete. The 2008 WRF simulation was evaluated against surface wind, temperature and mixing ratio observations and maps of precipitation analysis fields based on observations prepared by the Climate Prediction Center (CPC).

The initial evaluation of the 2008 WRF simulation revealed a precipitation overestimation bias in the western U.S. The precipitation overestimation bias was especially prevalent during the summer months in the intermountain west and was primarily due to overactive convective precipitation. WRF sensitivity tests were conducted for a summer period and an alternative WRF physics configuration was identified that reduced, but did not eliminate, the precipitation overestimation bias. A revised 2008 WRF 36/12/4 km simulation was performed that produced improved precipitation model performance.

The 2008 WRF model performance for surface winds, temperature and mixing ratios was evaluated across the entire 36, 12 or 4 km modeling domains, within the different Regional Planning Organizations (RPOs), by individual state, and within 4 km Detailed Source Apportionment Domains (DSADs) and Impact Assessment Domains (IADs) that will be used in later stages of the WestJumpAQMS[4]. The WRF model performance statistics were compared against meteorological model performance benchmarks that have been developed by analyzing the meteorological model performance of ~30 "good" performing prognostic model simulations conducted to support air quality modeling. Most of these simulations were for urban ozone modeling of stagnation episodes in fairly flat locations. Thus, the performance benchmarks represent good prognostic model performance under simple meteorological and simple terrain conditions. We would not expect a prognostic model to perform as well in the complex terrain of the western U.S. that also has some complex meteorological conditions. In some

1 http://www.camx.com/
2 http://www.cmaq-model.org/
3 http://www.wrf-model.org/index.php
4 http://www.wrapair2.org/pdf/WestJumpAQMS_Modeling_Plan_Final_Jan23_2012.pdf

cases the 2008 WRF model performance was compared against new complex model performance benchmarks. The revised 2008 WRF simulation model performance was mostly within or at the simple model performance benchmarks and almost always achieved the complex model performance benchmarks. The 2008 WRF simulation was also able to reproduce the spatial distribution of the CPC precipitation fields, albeit with an overestimation bias during the summer. An analysis of the summer precipitation bias found that it was more due to WRF estimating too much precipitation when observed precipitation occurs, rather than WRF estimating precipitation when none was observed.

The WestJumpAQMS 2008 WRF model performance was compared to other prognostic model performance evaluations for comparable regions and recent (2002-2006) modeling years. The WestJumpAQMS model performance was typically as good as or better than these other recent prognostic meteorological model applications that have been used for air quality model applications, which included the WRAP 2002 MM5 application.

We conclude that the WestJumpAQMS 2008 WRF application exhibited reasonably good model performance that was as good or better than other recent prognostic model applications used in air quality planning and it was therefore reasonable to proceed with their use as inputs for the WestJumpAQMS photochemical grid modeling.

1 INTRODUCTION

ENVIRON International Corporation (ENVIRON), Alpine Geophysics, LLC (Alpine) and the University of North Carolina (UNC) at Chapel Hill Institute for Environment are performing the West-wide Jump Start Air Quality Modeling Study (WestJumpAQMS) managed by the Western Governors' Association (WGA). The objectives of the WestJumpAQMS are to initiate the next generation of regional technical analysis for support of Ozone and Particulate Matter (PM) transport and attainment demonstrations across the Western United States. The WestJumpAQMS is designed to be an open regional photochemical modeling study whose databases will be available to all for use. WGA has been working with its partners to develop a plan for 2011-2012 that initiates gathering of air quality data and improvements to air quality models and source apportionment work. To provide resources for this work, WGA has acquired funding and substantial in-kind and leveraged support from western States, EPA, BLM, other Federal Land Managers, and BP. A regional air quality platform is being developed for Photochemical Grid Models (PGMs) using the 2008 calendar year, which can be used to address regional ozone and PM transport and local formation issues focused on the Intermountain West region. An important component of the 2008 PGM modeling platform is the meteorological inputs, whose development and evaluation are described in this document.

1.1 Meteorological Modeling

Over the past decade, emergent requirements for numerical simulation of urban and regional scale air quality have led to intensified efforts to construct high-resolution emissions, meteorological and air quality data sets. The concomitant increase in computational throughput of low-cost modern scientific workstations has ushered in a new era of regional air quality modeling. It is now possible, for example, to exercise sophisticated mesoscale prognostic meteorological models and Eulerian and Lagrangian photochemical/aerosol models for multi-seasonal periods over near-continental scale domains in a matter of weeks with the application tailored to a specific air quality modeling project.

The tool used for this meteorological modeling study is the Weather Research and Forecasting (WRF) model[5,6], more specifically, the Advanced Research WRF dynamic core (WRF-ARW, henceforth simply called WRF). WRF is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs[7,8,9]. WRF contains separate modules to compute different physical processes such as surface energy budgets and soil interactions, turbulence, cloud microphysics, and atmospheric radiation. Within WRF, the user has many options for selecting the different schemes for each type of physical process. There is a WRF Preprocessing System

5 Skamarock, W.C., J.B. Klemp, J. Dudhia, D.O. Gill, M. Barker, M.G. Duda, X.-Y. Huang, W. Wang, and J.G. Powers, 2008: A description of the Advanced Research WRF version 3. NCAR Technical Note NCAR/TN475+STR.
6 http://www.wrf-model.org/index.php
7 Skamarock, W. C. 2004. Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra. *Mon. Wea. Rev.*, Volume 132, pp. 3019-3032. December. (http://www.mmm.ucar.edu/individual/skamarock/spectra_mwr_2004.pdf)
8 Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang and J. G. Powers. 2005. A Description of the Advanced Research WRF Version 2. National Center for Atmospheric Research (NCAR), Boulder, CO. June. (http://www.mmm.ucar.edu/wrf/users/docs/arw_v2.pdf)
9 Skamarock, W. C. 2006. Positive-Definite and Monotonic Limiters for Unrestricted-Time-Step Transport Schemes. Mon. Wea. Rev., Volume 134, pp. 2241-2242. June. (http://www.mmm.ucar.edu/individual/skamarock/advect3d_mwr.pdf).

(WPS) that generates the initial and boundary conditions used by WRF, based on topographic datasets, land use information, and larger-scale atmospheric and oceanic models.

This report describes an application and performance evaluation of WRF for an atmospheric simulation for calendar year 2008 over a modeling domain that covers the continental United States at 36 km grid spacing (36 km CONUS domain), the Western and Midwestern United States at 12 km grid spacing (12 km WESTUS domain) and the Intermountain West 4 km resolution (4 km IMWD).

1.2 WestJumpAQMS WRF Meteorological Modeling

The WestJumpAQMS study performed an initial 2008 WRF meteorological modeling of the 36/12/4 km domains using an initial set of physics options. The preliminary model performance evaluation of the initial 2008 WRF simulation revealed overstated precipitation amounts when compared to the observations. The overstated precipitation was worse for the summer months over the western states. Sensitivity simulations were carried out to determine alternative WRF physics options designed to reduce the overstated precipitation. WRF sensitivity tests even investigated the use of no cumulus parameterization in the 36/12 km domains. Although use of no cumulus parameterization reduced the amount of WRF precipitation, especially in the summer, it could not be justified. Ultimately, the WRF physics options presented in Chapter 2 (see Table 2-1) were selected and a revised 2008 WRF simulation was performed that exhibited superior meteorological model performance. Because of the large size of the modeling domains used in the WestJumpAQMS WRF simulation, the rerunning of the 2008 WRF simulation resulted in some delays. However, there are also delays in some other aspects of the study (e.g., availability of Version 2.0 of the 2008 National Emissions Inventory, NEI) so that the delays in the WRF simulation did not compromise the WestJumpAQMS schedule. The revised WRF simulation also produced superior meteorological model performance over the initial WRF simulation so was worth the extra effort.

2 METHODOLOGY

The methodology used in the 2008 WRF application for the WestJumpAQMS was to apply the WRF model for the 2008 annual period using our assessment of the best physics options for the region and then evaluate the WRF results (e.g., wind speeds, wind directions, temperatures, precipitation) with available surface meteorological observations.

2.1 Model Selection and Application

A brief summary of the WRF input data preparation procedure used for this annual modeling exercise is provided below.

Model Selection: The publicly available version of WRF (version 3.3.1) was used in the modeling study. The WPS preprocessor programs including GEOGRID, UNGRIB, and METGRID were used to develop model inputs.

Horizontal Domain Definition: The computational domain on which WRF was applied was sized to accommodate the air quality and emissions modeling grids as presented in Figure 2-1. The WRF 36/12/4 km domains are defined with at least a 5 grid cell buffer in all directions from the air quality modeling domains to minimize any potential numeric noise along domain boundaries. The WRF horizontal domains are presented in Figure 2-2. The grid projection was Lambert Conformal with a pole of projection of 40 degrees North, -97 degrees East and standard parallels of 33 and 45 degrees, the so-called RPO projection.

Vertical Domain Definition: The WRF modeling was based on 37 vertical layers with an approximately 12 meter deep surface layer. The vertical domain is presented in both sigma and height coordinates in Table 2-2.

Topographic Inputs: Topographic information for the WRF was developed using the standard WRF terrain databases. The 36 km CONUS domain was based on the 10 min. (18 km) global data. The 12 km WESTUS domain was based on the 2 min. (~4 km) data. The 4 km IMWD was based on the 30 sec. (~900 m) data

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

Atmospheric Data Inputs: The first guess fields were taken from the 12 km (Grid #218) North American Model (NAM) archives available from the National Climatic Data Center (NCDC) NOMADS server.

Time Integration: Third-order Runge-Kutta integration was used with a fixed time step of 90 seconds for 36 km CONUS domain, 30 seconds for 12 km WESTUS domain, and 10 seconds for the 4 km IMWD.

Diffusion Options: Horizontal Smagorinsky first-order closure with sixth-order numerical diffusion and suppressed up-gradient diffusion was used.

Lateral Boundary Conditions: Lateral boundary conditions were specified from the initialization dataset on the 36 km CONUS domain with continuous updates nested from the 36 km domain to the 12 km WESTUS domain and continuous updates nested from the 12 km domain to the 4 km IMWD.

Top and Bottom Boundary Conditions: The top boundary condition was selected as an implicit Rayleigh dampening for the vertical velocity. Consistent with the model application for non-idealized cases, the bottom boundary condition was selected as physical, not free-slip.

Water Temperature Inputs: The water temperature data were taken from the NCEP RTG global one-twelfth degree analysis[10].

FDDA Data Assimilation: The WRF model was run with a combination of analysis and observation nudging (i.e., Four Dimensional Data assimilation [FDDA]). Analysis nudging was used on the 36 km and 12 km domain. For winds and temperature, analysis nudging coefficients of $5x10^{-4}$ and $3.0x10^{-4}$ were used on the 36 km and 12 km domains, respectively. For mixing ratio, an analysis nudging coefficient of $1.0x10^{-5}$ was used for both the 36 km and 12 km domains. The nudging used both surface and aloft nudging with nudging for temperature and mixing ratio not performed in the lower atmosphere (i.e., within the boundary layer). Observation nudging was performed on the 4 km grid domain using the Meteorological Assimilation Data Ingest System (MADIS)[11] observation archive. The MADIS archive includes the National Climatic Data Center (NCDC)[12] observations and the National Data Buoy Center (NDBC) Coastal-Marine Automated Network C-MAN[13] stations. The observational nudging coefficients for winds, temperatures and mixing ratios were $1.0x10^{-4}$, $1.0x10^{-4}$, and $1.0x10^{-5}$, respectively and the radius of influence was set to 50 km.

Physics Options: The WRF model contains many different physics options. The physics options chosen for this application are presented in Table 2-1.

Application Methodology: The WRF model was executed in 5-day blocks initialized at 12Z every 5 days with a 90 second integration time step. Model results were output every 60 minutes and output files were split at 24 hour intervals. Twelve (12) hours of spin-up was included in each 5-day block before the data were used in the subsequent evaluation. The model was run at the 36 km, 12 km and 4 km resolution from December 15, 2007 through January 4, 2009. WRF was configured to run in distributed memory parallel mode and was executed using 8 MPICH2 processes per segment on a Linux cluster using Intel Xeon processors (i.e., WRF simulations used multiprocessing with 8 nodes per run segment). The model calculation required approximately 25,000 core hours (~100 days of computing).

2.2 Evaluation Approach

The model evaluation approach was based on a combination of qualitative and quantitative analyses. The qualitative approach was to compare the model estimated monthly total precipitation with the monthly Center for Prediction of Climate (CPC) precipitation analysis using graphical outputs. The

10 Real-time, global, sea surface temperature (RTG-SST) analysis. http://polar.ncep.noaa.gov/sst/oper/Welcome.html
11 Meteorological Assimilation Data Ingest System. http://madis.noaa.gov/
12 National Climatic Data Center. http://lwf.ncdc.noaa.gov/oa/ncdc.html
13 National Data Buoy Center. http://www.ndbc.noaa.gov/cman.php

statistical approach was to examine tabulations of the model bias and error for temperature, wind direction and mixing ratio and wind speed RMSE and compare these to similar simulations.

Interpretation of bulk statistics over a continental or regional scale domain is difficult to interpret as seemingly good model performance (e.g., low bias) can be the result of model overestimation in one region compensating for model underestimation in another making it difficult to detect if the model is missing important sub-regional features. For this analysis, the statistics were performed on a state by state basis, a Regional Planning Organization (RPO) basis, and on a domain-wide basis for the continental U.S. 36 km and the regional western U.S. 12 km domain.

The observed database for winds, temperature, and water mixing ratio used in this analysis was the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) Meteorological Assimilation Data Ingest System (MADIS). The locations of the MADIS monitoring sites within the 36, 12 and 4 km WRF modeling domains are shown in Figures 2-2 through 2-5. The rain observations are taken from the NOAA Climate Prediction Center (CPC) retrospective rainfall archives[14].

Table 2-1. Physics options used in the WestJumpAQMS WRF Version 3.3.1 simulation of the 2008 calendar year.

WRF Treatment	Option Selected	Notes
Microphysics	WRF Single Moment -3 (WSM-3)	A simple efficient scheme with ice and snow processes suitable for mesoscale grid sizes.
Longwave Radiation	RRTMG	Rapid Radiative Transfer Model for GCMs includes random cloud overlap and improved efficiency over RRTM.
Shortwave Radiation	RRTMG	Same as above, but for shortwave radiation.
Land Surface Model (LSM)	NOAH	Two-layer scheme with vegetation and sub-grid tiling.
Planetary Boundary Layer (PBL) scheme	YSU	Yonsie University (Korea) Asymmetric Convective Model with non-local upward mixing and local downward mixing.
Cumulus parameterization	Kain-Fritsch in the 36 km and 12 km domains. None in the 4 km domain.	4 km can explicitly simulate cumulus convection so parameterization not needed.
Analysis nudging	Nudging applied to winds, temperature and moisture in the 36 km and 12 km domains	Temperature and moisture nudged above PBL only
Observation Nudging	Nudging applied to surface wind only in the 4 km domain	Surface temperature and moister observation nudging can introduce instabilities
Initialization Dataset	12 km North American Model (NAM)	

14 http://www.cpc.ncep.noaa.gov/products/precip/realtime/retro.shtml.

Table 2-2. Vertical layer definition for WRF simulations.

WRF Meteorological Model				
WRF Layer	Sigma	Pressure (mb)	Height (m)	Thickness (m)
37	0.0000	50.00	19260	2055
36	0.0270	75.65	17205	1850
35	0.0600	107.00	15355	1725
34	0.1000	145.00	13630	1701
33	0.1500	192.50	11930	1389
32	0.2000	240.00	10541	1181
31	0.2500	287.50	9360	1032
30	0.3000	335.00	8328	920
29	0.3500	382.50	7408	832
28	0.4000	430.00	6576	760
27	0.4500	477.50	5816	701
26	0.5000	525.00	5115	652
25	0.5500	572.50	4463	609
24	0.6000	620.00	3854	461
23	0.6400	658.00	3393	440
22	0.6800	696.00	2954	421
21	0.7200	734.00	2533	403
20	0.7600	772.00	2130	388
19	0.8000	810.00	1742	373
18	0.8400	848.00	1369	271
17	0.8700	876.50	1098	177
16	0.8900	895.50	921	174
15	0.9100	914.50	747	171
14	0.9300	933.50	577	84
13	0.9400	943.00	492	84
12	0.9500	952.50	409	83
11	0.9600	962.00	326	82
10	0.9700	971.50	243	82
9	0.9800	981.00	162	41
8	0.9850	985.75	121	24
7	0.9880	988.60	97	24
6	0.9910	991.45	72	16
5	0.9930	993.35	56	16
4	0.9950	995.25	40	16
3	0.9970	997.15	24	12
2	0.9985	998.58	12	12
1	1.0000	1000	0	

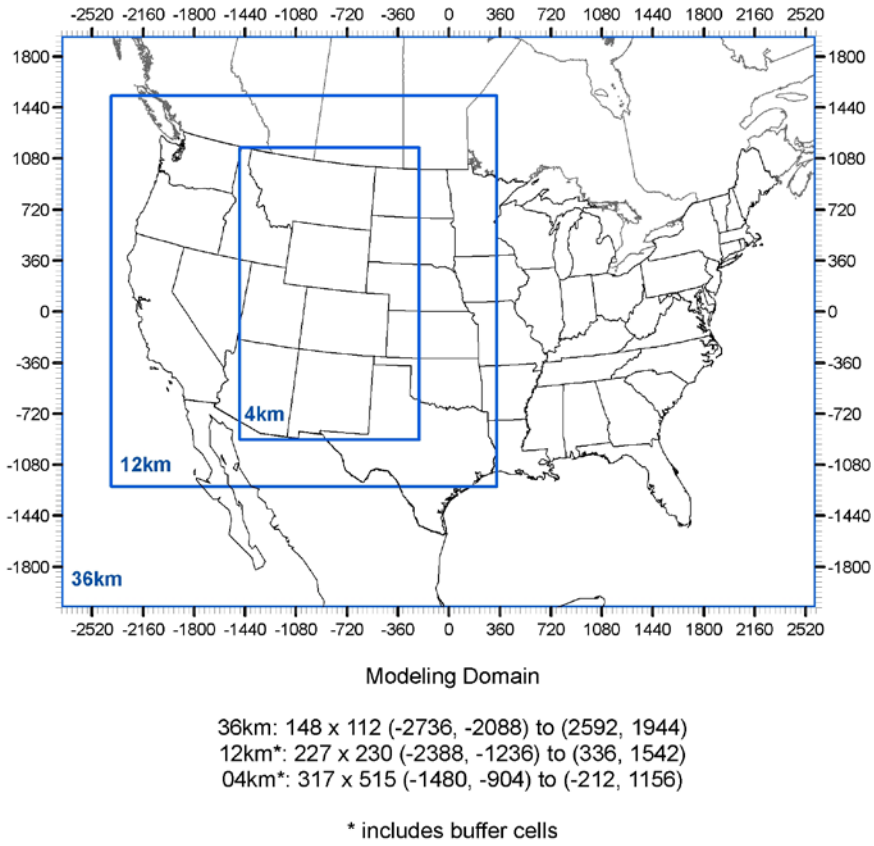


Figure 2-1. 36 km CONUS 12 km WESTUS and 4 km IMWD processing domain that air quality modeling inputs will be developed for (note that actual 4 km air quality domains will be subsets of the 4 km IMWD).

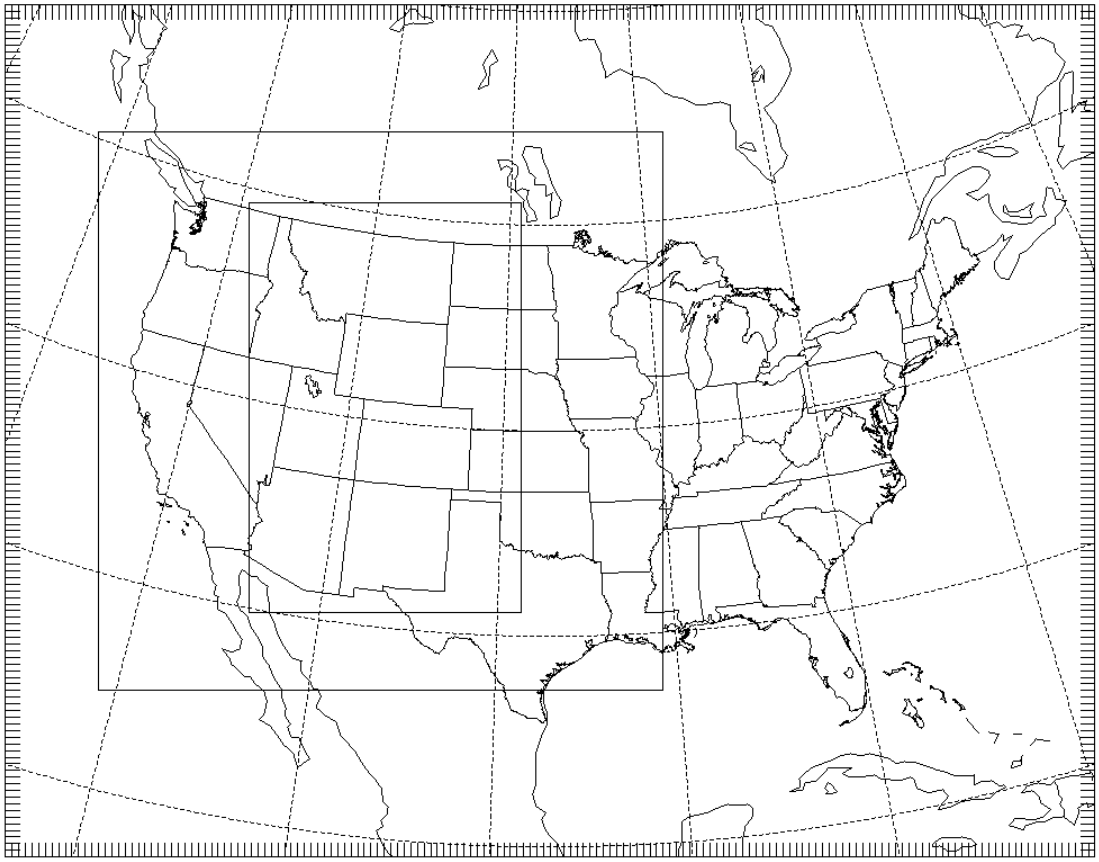


Figure 2-2. 36/12/4 km WRF meteorological modeling domains.

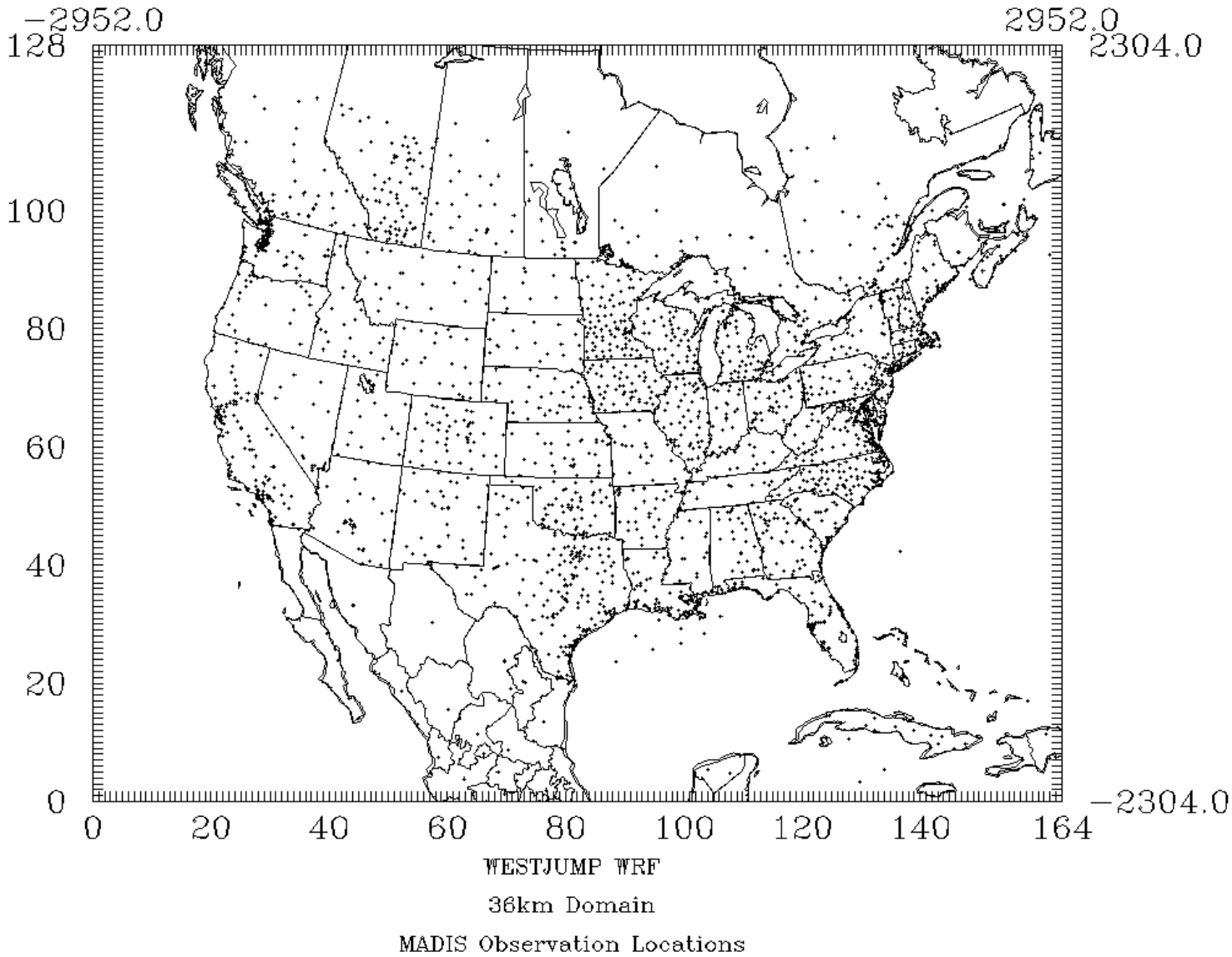


Figure 2-3. Locations of MADIS surface meteorological modeling sites with the WRF 36 km CONUS modeling domain.

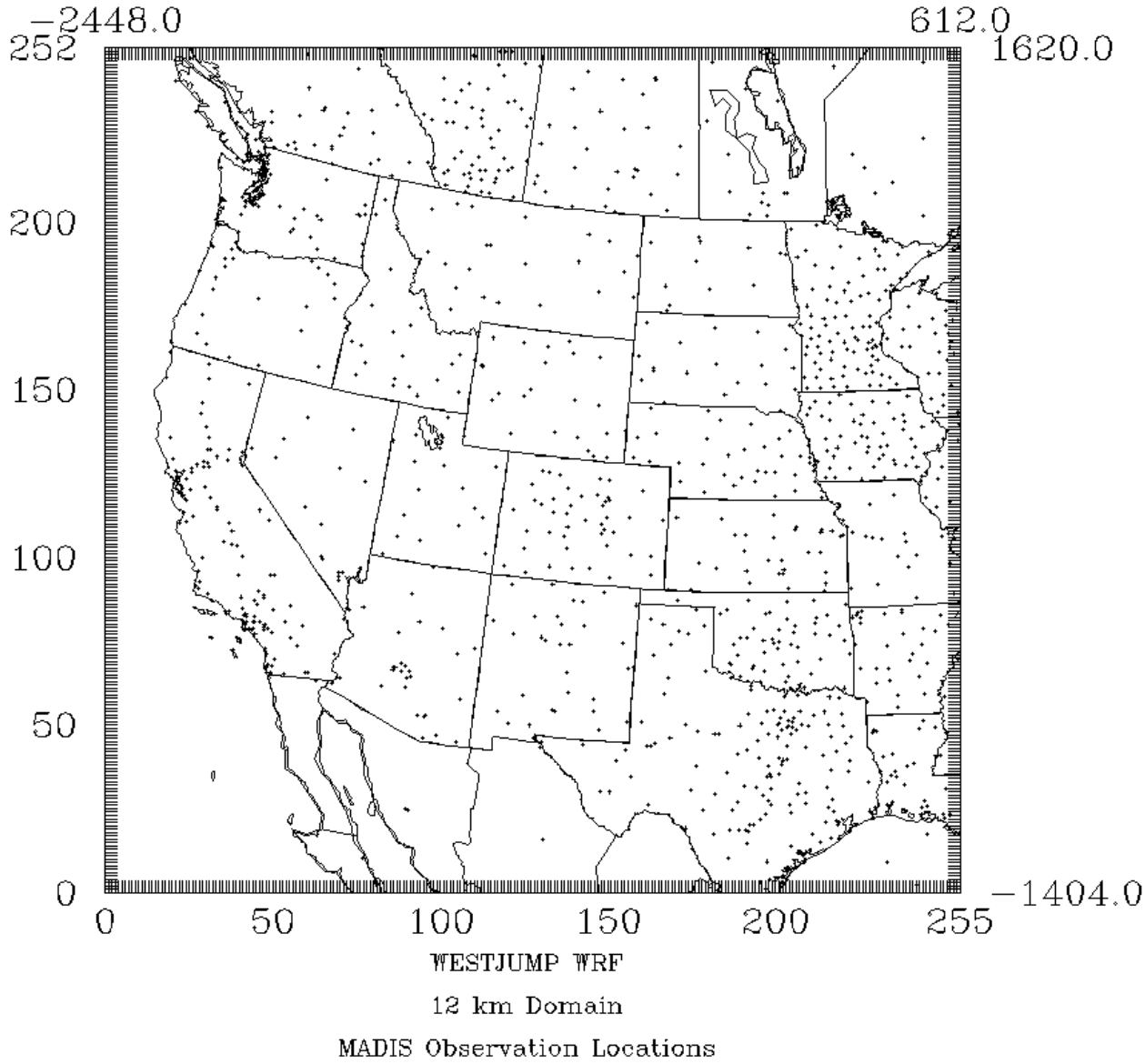


Figure 2-4. Locations of MADIS surface meteorological modeling sites with the WRF 12 km WESTUS modeling domain.

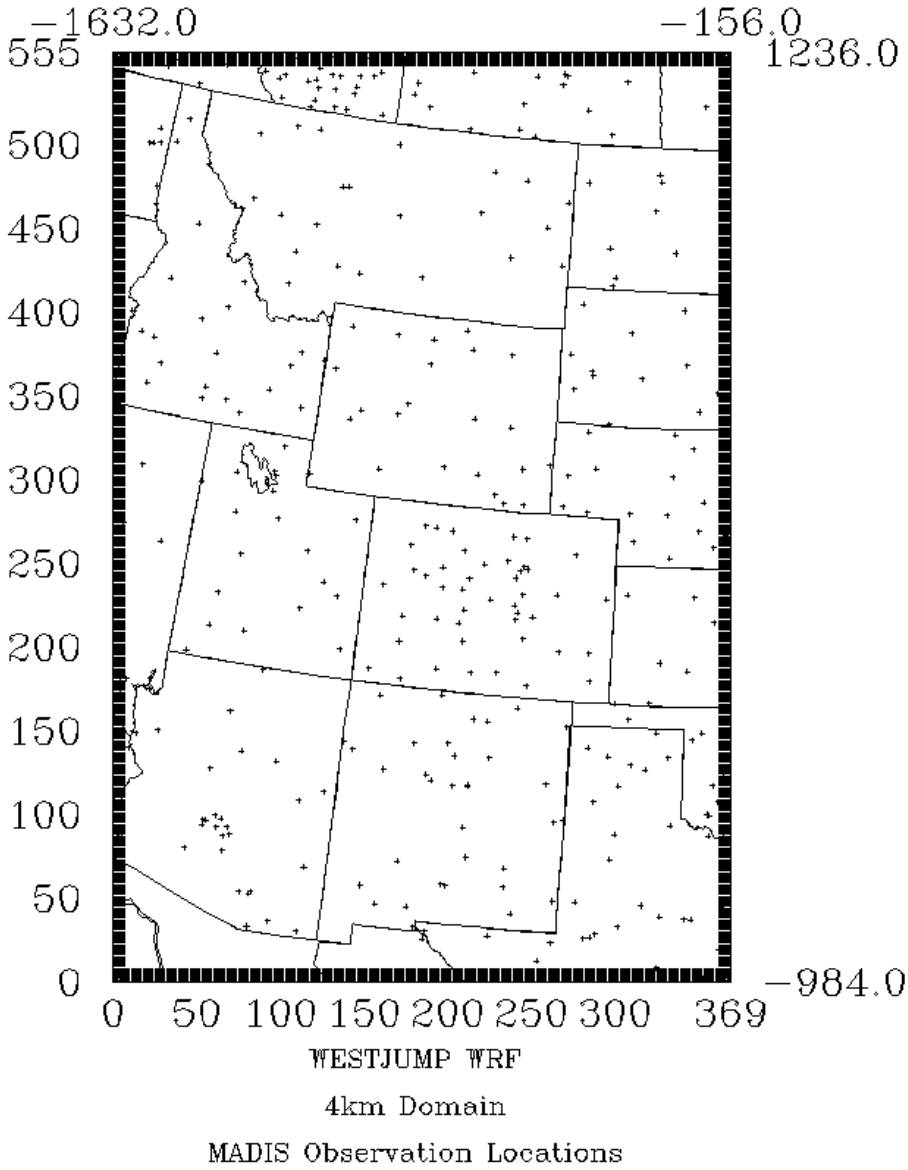


Figure 2-5. Locations of MADIS surface meteorological modeling sites with the WRF 4 km IMWS modeling domain.

3 WRF MODEL PERFORMANCE EVALUATION RESULTS

3.1 Quantitative Model Evaluation Results

Statistical model evaluation results are presented in this section. The quantitative model performance evaluation of WRF using surface meteorological measurements was performed using the publicly available METSTAT[15] evaluation tool. METSTAT calculates statistical performance metrics for bias, error and correlation for surface winds, temperature and mixing ratio and can produce time series of predicted and observed meteorological variables and performance statistics. A full annual model evaluation is very difficult to summarize in a single document, especially a simulation that could be used for many different purposes. With this in mind, this section presents results so potential data users can independently judge the adequacy of the model simulation. Overall comparisons are offered herein to judge the model efficacy, but this review does not necessarily cover all potential user needs and applications.

Table 3-1 through 3-21 present the statistical metrics for each state, for each RPO, and for the United States portion of the 36 km, 12 km, and 4 km modeling domains. For reference, a graphic of RPO boundaries is presented in Figure 3-1a. Results are also presented for each of the WestJumpAQMS Detailed Source Apportionment Domains (DSADs) and Impact Assessment Domains (IADs) whose locations and definitions are shown in, respectively, Figures 3-1b and 3-1c.

To evaluate the performance of the WRF 2008 simulation for the U.S., a number of performance benchmarks for comparison were used. Emery and co-workers[16] derived and proposed a set of daily performance "benchmarks" for typical meteorological model performance. These standards were based upon the evaluation of about 30 MM5 and RAMS meteorological simulations of limited duration (multi-day episodes) in support of air quality modeling study applications performed over several years. These were primary ozone model applications for cities in the eastern and Midwestern U.S. and Texas that were primarily simple (flat) terrain and simple (stationary high pressure causing stagnation) meteorological conditions. More recently these benchmarks have been used in annual meteorological modeling studies that include areas with complex terrain and more complicated meteorological conditions; therefore, they must be viewed as being applied as *guidelines* and not *bright-line* numbers. That is, the purpose of these benchmarks is not to give a passing or failing grade to any one particular meteorological model application, but rather to put its results into the proper context of other models and meteorological data sets. Recognizing that these simple conditions benchmarks may not be appropriate for more complex conditions, McNally[17] analyzed multiple annual runs that included complex terrain conditions and suggested an alternative set of benchmarks for temperature, namely a guideline of within ±1.0 °K for bias and 3.0 °K for error.

15 http://www.camx.com/down/support.php

16 Emery, C., E. Tai, and G. Yarwood, 2001. "Enhanced Meteorological Modeling and Performance Evaluation for Two Texas Ozone Episodes." Prepared for the Texas Natural Resource Conservation Commission, prepared by ENVIRON International Corporation, Novato, CA. 31-August. http://www.tceq.texas.gov/assets/public/implementation/air/am/contracts/reports/mm/EnhancedMetModelingAndPerformanceEvaluation.pdf

17 McNally, D. E., 2009. "12km MM5 Performance Goals." Presentation to the Ad-hov Meteorology Group. 25-June. http://www.epa.gov/scram001/adhoc/mcnally2009.pdf

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

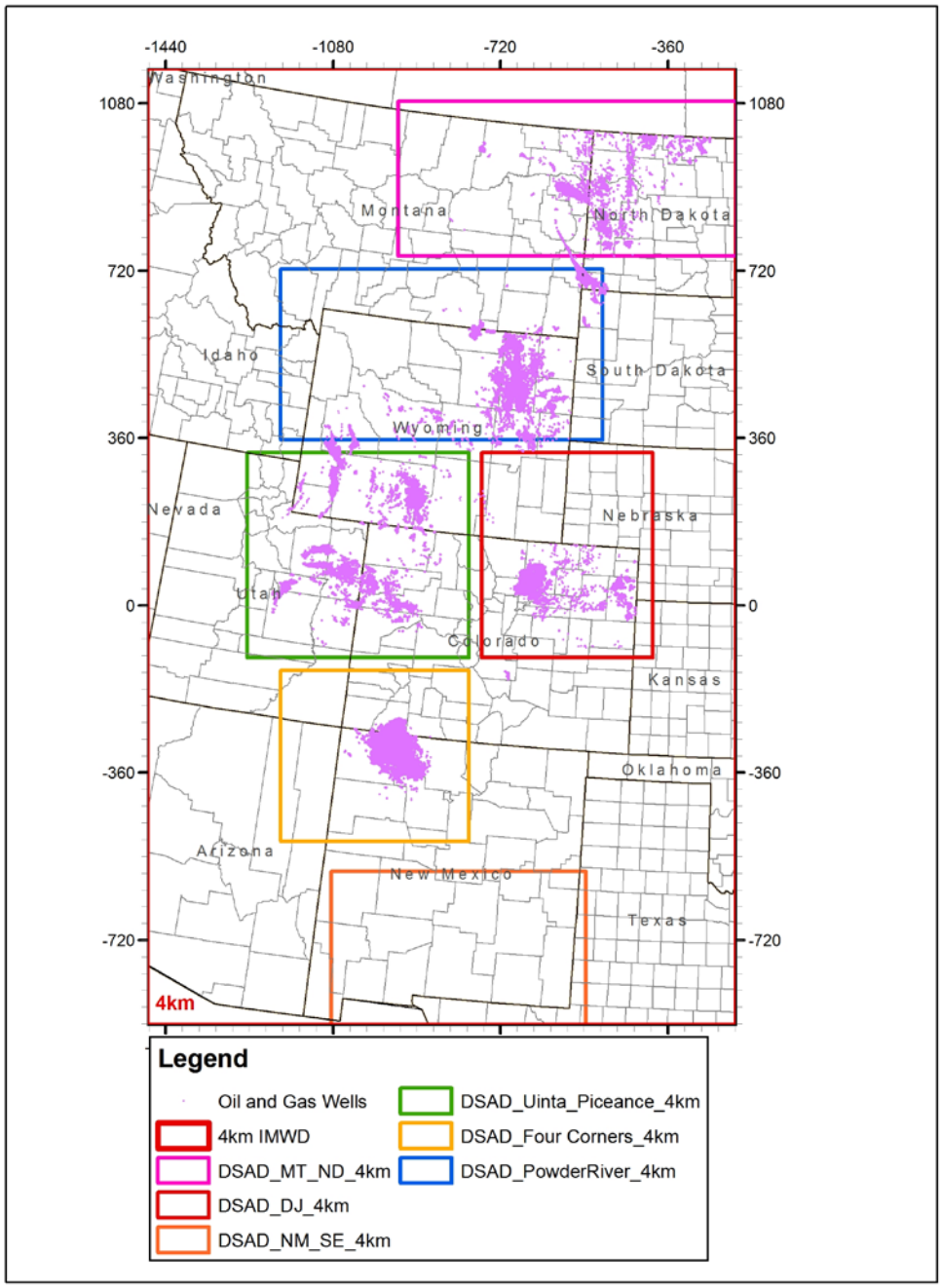


Figure 3-2b. Locations of the 4 km Detailed Source Apportionment Domains (DSAD).

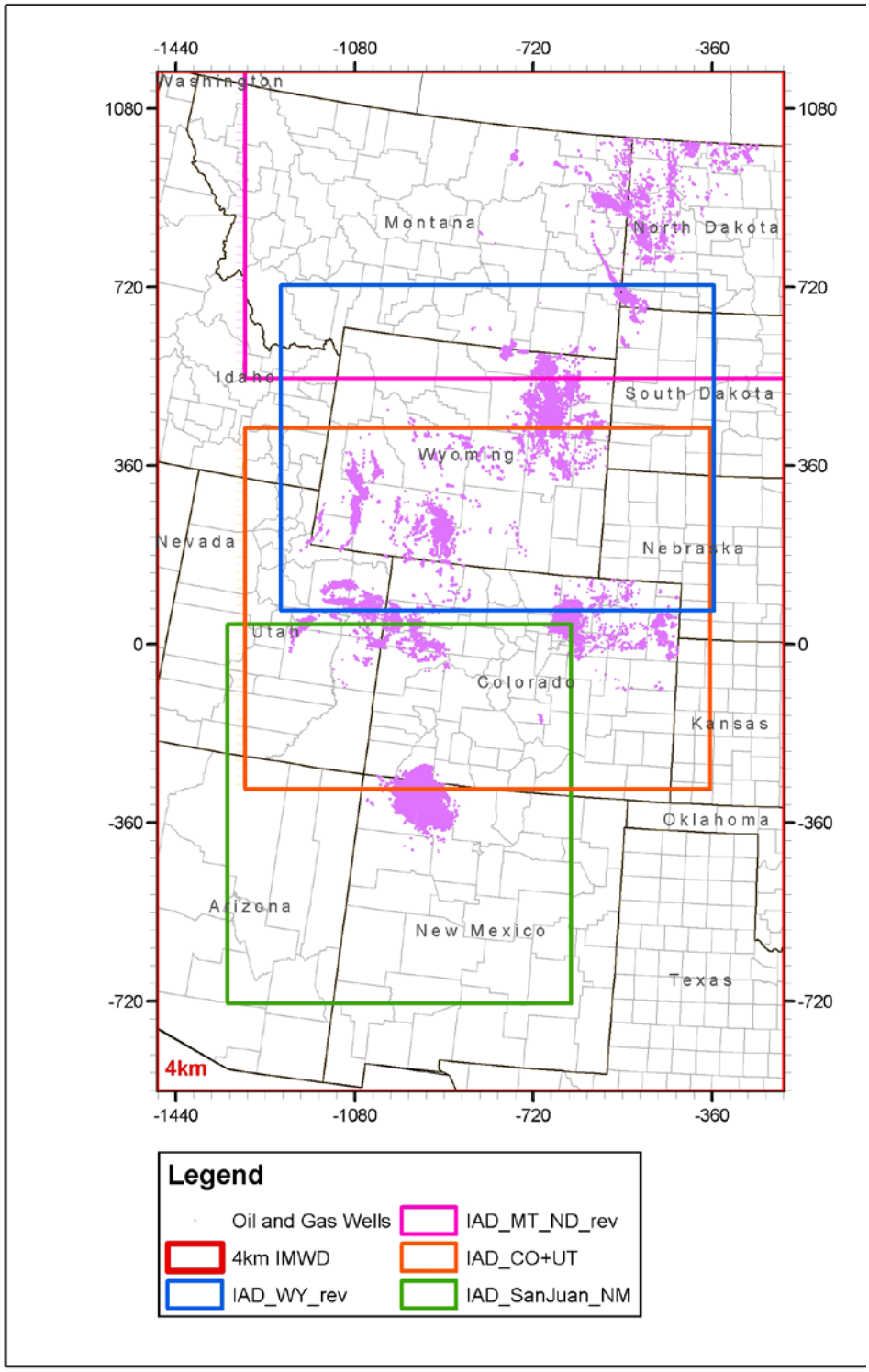


Figure 3-3c. Locations of the 4 km Impact Assessment Domains (IAD).

The key to the benchmarks is to understand how good or poor the results are relative to other model applications run for the U.S. A comparison to other similar model applications is presented in Section 4 of this report. In this section, the meteorological variables are compared to the benchmarks as an initial indication of the WRF performance. These benchmarks include bias and error in temperature, wind direction and mixing ratio as well as the wind speed bias and Root Mean Squared Error (RMSE) between the models and databases. The benchmark for each variable to judge whether predictions from a meteorological model are on par with previous meteorological modeling studies is as follows:

- Temperature Bias: less than or equal to ±0.5 °K; alternative of ≤±1.0 °K for complex conditions.
- Temperature Error: less than or equal to 2.0 °K; alternative of ≤3.0 °K for complex conditions.
- Mixing Ratio Bias: less than or equal to ±1.0 g/kg.
- Mixing Ratio Error: less than or equal to 2.0 g/kg.
- Wind Direction Bias: less than or equal to ±10 degrees.
- Wind Direction Error: less than or equal to 30 degrees.
- Wind Speed Bias: less than or equal to ±0.5 m/s.
- Wind Speed RMSE: less than or equal to 2 m/s

The equations for bias and error are given below, with the equation for the Root Mean Squared Error (RMSE) similar only being the square of the differences between the prediction and observation and a square root is taken of the entire quantity.

$$\text{Bias} = \frac{1}{N}\sum_{i=1}^{N}\left(P_i - O_i\right)$$

$$\text{Error} = \frac{1}{N}\sum_{i=1}^{N}\left|P_i - O_i\right|$$

3.1.1 Temperature Bias and Error

Temperature bias statistics for the 36 km CONUS modeling domain are presented in Table 3-1. As can be seen in Table 3-1, when the temperatures are averaged over the entire 2008 period for the entire modeling domain (CONUS), the model has a bias of 0.29 °K that achieves the benchmark (≤±0.5 °K). That is, the WRF model overestimates mean annual observed temperatures across the 36 km CONUS domain by 0.29 °K. The model exhibits positive bias for all months, with the largest positive biases occurring during October through December (0.54-0.73 °K) that exceed the simple (episodic) benchmark (≤±0.5 °K) but not the complex (Annual) benchmark (≤±1.0 °K).

Examination of Table 3-1 indicates that the model has an over prediction bias for the mean annual observed temperatures for all RPO sub domains with the largest bias for CENRAP central states (0.93 °K) and the smallest negative bias for WRAP (-0.05 °K).

States with annual temperature biases that fail to achieve the complex benchmark of ±1.0 °K are principally found in the western and central U.S. and include Idaho (1.13 °K), North Dakota (1.53 °K), Nevada (-1.75 °K), South Dakota (1.39 °K), Kansas (1.58 °K), Nebraska (1.50 °K), Oklahoma (1.41 °K) and Texas (1.32 °K).

Temperature bias statistics for the 12 km domain are presented in Table 3-2. When the temperatures are averaged over the entire 2008 period and the entire 12 km WESTUS modeling domain, the model has a bias of 0.67 °K. That is, the model over-predicts mean annual observed temperatures by 0.67 °K on average across the WESTUS domain during 2008. For the 12 km domain the best performing states for annual average temperature bias are Idaho (0.03 °K), and Arizona (0.14 °K). With the exception of Nevada, all state's temperatures were overestimated in the annual average.

On a month-by-month basis over the entire 12 km domain, the model exhibits temperature biases that fall within the ±1.0 °K complex benchmark for the majority of states. The benchmark is exceeded in Montana (1.01 °K), New Mexico (1.02 °K), North Dakota (1.50 °K), South Dakota (1.31 °K), Kansas (1.61 °K), Nebraska (1.51 °K), Oklahoma (1.43 °K), and Texas (1.27 °K).

Similar to the 36 km domain temperature bias results, the 12 km temperature biases exhibit primarily positive temperature biases on a month-by-month and state-by-state basis.

Temperature bias for the 4 km IMWD domain is presented Table 3-3. For the 4 km domain the annual mean temperature bias was 0.86 °K with the highest value of 1.44 °K in December and the lowest value of 0.38 °K in February. The bias was less than the ±1.0 °K benchmark in January through July, and was greater than the benchmark from August through December, although the benchmark was exceeded by less than 0.2 °K in all but December.

The temperature gross error for the 36 km CONUS modeling domain are presented in Table 3-4. The overall temperature error over all states and for all 2008 is 1.94 °K on the 36 km domain. Over the entire domain the model exhibits error within the 3.0 °K benchmark throughout the year.

Examination of Table 3-4 reveals that the WRF model 36 km simulation exhibits temperature gross errors within the 3.0 °K complex benchmark for all RPO subdomains and, with the exception of the WRAP RPO subdomain, the model achieves the even more stringent 2.0 °K simple benchmark. On a per state/per month basis the majority of values are within the 3.0 °K benchmark with the only values that exceed the complex benchmark being in the Western U.S.

Temperature error data for the 12 km WESTUS domain are presented in Table 3-5. The overall temperature error for the 12 km domain is 2.01 °K. On an annual basis, all states and regions are within the 3.0 °K benchmark.

Similar to the 36 km temperature error results, the 12 km temperature errors exhibit mixed performance on a month-by-month and state-by-state basis. The model tends to have a lower temperature error in the warmer months than the colder months.

Temperature error results for the 4 km IMWD domain are presented in Table 3-6. The annual mean temperature error for the 4 km domain was 2.10 °K with the best results in May (1.74 °K) and the worst results in December (3.08 °K).

The domain monthly average temperature bias and error for the 36 km, 12 km, and 4 km domains are displayed graphically in Figure 3-4 using the so-called "soccerplot" displays. Soccerplots plot the monthly average temperature bias versus the monthly average error. Along with the results are the simple and complex benchmark results (plotted in black). It is desirable to have all the monthly values lay inside the benchmark figure (a "goal"). On the 36 km CONUS domain (Figure 3-4 top left) the WRF model results monthly average temperature are all within the complex benchmark, but very near the upper bound of the simple benchmark for error (2.0 °K). The warmer months (April through October using the red symbols) mostly achieve the temperature bias simple benchmark, whereas Oct, Nov and Dec have a positive bias that fails to achieve the simple but does achieve the complex benchmark. For the 12 km WESTUS domain (Figure 3-4 top right) the results are all inside the complex benchmark except for July, where the bias does not achieve the ±1.0 °K benchmark due to an overestimation bias. Examination of the 4 km WRF results in the IMW domain (Figure 3-4 bottom) shows the model fails to achieve the temperature complex benchmark for five months due to a temperature bias that is too warm; for four of these months the monthly WRF 4 km temperature bias is just barely greater than 1.0 °K, but for July it is ~1.5 °K.

One reason for the degradation in temperature model performance for the 36 km, 12 km and 4 km WRF simulations is due to the presence of a higher proportion of monitoring sites in complex terrain locations for the finer grid domains. Appendix A displays WRF 36, 12 and 4 km temperature model performance for the four IAD domains (see Figure 3-1c) that are common to the three grid resolutions so use the same monitoring sites in the comparisons. The San Juan NM IAD domain covers the Four Corners region where the WRF 36 km simulation has a temperature underestimation bias in February and March that fails to achieve the complex benchmark, whereas the 12 km and 4 km WRF simulations achieve or nearly achieves the complex benchmark for all months (Figure A-1 left). The WRF 12 and 4 km simulation temperature bias in the San Juan IAD domain is similar with temperature errors being between the simple and complex benchmarks and the temperature bias achieving the simple benchmark from February to July but exceeding it due to overestimation the rest of the year.

For the CO-UT IAD domain (Figure A-1a right) the 36 km WRF simulation exhibits better temperature bias but worse temperature error than the 12 and 4 km WRF results. Both the 12 and 4 km WRF results exhibit temperature bias that is too warm and exceed the complex benchmark for September through December with the 4 km WRF results performing better than the 12 km WRF results with lower temperature bias and error across the CO-UT IAD region. WRF temperature model performance across the WY and MT-ND IAD regions (Figure A-1b) are similar with all three grid resolutions tending toward overestimation of temperature. The WRF 12 km results are performing worst with the majority of the months exhibiting an overestimation bias that fails to achieve the complex benchmark. The 4 km WRF simulation is performing the best with the lowest temperature error across the WY and MT-ND IAD regions.

3.1.2 Mixing Ratio Bias and Error

Mixing ratio (humidity) bias performance results for the 36 km CONUS modeling domain are presented in Table 3-7. Averaged over the entire 2008 year and over all states, WRF has a very low over-prediction mixing ratio bias of 0.04 g/kg, which is well within the ± 1.0 g/kg benchmark. That is, the model overestimates mean annual observed mixing ratios by 0.04 g/kg. The model exhibits a mix of positive and negative bias by month that cancels each other to yield the very low annual average mixing ratio bias. The model tends to underestimate mixing ratio in the warmer and more humid months of June through October with near zero bias to slight overestimate in the cooler months, which is most easily seen in the mixing ratio soccerplots (Figure 3-5).

The model also has a balance of positive and negative bias for the mean annual observed mixing ratio by RPO sub domains, the largest positive bias was for MANE-VU (0.29 g/kg) and the largest negative bias for WRAP (-0.18 g/kg), both of which achieve the benchmark.

Regionally, the WRF 36 km simulation has all months for all the RPOs fall within the ±1.0 g/kg benchmark. On a state-by-state and monthly basis, the benchmark is exceeded only in a few cases. For example, for the western U.S. the ±1.0 g/kg mixing ratio benchmark is only exceed by the 36 km WRF simulation for New Mexico during July and August (-1.47 and -1.43 g/kg) and North Dakota for August (-1.17 g/kg).

Mixing ratio bias model performance results for the 12 km WESTUS modeling domain are presented in Table 3-8. The WRF mixing ratio bias over the whole 12 km domain for all states on an annual basis is -0.16 g/kg, which achieves the benchmark. As with the 36 km domain results, the WRF model is underestimating in June through October and over estimating in the other months. On an annual basis, all states are within the ±1.0 g/kg benchmark.

Mixing ratio bias for the 4 km domain is presented in Table 3-9. The annual mean mixing ratio bias was -0.05 g/kg for the 4 km IMWD region. The model performs significantly better for mixing ratio on the 4 km grid than for the 36 and 12 km domains with all monthly values within the ±1.0 g/kg benchmark. For example, for New Mexico, where the July and August mixing ratio biases were approximately -1.4 g/kg in the WRF 36 and 12 km simulations so failed to achieve the ≤±1.0 g/kg benchmark, the mixing ratio biases are -0.64 and -0.73 g/kg for the WRF 4 km simulation so achieve the benchmark.

Mixing ratio error model performance results for the 36 km CONUS domain are presented in Table 3-10. The mean error across the CONUS domain in 2008 is 0.90 g/kg, which achieves the 2.0 g/kg mixing ratio error benchmark. On a monthly basis, the entire domain and the individual subdomains all exhibit mixing ratio errors that are almost always less than the 2.0 g/kg benchmark. The only state/months that exceed the benchmark are Kansas in July (2.02 g/kg) and Oklahoma in July through August (2.25 g/kg, 2.65 g/kg, and 2.32 g/kg, respectively).

Mixing ratio error model performance results for the 12 km WESTUS modeling domain are presented in Table 3-11. The annual mean mixing ratio error for the entire domain is 0.90 g/kg and on an annual basis mixing ratio errors for all states are less than the 2.0 g/kg benchmark with the highest value being 1.19 g/kg for California. As with the 36 km mixing ratio error performance results, the benchmark value

of 2.0 g/kg is met in all states for the monthly averages except for Kansas in July and Oklahoma in June through August.

Mixing ratio error results for the 4 km IMWD region are presented in Table 3-12. The annual mean mixing ratio bias results for the 4 km domain is 0.79 g/kg. The monthly mean mixing ratio error results for all regions/states by month are less than the 2.0 g/kg benchmark. In most cases and domains, the values of mean error are generally the greatest in the more moist summertime months of May through September, but still achieve the benchmark.

The domain average mixing ratio bias and error are displayed graphically in Figure 3-5. Examination of the figures shows that "goals" are scored in all months for the 36 km, 12 km and 4 km domains. The model tends to have about equal spread in the mixing ratio bias (horizontal scatter) and in the mixing ratio error (vertical scatter). As noted previously, the warmer months have an underestimation and the cooler months no to slight overestimation bias for mixing ratio.

Soccerplots of mixing ratio bias versus error for the four IAD regions are shown in Figure A-2 with the benchmark achieved for all months and regions. For all four IAD regions, the 36 and 12 km WRF results display a range of bias with the warmer months having an underestimation bias with July and August exhibiting mix ratio biases between -0.5 and -1.0 g/kg. However, the 4 km WRF results exhibit much better mixing ratio bias that is centered on zero even for the warm months and within ±0.5 g/kg.

3.1.3 Wind Direction and Wind Speed Performance

Comparisons between the WRF modeling results and winds from the MADIS surface observations were made using the wind direction bias and error and the wind speed Root Mean Square Error (RMSE). Soccer plots were also used to analyze the wind speed bias and RMSE. Note that the MADIS observations have a low wind speed bias because it only reports wind speed to the nearest knot (kt) using truncation. For example, a 3.9 kt wind speed would be reported as 3.0 kt. Consequently, the observed wind speed observations are biased low by ~½ kt on average (~0.26 m/s). No adjustments were made to the WRF wind speed estimates to account for this measurement artifact.

The wind direction bias model performance results for the 36 km CONUS domain are presented in Table 3-13. The 36 km domain-wide 2008 annual average wind direction bias is 5.50 degrees, which is approximately half the benchmark of ±10 degrees. Month-to-month wind direction bias values for the entire CONUS domain are all below the benchmark with the highest value of 7.80 occurring in January.

The annual wind direction bias by RPO was best for the Midwest RPO (4.05 degrees) followed by VISTAS (5.28 degrees). The worst performing RPO was the MANE_VU with a direction bias of 6.28 degrees, although this value is still within the benchmark.

The wind direction bias model performance results for the 12 km WESTUS modeling domain are presented in Table 3-14. The 12 km domain-wide 2008 annual average was 5.16 degrees. The annual average wind direction bias for the WRAP region and the 12 km WRF simulation (4.24 degrees) is better than seen for the WRF 36 km simulation (5.87 degrees).

On a state-by-state basis the annual wind speed bias for the 12 km WRF simulation outperformed the 36 km WRF simulation for all states with the exception of Arizona (0.94 vs. 1.18) whose 12 km and 36 km wind direction bias performance is almost identical. In fact, the 36 km WRF simulation wind direction bias exceeded the benchmark for Montana and Idaho but the benchmark was not exceeded by the 12 km WRF simulation for these two states.

Wind direction bias for the 4 km domain is presented in Table 3-15. For the 4 km domain the annual average wind direction bias was 3.35 degrees. As was seen with the increase in resolution from 36 km to 12 km, when the resolution is increased from 12 km to 4 km the annual average wind direction bias for the WRAP region decreases from 4.36 degrees to 3.28 degrees. For WRAP states in the 4 km IMWD, the wind direction bias is improved in the 4 km WRF simulation compared to the 12 km WRF simulation. For example, the annual wind direction bias in Montana and Idaho are reduced from 9.85 to 6.48 and 8.44 to 3.45 degrees, respectively, when going from the 12 km to 4 km WRF simulations.

Wind direction error for the 36km grid is presented in Table 3-16. The domain average annual wind direction error is less than the 30 degree benchmark with a value of 28.44 degrees. The WRAP region had the highest annual average wind direction error of 43.36 degrees that exceeds the benchmark. The other RPOs were all within the benchmark. This is not surprising given that the benchmarks were developed based on simple terrain meteorological modeling and many of the WRAP states are characterized by complex terrain.

Wind direction error for the 12 km WESTUS domain is presented in Table 3-17. The annual average over the entire domain was 29.99 degrees, within the ±30 degree benchmark. The WRAP region annual error was 40.35 degrees, slightly less than the value of 43.36 degrees for the 36 km grid.

Wind direction error results for the 4 km WRF simulation are presented in Table 3-17. The mean wind direction error for the 4 km domain was 33.96 degrees which is slightly greater than the ±30 degree benchmark. Again, the WRAP subregion performance improved with the increased resolution, dropping from 39.95 with for the 12 km WRF simulation to 36.97 with 4 km WRF simulation.

Wind direction bias and error are presented graphically in Figure 3-6. For the 36 km domain (top left) the wind direction errors somewhat exceed the benchmark for a few months, but wind direction bias values are within the benchmark. For the 12 km domain (top right) the wind direction error benchmark is again exceeded for a few months. The model shows little month to month variation for either the 36 km or the 12 km domains. The 4 km results (bottom left) show that the model has little month-by-month variation in wind direction bias (the horizontal axis), and the wind direction bias is well within the benchmark. However, the wind direction error exceeds the benchmark for all months. The all domain wind direction soccer plots in Figure 3-4 imply that there is degradation in model performance between the 36/12 km WRF simulations and the 4 km WRF simulation. However, this seemingly degradation in performance for the 4 km WRF simulation is due to the fact that that the 4 km domain contains a higher proportion of stations located in complex terrain than the other domains. The 4 km WRF simulation also explicitly resolves convective activity, which is always a challenge for a meteorological model to reproduce. Examining the wind direction error model performance in WRAP states that are common to the 36/12/4 km domains reveals that the 4 km domain typically produces the best model performance,

this includes states such as Colorado (45.85/42.32/39.57 degrees), Idaho (53.82/50.21/41.81 degrees) and New Mexico (39.09/36.26/35.19 degrees).

Soccerplots of the WRF 36, 12 and 4 km wind direction bias and error for the four IAD regions show that the wind direction performance actually improves when using finer grid resolution (Figure A-3). For the San Juan and CO-UT IADs, the wind direction bias is centered on zero but the error exceeds the 30 degree benchmark (Figure A-3a) with the 4 km WRF results exhibiting lower error than the 36 and 12 km WRF results. Wind direction performance in the WY and MT-ND IADs is much better in the 4 km simulation than in the 36/12 km WRF results (Figure A-3b). The WRF 36/12 km results exhibit a positive wind direction bias that is reduced in the 4 km results.

Table 3-19 presents the wind speed RMSE by state and RPO by month for the 36 km CONUS domain. The mean wind speed RMSE for the entire year for the entire domain is 1.78 m/s, inside the 2.0 m/s benchmark. The annual average values for all RPOs are within the benchmark. The model shows a slight trend toward lower wind speed RMSE in the summer than in the other months.

The wind speed RMSE for the 12 km grid are presented in Table 3-20. The region wide annual average value is 1.81 m/s. The WRAP region has nearly the same value for the 12 km WRF simulation (1.94 m/s) as for the 36 km WRF simulation (1.99 m/s).

Wind speed RMSE results for the 4 km domain are presented in Table 3-21. The annual average wind speed RMSE for the 4 km grid was 2.09 m/s. The wind speed RMSE performance in the WRAP region was somewhat degraded for the 4 km versus the 12 km WRF simulation with the value increasing slightly from 2.01 m/s in the 12 km to 2.09 m/s for the 4 km WRF simulation. When examining the individual WRAP states that are common to the 36/12/4 km domains, unlike for wind direction we fail to see a consistent improvement in WRF model performance for wind speed RMSE when higher resolution is used. Instead we typically see a slight degradation in wind speed RMSE performance using higher resolution.

Wind speed bias and RMSE for the 36 km, 12 km and 4 km domains are presented graphically **in** Figure 3-7. For the 36 km and 12 km domains (top left and top right, respectively) the model shows little month to month variation in wind speed RMSE with values right below the 2.0 m/s benchmark. The wind speed bias has variation centered on zero and “goals” are scored for all months, with the warmer months having a more negative bias than the cooler months. The model results for the 4 km domain (bottom) are somewhat worse than the results for the 36 km and 12 km domains. For the 4 km domain the model shows a systematic negative wind speed bias and wind speed RMSE that just exceed the 2.0 m/s benchmark on many months. Like wind direction, this seemingly degradation in wind speed model performance is likely due to the higher preponderance of states with complex terrain in the 4 km domain versus the 36 and 12 km domains.

Figure A-4 displays the wind speed bias and RMSE soccerplots for the four IAD regions and confirms that the 4 km WRF results are performing better than the 36/12 km WRF results. For the San Juan and CO-UT IADs, the 36/12 km WRF results exhibit a wind speed underestimation bias of -0.5 to -1.5 m/s that fails to achieve the benchmark (≤±0.5 m/s), whereas the 4 km WRF results are right at the benchmark. Similar results are seen in the WY and MT-ND IADs with the 4 km WRF results generating performing better than the coarser grid WRF results.

Table 3-1. Temperature Bias (K) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.41	0.13	0.01	0.21	0.28	0.02	0.17	0.13	0.28	0.54	0.57	0.73	0.29
Western Regional Air Partnership (WRAP)													
WRAP	-0.01	-0.49	-0.36	-0.37	-0.19	-0.20	0.13	0.14	0.17	0.11	0.20	0.30	-0.05
AZ	-0.43	-1.03	-0.71	-0.99	-0.95	-1.19	0.37	0.18	-0.72	-0.84	-0.75	-0.34	-0.62
CA	0.21	0.48	-0.11	-0.39	-0.19	0.45	0.62	0.24	0.33	0.25	0.31	0.63	0.24
CO	-0.55	-2.04	-0.84	-0.66	-0.26	-0.54	-0.17	0.15	0.00	0.05	0.13	0.08	-0.39
ID	-1.35	-1.60	-1.67	-1.51	-0.90	-1.29	-1.33	-0.93	-0.77	-0.56	-0.56	-1.04	-1.13
MT	0.38	-0.04	-0.42	-0.45	-0.08	-0.20	-0.40	-0.13	0.34	-0.14	-0.19	1.02	-0.03
NM	0.18	-0.89	0.01	0.29	0.22	0.16	1.41	1.24	0.85	0.34	0.48	0.40	0.39
ND	-0.12	0.79	0.97	2.19	1.82	1.50	1.53	2.37	2.10	1.79	1.47	1.97	1.53
NV	-1.14	-1.94	-2.05	-1.96	-1.57	-2.23	-1.84	-2.25	-2.09	-1.68	-1.20	-1.08	-1.75
OR	-0.01	-0.58	-0.60	-0.89	-1.22	-1.29	-1.42	-1.05	-0.78	-0.14	0.20	-0.04	-0.65
SD	0.90	-0.27	1.68	2.10	1.80	1.33	1.93	1.79	1.78	1.20	0.99	1.49	1.39
UT	-0.21	-0.97	-1.64	-1.47	-1.06	-1.89	-1.57	-1.62	-0.95	-0.18	0.11	0.18	-0.94
WA	0.49	-0.83	-0.79	-1.15	-1.33	-1.63	-1.77	-0.96	-1.21	-0.90	-0.27	-1.00	-0.95
WY	0.02	-2.07	-1.32	-1.16	0.01	0.00	0.04	0.27	0.80	-0.32	-0.01	0.15	-0.30
Westjump DSAD Domains													
DJ_4km_rev	1.12	-0.11	1.20	1.27	1.46	1.08	1.46	2.16	1.86	1.64	1.65	1.94	1.39
FourCorners_4km	-0.57	-3.14	-1.42	-1.00	-0.45	-0.71	0.42	-0.07	-0.40	-0.41	-0.31	-0.80	-0.74
MT_ND_4km_rev	0.97	0.60	1.78	2.35	1.76	2.00	2.05	2.27	2.17	1.93	1.52	2.58	1.83
NM_SE_4km	0.18	-0.56	0.23	0.15	-0.02	0.28	1.69	1.92	1.62	0.65	0.66	0.82	0.64
PowderRiver_4km	-0.02	-1.79	-1.59	-1.57	-0.31	-0.30	-0.26	-0.15	0.40	-0.62	-0.49	-0.06	-0.56
Uinta_Piceance_4km	-1.50	-3.37	-2.87	-2.47	-1.76	-2.19	-2.17	-2.15	-1.40	-1.11	-0.66	-1.09	-1.90
Westjump IAD Domains													
CO_UT	0.03	-1.69	-0.68	-0.45	0.06	-0.28	0.03	0.30	0.40	0.26	0.44	0.43	-0.10
MT_ND_rev	0.67	0.60	0.70	0.70	0.92	0.77	0.82	1.04	1.11	0.78	0.61	1.60	0.86
SanJuan_NM	-0.35	-2.33	-1.05	-0.74	-0.37	-0.75	0.13	0.16	-0.10	-0.15	-0.09	-0.29	-0.49
WY_rev	0.51	-1.29	-0.42	-0.21	0.49	0.35	0.49	0.70	0.98	0.25	0.40	0.77	0.25
Mid-Atlantic/Northeast Visibility Union (MANE-VU)													
MANE_VU	0.39	1.14	-0.09	-0.11	0.10	-0.45	-0.31	-0.16	0.03	0.66	0.35	0.48	0.17
CT	0.25	0.69	-0.23	-0.44	-0.25	-0.99	-0.91	-0.27	0.09	0.96	0.66	0.92	0.04
DE	0.70	1.51	0.50	0.45	0.92	0.28	0.32	0.19	0.34	0.90	0.82	0.65	0.63
MA	0.61	1.46	0.09	-0.46	-0.31	-1.41	-1.20	-0.26	0.06	1.08	0.79	0.93	0.12
MD	0.73	1.34	0.51	0.36	0.64	0.40	0.81	0.64	0.57	0.72	0.36	0.60	0.64
ME	0.49	0.79	-0.48	0.26	0.00	-0.40	-0.88	-0.51	-0.09	0.71	0.55	0.80	0.10
NH	0.43	1.38	-0.01	0.52	0.46	0.03	0.05	-0.21	-0.04	0.87	0.40	0.26	0.35

Table 3-1. Temperature Bias (K) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NJ	0.62	1.01	0.24	0.07	0.83	0.08	0.51	0.83	0.87	1.57	0.89	0.91	0.70
NY	0.37	1.53	-0.47	-0.58	-0.21	-0.73	-0.44	-0.08	0.11	0.72	0.38	0.38	0.08
PA	0.22	0.59	0.10	0.04	0.22	-0.19	-0.19	-0.58	-0.41	-0.06	-0.23	0.12	-0.03
RI	0.24	1.54	-0.08	-0.46	-0.29	-1.34	-0.79	0.04	0.25	0.86	0.55	0.92	0.12
VT	-0.67	1.37	-1.34	-0.75	-0.62	-0.81	-0.73	-1.24	-1.01	-0.22	-0.59	-0.87	-0.62
Visibility Improvement State and Tribal Association of the Southeast (VISTAS)													
VISTAS	0.68	0.61	0.38	0.42	0.17	-0.02	0.38	0.19	0.16	0.36	0.78	0.69	0.40
AL	0.55	0.28	0.33	0.38	0.10	-0.16	0.20	0.25	0.29	0.35	0.64	0.77	0.33
GA	0.81	0.32	0.50	0.64	0.44	0.17	0.83	0.59	0.46	0.55	0.83	0.54	0.56
FL	1.48	1.97	0.75	0.55	-0.01	0.67	0.91	0.77	0.36	0.94	1.66	1.12	0.93
KY	0.68	-0.40	0.21	0.02	-0.01	-0.84	-0.71	-1.19	-1.14	-0.79	0.19	0.61	-0.28
MS	1.02	0.67	0.64	0.87	0.67	0.51	0.65	0.66	0.43	0.69	1.20	1.33	0.78
NC	0.48	0.46	0.39	0.50	0.32	-0.07	0.49	0.21	0.29	0.36	0.64	0.77	0.40
SC	0.95	0.33	0.34	0.41	0.19	-0.02	0.61	0.46	0.42	0.56	0.84	0.70	0.48
TN	1.00	0.45	0.36	0.33	0.39	-0.23	-0.32	-0.48	-0.15	-0.04	0.53	0.80	0.22
VA	-0.13	0.17	-0.08	0.06	-0.08	-0.66	0.05	-0.28	0.06	0.12	0.28	0.20	-0.02
WV	-0.30	-0.24	-0.22	-0.06	-0.36	-0.60	-0.96	-1.20	-1.17	-0.90	-0.27	-0.33	-0.55
Midwest Regional Planning Organization (MRPO)													
MW	0.62	-0.02	-0.01	0.29	0.26	-0.25	-0.27	-0.53	-0.14	0.76	0.62	0.54	0.16
IL	1.20	0.43	0.79	1.11	1.33	0.56	0.38	-0.27	-0.09	0.83	0.85	0.84	0.66
IN	1.22	0.27	0.55	0.84	0.91	0.47	-0.07	-0.51	-0.50	0.65	0.70	0.87	0.45
MI	0.67	-0.04	-0.05	-0.40	-0.48	-1.17	-0.74	-0.18	0.39	1.29	0.92	0.89	0.09
OH	0.73	0.05	-0.50	-0.17	0.13	-0.15	-0.58	-0.93	-0.67	0.16	0.21	0.49	-0.10
WI	-0.40	-0.61	-0.73	0.36	-0.12	-0.28	-0.23	-1.01	-0.42	0.42	0.20	-0.33	-0.26
Central States Regional Air Partnership (CENRAP)													
CENRAP	1.03	0.42	0.78	1.12	1.05	0.87	1.04	0.81	0.91	0.96	0.95	1.27	0.93
AR	1.24	1.03	0.64	1.01	0.64	0.49	0.22	0.15	0.02	0.33	0.60	1.25	0.64
IA	0.91	-0.52	0.81	1.29	0.84	0.40	0.10	-0.83	-0.02	0.61	0.59	0.70	0.41
KS	2.08	0.56	1.81	1.59	1.90	1.85	2.26	1.38	1.14	1.11	1.34	1.95	1.58
LA	1.06	1.44	0.07	0.20	0.27	0.27	0.15	0.23	0.02	0.48	1.10	1.17	0.54
MN	-0.42	-0.62	-0.56	1.06	0.74	0.16	0.07	0.29	0.85	1.09	0.79	0.49	0.33
MO	1.35	0.30	1.02	0.75	0.92	0.74	0.54	-0.25	-0.06	0.27	0.45	1.11	0.60
NE	1.71	0.50	1.91	1.93	1.91	1.28	1.48	0.73	1.27	1.47	1.85	1.94	1.50
OK	1.60	0.57	1.48	1.19	1.31	1.97	2.16	1.72	1.22	1.26	0.93	1.51	1.41
TX	1.49	1.13	1.07	1.05	1.11	1.03	1.73	1.80	1.58	1.11	1.02	1.66	1.32

(a) ALL in this case refers to those states within the area covered by the 36 km modeling domain.

Table 3-2. Temperature Bias (K) for 2008 WRF by Month and by State in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.71	0.25	0.41	0.57	0.62	0.50	0.68	0.63	0.75	0.86	0.93	1.10	0.67
Western Regional Air Partnership (WRAP)													
WRAP	0.75	0.18	0.35	0.33	0.37	0.34	0.62	0.67	0.73	0.78	0.88	0.95	0.58
AZ	0.40	-0.17	0.03	-0.23	-0.29	-0.47	0.93	0.79	0.08	0.06	0.14	0.43	0.14
CA	0.94	0.61	0.40	0.17	0.13	0.49	0.57	0.31	0.49	0.75	0.85	1.10	0.57
CO	0.34	-0.86	0.07	0.19	0.57	0.40	0.78	1.00	0.90	0.85	1.04	0.79	0.51
ID	-0.11	-0.12	-0.44	-0.24	0.06	-0.33	-0.31	0.13	0.36	0.63	0.50	0.28	0.03
MT	1.39	1.06	0.69	0.58	0.87	0.81	0.69	0.91	1.33	0.93	0.90	1.95	1.01
NM	0.90	0.18	0.67	0.79	0.72	0.72	1.88	1.77	1.40	0.94	1.13	1.09	1.02
ND	0.10	0.82	0.94	1.94	1.60	1.41	1.40	2.24	2.04	1.80	1.67	1.99	1.50
NV	0.11	-0.32	-0.84	-0.76	-0.44	-0.93	-0.57	-1.03	-0.63	-0.23	-0.03	0.25	-0.45
OR	0.88	0.39	0.34	0.03	-0.40	-0.47	-0.61	-0.16	0.15	0.71	0.87	0.73	0.21
SD	0.85	-0.39	1.52	1.82	1.57	1.15	1.75	1.62	1.73	1.24	1.18	1.68	1.31
UT	0.92	0.85	-0.08	0.02	0.38	-0.01	0.35	0.22	0.83	1.37	1.43	1.49	0.65
WA	1.00	0.53	0.50	0.31	0.16	-0.10	-0.12	0.08	0.01	0.53	0.61	0.14	0.30
WY	0.72	-1.24	-0.33	-0.03	0.88	0.99	1.01	1.12	1.58	0.48	0.99	0.94	0.59
Westjump DSAD Domains													
DJ_4km_rev	1.13	0.04	1.24	1.30	1.59	1.22	1.60	2.12	1.85	1.46	1.69	1.69	1.41
FourCorners_4km	0.35	-1.98	-0.75	-0.47	0.13	0.06	1.11	0.66	0.43	0.43	0.52	0.03	0.04
MT_ND_4km_rev	1.34	0.70	1.89	2.28	1.74	2.03	2.08	2.25	2.22	1.99	1.74	2.79	1.92
NM_SE_4km	0.58	0.11	0.69	0.54	0.33	0.69	2.03	2.24	1.95	1.04	1.09	1.32	1.05
PowderRiver_4km	0.93	-0.86	-0.44	-0.24	0.65	0.77	0.91	0.93	1.43	0.48	0.74	0.92	0.52
Uinta_Piceance_4km	0.21	-1.03	-0.80	-0.53	0.06	-0.10	-0.01	-0.07	0.60	0.73	1.07	0.56	0.06
Westjump IAD Domains													
CO_UT	0.77	-0.65	0.19	0.39	0.86	0.65	0.98	1.14	1.24	1.00	1.28	1.09	0.75
MT_ND_rev	1.31	1.08	1.25	1.19	1.35	1.29	1.38	1.57	1.66	1.43	1.36	2.21	1.42
SanJuan_NM	0.58	-0.99	-0.18	0.04	0.40	0.17	0.99	0.99	0.77	0.69	0.83	0.57	0.41
WY_rev	1.19	-0.56	0.41	0.65	1.18	1.10	1.30	1.40	1.64	0.90	1.18	1.33	0.98
Central States Regional Air Partnership (CENRAP)													
CENRAP	1.00	0.34	0.67	0.98	0.98	0.85	1.02	0.82	0.92	0.97	1.01	1.33	0.91
AR	1.35	1.01	0.61	0.97	0.66	0.56	0.30	0.17	0.11	0.49	0.78	1.38	0.70
IA	0.81	-0.56	0.62	1.11	0.70	0.33	0.03	-0.79	-0.03	0.60	0.55	0.71	0.34
KS	2.12	0.61	1.68	1.45	1.92	1.86	2.33	1.45	1.19	1.16	1.45	2.06	1.61
LA	0.75	1.21	0.01	0.38	0.45	0.47	0.20	0.26	-0.15	0.22	0.86	1.08	0.48
MN	-0.46	-0.79	-0.69	0.68	0.50	0.01	-0.03	0.22	0.82	1.07	0.86	0.62	0.23

Table 3-2. Temperature Bias (K) for 2008 WRF by Month and by State in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
MO	1.38	0.17	0.93	0.68	0.96	0.92	0.74	-0.11	0.10	0.35	0.51	1.11	0.65
NE	1.75	0.52	1.80	1.76	1.82	1.32	1.56	0.80	1.30	1.48	1.95	2.09	1.51
OK	1.67	0.74	1.38	1.08	1.26	1.94	2.12	1.71	1.29	1.30	1.08	1.61	1.43
TX	1.45	1.09	0.95	0.93	1.04	1.02	1.63	1.80	1.56	1.09	1.07	1.66	1.27

Table 3-3. Temperature Bias (K) for 2008 WRF by Month and by State in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.80	0.38	0.63	0.60	0.73	0.54	0.83	1.03	1.12	1.08	1.17	1.44	0.86
Western Regional Air Partnership (WRAP)													
WRAP	0.61	0.07	0.30	0.36	0.49	0.30	0.53	0.78	0.97	0.95	1.08	1.21	0.64
AZ	0.78	-0.03	0.26	-0.07	-0.17	-0.29	0.47	0.18	0.28	0.58	0.89	1.04	0.33
CO	0.28	-0.50	0.06	0.18	0.55	0.37	0.09	0.76	1.04	1.04	1.01	0.98	0.49
ID	0.53	0.60	0.14	0.28	0.47	0.33	0.31	0.65	0.80	1.18	1.09	0.98	0.61
MT	0.97	0.94	0.42	0.32	0.54	0.31	0.30	0.63	0.99	0.77	0.94	1.57	0.73
NM	0.80	-0.19	0.50	0.65	0.63	0.28	1.19	1.32	1.27	1.24	1.48	1.45	0.89
UT	1.49	1.81	0.58	0.53	0.51	0.31	0.50	0.61	0.99	1.45	1.69	2.12	1.05
WY	0.28	-1.05	-0.20	0.11	0.58	0.56	0.56	0.68	1.16	0.61	0.87	1.06	0.44
Westjump DSAD Domains													
DJ_4km_rev	0.51	0.29	0.67	0.73	0.84	0.45	0.40	1.05	1.24	1.14	0.95	1.22	0.79
FourCorners_4km	0.98	-1.33	-0.35	-0.29	0.26	0.24	0.63	0.74	0.75	0.96	1.23	1.00	0.40
MT_ND_4km_rev	0.62	0.51	1.03	1.41	1.01	0.87	0.94	1.38	1.44	1.35	1.29	1.87	1.14
NM_SE_4km	0.62	-0.13	0.57	0.43	0.36	0.27	1.53	1.80	1.77	1.30	1.53	1.66	0.98
PowderRiver_4km	0.52	-0.79	-0.22	0.11	0.64	0.52	0.64	0.75	1.20	0.64	0.87	1.19	0.51
Uinta_Piceance_4km	0.77	-0.26	-0.16	0.06	0.38	0.35	0.17	0.57	1.01	1.12	1.37	1.19	0.55
Westjump IAD Domains													
CO_UT	0.61	-0.27	0.20	0.37	0.66	0.49	0.36	0.82	1.13	1.09	1.15	1.24	0.65
MT_ND_rev	0.80	0.75	0.75	0.75	0.81	0.63	0.85	1.14	1.23	1.13	1.17	1.68	0.97
SanJuan_NM	0.68	-0.95	-0.09	0.08	0.46	0.24	0.42	0.79	0.90	0.96	1.07	1.00	0.46
WY_rev	0.72	-0.41	0.28	0.56	0.78	0.63	0.71	0.91	1.20	0.87	0.98	1.32	0.71

Table 3-4. Temperature Error (K) for 2008 WRF by Month and by State in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	1.88	2.06	1.91	1.82	1.79	1.86	2.05	2.03	1.81	2.02	1.93	2.16	1.94
Western Regional Air Partnership (WRAP)													
WRAP	2.14	2.53	2.18	2.27	2.11	2.50	2.40	2.46	2.51	2.21	2.23	2.89	2.37
AZ	1.90	2.18	1.94	2.46	1.80	1.99	1.57	2.23	2.16	1.73	1.61	2.05	1.97
CA	1.94	2.41	1.84	1.94	2.08	2.71	2.46	2.33	2.89	2.13	2.78	2.68	2.35
CO	2.97	3.31	3.15	3.70	2.55	2.92	2.86	2.90	2.67	2.54	2.46	4.43	3.04
ID	2.37	3.46	2.82	2.18	2.02	2.58	2.76	3.18	2.24	2.54	2.22	2.77	2.60
MT	3.17	2.54	2.66	2.27	1.95	2.96	2.52	2.64	2.35	2.50	2.28	3.33	2.60
NM	1.94	2.70	2.14	2.50	1.87	2.17	2.24	2.16	1.67	2.08	2.30	3.12	2.24
ND	2.21	2.42	1.88	2.24	2.15	1.76	2.32	3.86	2.50	3.00	1.45	3.86	2.47
NV	2.43	2.97	2.18	2.74	2.73	3.08	2.89	2.67	2.52	2.83	2.53	2.84	2.70
OR	1.47	2.49	2.26	1.66	1.96	2.28	2.74	2.16	2.90	2.22	2.49	1.83	2.21
SD	2.14	2.28	2.28	2.73	2.59	1.91	2.47	2.63	1.67	1.70	1.38	4.00	2.32
UT	3.48	2.20	1.77	2.75	2.37	2.95	2.70	2.79	2.33	2.04	2.88	3.35	2.63
WA	1.52	1.91	1.78	1.54	2.22	2.68	2.02	1.89	2.65	1.95	1.49	1.39	1.92
WY	2.28	2.68	2.25	2.25	1.58	1.98	2.01	2.22	2.19	2.81	1.74	3.96	2.33
Westjump DSAD Domains													
DJ_4km_rev	2.71	1.91	3.55	2.80	1.83	2.18	2.52	2.85	2.33	2.66	1.53	3.91	2.57
FourCorners_4km	2.80	3.94	2.20	2.82	2.48	2.39	2.14	1.87	2.05	2.55	2.55	5.36	2.76
MT_ND_4km_rev	2.72	2.19	3.01	2.37	2.40	2.51	2.22	2.73	2.59	2.53	1.33	3.46	2.51
NM_SE_4km	1.66	1.86	2.20	2.33	1.97	2.22	2.67	2.88	1.51	2.05	2.60	2.08	2.17
PowderRiver_4km	2.72	3.10	2.26	2.38	1.71	2.24	2.12	2.66	2.24	2.67	1.90	3.93	2.49
Uinta_Piceance_4km	3.76	2.99	1.92	3.83	2.60	3.35	3.05	3.17	2.75	2.23	3.00	3.81	3.04
Westjump IAD Domains													
CO_UT	2.97	2.78	2.73	3.19	2.22	2.61	2.67	2.81	2.50	2.52	2.30	4.17	2.79
MT_ND_rev	3.03	2.26	2.55	2.45	2.12	2.62	2.36	2.85	2.36	2.57	2.03	3.85	2.59
SanJuan_NM	2.89	3.30	2.68	3.12	2.47	2.82	2.51	2.63	2.33	2.33	2.44	3.98	2.79
WY_rev	2.68	2.49	2.31	2.78	1.86	2.26	2.21	2.78	2.40	2.57	1.80	4.38	2.54
Mid-Atlantic/Northeast Visibility Union (MANE-VU)													
MANE_VU	1.44	1.19	1.82	1.47	1.93	1.54	2.01	1.66	1.95	2.29	2.26	1.80	1.78
CT	1.82	0.99	1.10	1.12	1.13	1.40	2.00	1.39	1.36	2.23	2.76	1.52	1.57
DE	1.27	0.76	1.04	1.44	2.33	1.61	2.12	1.21	1.27	1.51	1.52	1.04	1.43
MA	1.31	0.87	2.43	1.42	1.54	1.75	2.49	1.34	1.66	2.92	3.34	1.74	1.90
MD	1.66	1.09	1.33	1.77	2.72	1.87	2.39	1.67	2.60	2.93	2.06	1.63	1.98
ME	1.29	1.40	2.78	2.11	1.83	1.29	2.35	1.45	1.06	1.89	2.61	2.20	1.86
NH	2.32	2.09	2.95	1.95	1.96	1.93	2.97	2.07	2.37	2.29	3.01	2.07	2.33

Table 3-4. Temperature Error (K) for 2008 WRF by Month and by State in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NJ	1.48	0.90	1.31	1.79	1.77	1.51	1.49	1.55	1.94	2.78	2.39	1.97	1.74
NY	1.32	1.16	1.62	0.98	1.70	1.46	1.68	1.59	2.06	2.22	2.01	2.11	1.66
PA	1.18	1.17	1.47	1.45	2.53	1.41	1.53	1.92	2.40	1.83	1.42	1.40	1.64
RI	1.45	1.15	1.42	1.00	0.87	1.10	2.07	0.90	1.37	1.83	2.59	1.46	1.43
VT	1.33	1.80	2.21	0.89	1.53	1.44	1.88	2.39	1.37	1.97	1.68	2.05	1.71
Visibility Improvement State and Tribal Association of the Southeast (VISTAS)													
VISTAS	1.82	1.54	1.53	1.48	1.39	2.00	1.89	1.45	1.81	1.88	1.80	1.69	1.69
AL	1.54	1.45	1.80	1.31	1.43	1.66	1.26	1.30	1.29	1.63	1.57	1.45	1.47
GA	2.08	1.71	1.44	1.36	1.14	2.82	1.80	1.27	1.35	1.86	1.90	1.56	1.69
FL	1.67	2.25	1.49	1.77	1.20	2.41	2.11	1.08	1.61	2.09	2.27	2.17	1.84
KY	1.18	1.02	1.47	1.53	1.31	1.52	1.17	1.89	2.56	1.53	1.61	1.08	1.49
MS	1.79	1.36	1.65	1.19	1.35	1.35	2.00	1.26	1.21	1.24	1.55	1.25	1.43
NC	2.09	1.29	1.59	1.26	1.30	1.63	2.19	1.35	1.81	1.87	1.83	1.75	1.66
SC	2.06	1.70	1.05	1.72	1.59	1.74	1.72	1.14	1.72	2.18	1.53	1.71	1.66
TN	1.98	1.46	1.50	1.38	1.45	1.60	1.79	1.56	1.96	1.57	1.56	1.08	1.57
VA	1.59	1.19	1.52	1.61	1.79	2.14	2.00	2.00	2.54	2.22	1.53	1.74	1.82
WV	1.95	1.10	1.73	1.68	1.72	1.79	1.67	2.44	2.61	1.80	1.72	1.72	1.83
Midwest Regional Planning Organization (MRPO)													
MW	1.52	2.33	1.34	1.33	1.59	1.22	1.81	2.06	1.31	1.73	1.32	1.23	1.57
IL	1.00	1.81	1.45	1.33	1.52	0.92	1.59	2.14	1.28	1.71	0.98	0.96	1.39
IN	1.17	1.69	1.12	1.08	1.79	0.87	1.38	2.08	1.09	1.64	1.24	1.18	1.36
MI	1.51	2.03	1.26	1.40	1.67	1.45	1.84	1.85	1.15	1.82	1.88	1.31	1.60
OH	1.52	1.68	1.53	1.23	1.92	1.29	1.44	2.21	1.60	1.76	1.09	1.13	1.53
WI	2.22	3.92	1.27	1.38	1.29	1.31	2.43	2.17	1.46	1.65	1.13	1.48	1.81
Central States Regional Air Partnership (CENRAP)													
CENRAP	1.81	2.02	1.70	1.81	1.74	1.65	1.98	2.18	1.52	2.05	1.92	2.01	1.87
AR	1.25	1.62	2.39	1.29	1.48	1.24	1.49	1.46	1.24	1.81	1.36	1.16	1.48
IA	1.16	1.88	1.62	1.34	1.59	1.14	1.70	1.76	1.51	1.81	0.72	1.94	1.51
KS	2.31	1.83	2.21	2.85	2.04	1.22	2.00	2.41	1.33	2.03	2.00	2.57	2.07
LA	1.71	1.56	1.52	1.60	1.30	1.95	1.39	1.40	1.41	1.87	1.57	1.31	1.55
MN	1.84	2.53	1.17	1.76	1.42	1.61	2.58	3.00	1.82	1.65	1.74	2.76	1.99
MO	1.31	1.54	2.47	1.37	2.24	1.22	1.73	2.10	1.26	1.78	1.19	1.57	1.65
NE	2.16	1.66	2.44	1.82	1.62	1.45	2.29	1.86	1.73	2.39	1.48	2.89	1.98
OK	2.17	1.44	1.85	2.02	2.50	1.31	1.63	2.49	1.53	2.83	2.26	1.97	2.00
TX	1.95	2.28	1.51	1.97	1.78	2.21	1.99	2.06	1.44	2.19	2.76	1.59	1.98

(a) ALL in this case refers to those states within the area covered by the 36 km modeling domain.

Table 3-5. Temperature Error (K) for 2008 WRF by Month and by State in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	2.00	2.14	1.84	1.90	1.76	1.91	2.07	2.19	1.84	2.15	1.94	2.37	2.01
Western Regional Air Partnership (WRAP)													
WRAP	1.93	2.17	1.82	1.86	1.78	2.13	2.04	2.16	2.22	2.15	1.90	2.78	2.08
AZ	1.79	2.09	1.49	1.86	1.36	1.81	1.28	2.54	1.63	1.41	1.46	2.20	1.74
CA	1.69	2.28	1.46	1.47	1.53	2.13	1.99	1.89	2.38	1.78	2.25	2.16	1.92
CO	2.53	2.82	2.62	2.62	2.10	2.20	2.21	2.50	2.12	2.37	1.97	4.01	2.51
ID	1.91	2.51	2.38	1.95	1.81	2.55	2.37	2.32	2.65	3.52	1.84	2.71	2.38
MT	2.55	1.66	2.19	2.09	1.76	2.49	2.22	2.43	2.56	3.37	1.91	3.40	2.39
NM	1.72	2.35	1.77	2.32	1.74	2.20	2.32	2.33	1.62	2.08	2.14	2.70	2.11
ND	2.02	2.52	1.85	2.07	2.21	1.75	2.46	3.71	2.64	3.12	1.45	3.41	2.43
NV	2.02	2.17	1.66	1.82	1.87	2.33	2.06	2.28	1.86	2.23	2.17	3.25	2.14
OR	1.53	2.12	1.96	1.58	1.76	2.00	2.20	1.75	2.49	2.04	2.50	1.76	1.97
SD	2.06	2.44	2.01	2.60	2.58	1.81	2.53	2.46	1.78	1.87	1.41	4.11	2.31
UT	3.05	1.97	1.79	2.01	1.82	2.16	2.19	2.51	2.22	2.35	2.25	4.27	2.38
WA	1.69	1.37	1.43	1.37	1.85	2.29	1.64	1.47	2.05	1.56	1.27	1.23	1.60
WY	2.01	1.81	1.87	1.87	1.61	1.96	1.78	2.08	2.31	3.13	1.37	3.76	2.13
Westjump DSAD Domains													
DJ_4km_rev	2.56	1.66	3.04	2.43	1.58	2.01	2.27	2.75	2.05	2.49	1.53	3.66	2.34
FourCorners_4km	2.34	3.48	1.73	2.49	2.27	2.61	2.04	1.97	1.80	2.33	2.19	3.67	2.41
MT_ND_4km_rev	2.64	2.39	2.81	2.22	2.56	2.40	2.50	2.80	2.73	2.66	1.45	3.63	2.57
NM_SE_4km	1.60	1.95	1.94	2.25	1.82	2.00	2.82	2.89	1.55	1.97	2.48	2.16	2.12
PowderRiver_4km	2.16	2.06	1.81	2.06	1.61	2.31	1.81	2.18	2.62	3.47	1.50	3.92	2.29
Uinta_Piceance_4km	2.83	2.20	1.83	2.42	2.02	2.23	2.28	2.47	2.19	2.38	2.06	4.20	2.43
Westjump IAD Domains													
CO_UT	2.56	2.31	2.36	2.43	1.92	2.16	2.25	2.50	2.22	2.51	1.85	3.96	2.42
MT_ND_rev	2.67	1.86	2.22	2.26	2.04	2.46	2.24	2.78	2.61	3.14	1.86	3.91	2.50
SanJuan_NM	2.45	2.71	2.15	2.27	2.07	2.39	1.99	2.48	1.89	2.10	2.01	3.45	2.33
WY_rev	2.30	1.85	2.08	2.43	1.84	2.17	2.05	2.53	2.44	2.96	1.55	4.22	2.37
Central States Regional Air Partnership (CENRAP)													
CENRAP	1.75	2.03	1.61	1.81	1.70	1.61	1.96	2.10	1.50	2.10	1.96	1.99	1.84
AR	1.17	1.60	2.41	1.49	1.35	1.13	1.38	1.39	1.10	1.94	1.48	1.09	1.46
IA	1.21	2.19	1.33	1.37	1.62	1.14	1.66	1.65	1.47	1.95	0.75	1.87	1.52
KS	2.21	1.79	2.14	2.78	1.93	1.20	2.04	2.10	1.47	2.21	2.01	2.58	2.04
LA	1.49	1.26	1.37	1.51	1.26	1.89	1.46	1.35	1.34	1.33	1.65	1.33	1.44
MN	1.82	2.62	1.11	1.77	1.50	1.66	2.52	2.88	1.74	1.74	1.91	2.66	1.99

Table 3-5. Temperature Error (K) for 2008 WRF by Month and by State in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
MO	1.38	1.41	2.52	1.39	2.03	0.96	1.88	1.78	1.18	1.87	1.11	1.52	1.59
NE	2.22	1.64	2.21	1.76	1.58	1.40	2.20	1.82	1.75	2.59	1.51	2.86	1.96
OK	1.93	1.43	1.82	2.03	2.37	1.22	1.53	2.39	1.51	2.90	2.32	2.06	1.96
TX	1.85	2.21	1.46	1.94	1.70	2.21	1.98	2.04	1.44	2.17	2.72	1.55	1.94

Table 3-6. Temperature Error (K) for 2008 WRF by Month and by State in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	2.09	2.06	2.02	1.97	1.74	1.92	2.05	2.07	2.07	2.35	1.81	3.08	2.10
Western Regional Air Partnership (WRAP)													
WRAP	1.95	2.16	1.79	1.86	1.59	1.81	1.86	1.89	2.06	2.35	1.68	3.19	2.02
AZ	2.08	2.74	1.52	1.80	1.58	1.56	1.42	2.36	1.74	1.59	1.76	2.80	1.91
CO	2.22	2.61	2.34	2.26	1.61	1.74	1.87	1.84	1.95	2.27	1.57	3.55	2.15
ID	1.58	1.98	1.98	1.50	1.51	2.58	1.92	1.83	2.79	3.21	1.49	2.57	2.08
MT	2.37	1.55	1.44	1.68	1.34	1.65	1.62	1.93	2.10	2.97	1.62	2.82	1.92
NM	1.57	2.73	2.06	2.35	2.10	1.66	2.78	1.56	1.92	2.37	2.72	2.87	2.22
UT	2.80	2.12	1.36	1.43	1.67	2.14	2.03	1.89	2.14	2.47	1.98	4.90	2.24
WY	1.78	1.51	1.75	1.74	1.24	1.64	1.40	1.89	2.03	2.73	1.27	3.55	1.88
Westjump DSAD Domains													
DJ_4km_rev	1.76	1.62	2.36	2.18	1.18	1.51	1.81	2.08	1.73	2.26	1.31	3.14	1.91
FourCorners_4km	2.07	3.38	1.78	2.67	2.26	1.96	2.17	1.45	1.93	2.40	2.09	3.43	2.30
MT_ND_4km_rev	2.31	1.67	1.81	1.95	1.79	1.44	1.72	2.18	2.23	2.08	1.33	2.86	1.95
NM_SE_4km	1.37	2.26	2.12	2.29	2.02	1.54	3.49	2.02	1.94	2.28	3.06	2.50	2.24
PowderRiver_4km	1.83	1.70	1.71	1.62	1.30	1.80	1.58	1.84	2.22	3.01	1.41	3.76	1.98
Uinta_Piceance_4km	2.62	2.21	1.45	1.87	1.66	1.96	1.87	1.83	2.06	2.53	1.63	4.26	2.16
Westjump IAD Domains													
CO_UT	2.12	2.16	2.05	2.06	1.52	1.76	1.89	1.84	1.98	2.30	1.49	3.67	2.07
MT_ND_rev	2.33	1.45	1.42	1.78	1.50	1.79	1.65	2.16	2.16	2.49	1.58	3.11	1.95
SanJuan_NM	2.28	2.78	1.95	2.07	1.83	1.86	1.97	1.71	1.85	2.13	2.00	3.22	2.14
WY_rev	1.79	1.61	1.66	1.94	1.31	1.69	1.69	2.00	2.08	2.56	1.31	3.81	1.95

Table 3-7. Mixing Ratio Bias (g/kg) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.34	0.27	0.34	0.37	0.26	-0.12	-0.38	-0.49	-0.44	-0.10	0.16	0.25	0.04
Western Regional Air Partnership (WRAP)													
WRAP	0.17	0.04	0.06	0.17	-0.03	-0.32	-0.57	-0.64	-0.67	-0.26	-0.11	0.00	-0.18
AZ	0.04	-0.22	-0.01	0.26	0.10	-0.40	-1.26	-0.61	-0.11	0.35	0.11	-0.15	-0.16
CA	-0.09	-0.57	-0.33	-0.17	-0.62	-1.16	-1.32	-1.12	-1.41	-0.70	-0.59	-0.43	-0.71
CO	0.38	0.44	0.33	0.35	0.14	-0.13	-0.26	-0.82	-0.67	-0.23	0.11	0.27	-0.01
ID	0.15	0.20	0.04	0.30	0.22	-0.14	-0.37	-0.56	-0.65	-0.29	-0.17	0.00	-0.11
MT	0.42	0.55	0.44	0.52	0.26	0.13	0.11	-0.11	-0.45	0.05	0.17	0.31	0.20
NM	0.37	0.33	0.23	0.07	-0.32	-0.61	-1.47	-1.43	-0.77	-0.13	0.19	0.26	-0.27
ND	0.23	0.19	0.26	0.14	0.11	-0.14	-0.81	-1.17	-0.61	-0.24	0.18	0.23	-0.14
NV	0.35	0.34	0.35	0.32	-0.12	0.06	-0.55	-0.23	-0.18	0.18	-0.01	0.15	0.06
OR	0.22	0.38	0.06	0.30	0.32	0.55	0.76	0.26	-0.05	-0.14	-0.08	0.12	0.23
SD	0.44	0.37	0.41	0.36	0.28	-0.13	-0.79	-0.87	-0.72	-0.09	0.30	0.36	-0.01
UT	0.52	0.54	0.42	0.42	0.13	-0.02	-0.56	-0.13	-0.08	0.05	0.23	0.39	0.16
WA	0.12	0.14	0.02	0.18	0.35	0.43	0.68	0.19	-0.05	-0.24	-0.10	0.01	0.14
WY	0.31	0.07	0.32	0.43	0.24	-0.07	-0.18	-0.31	-0.40	0.03	0.23	0.31	0.08
Westjump DSAD Domains													
DJ_4km_rev	0.47	0.14	0.36	0.20	0.13	-0.13	-0.60	-1.15	-0.85	-0.32	0.08	0.36	-0.11
FourCorners_4km	0.51	0.28	0.37	0.38	0.10	-0.12	-0.97	-0.88	-0.22	0.05	0.20	0.23	-0.01
MT_ND_4km_rev	0.41	0.36	0.41	0.25	0.09	-0.19	-0.65	-0.80	-0.64	-0.13	0.21	0.31	-0.03
NM_SE_4km	0.31	0.37	0.13	-0.02	-0.40	-0.90	-1.80	-1.94	-1.33	-0.23	0.28	0.37	-0.43
PowderRiver_4km	0.34	0.11	0.30	0.48	0.30	0.05	-0.19	-0.28	-0.40	0.02	0.20	0.30	0.10
Uinta_Piceance_4km	0.31	0.57	0.34	0.46	0.22	0.13	-0.02	-0.01	-0.21	0.09	0.19	0.22	0.19
Westjump IAD Domains													
CO_UT	0.41	0.36	0.35	0.34	0.16	-0.09	-0.37	-0.62	-0.52	-0.12	0.15	0.31	0.03
MT_ND_rev	0.38	0.39	0.38	0.41	0.19	-0.01	-0.29	-0.44	-0.54	-0.05	0.17	0.29	0.07
SanJuan_NM	0.42	0.43	0.33	0.36	0.09	-0.09	-0.51	-0.76	-0.34	0.01	0.20	0.23	0.03
WY_rev	0.36	0.12	0.30	0.30	0.14	-0.17	-0.55	-0.64	-0.59	-0.10	0.12	0.29	-0.04
Mid-Atlantic/Northeast Visibility Union (MANE-VU)													
MANE_VU	0.45	0.34	0.42	0.59	0.47	0.18	-0.17	0.09	0.12	0.24	0.35	0.39	0.29
CT	0.69	0.35	0.54	0.65	0.55	0.37	-0.03	0.09	0.25	0.29	0.48	0.51	0.40
DE	0.31	0.28	0.29	0.21	0.02	-0.45	-0.72	-0.12	-0.05	0.02	0.21	0.28	0.02
MA	0.60	0.44	0.46	0.54	0.67	0.31	0.21	0.62	0.41	0.53	0.44	0.44	0.47
MD	0.28	0.17	0.27	0.21	0.09	-0.55	-0.72	-0.26	-0.12	-0.04	0.28	0.33	-0.01
ME	0.38	0.32	0.41	0.73	0.60	0.39	0.10	0.18	0.27	0.42	0.33	0.41	0.38

Table 3-7. Mixing Ratio Bias (g/kg) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NH	0.46	0.38	0.46	0.64	0.55	0.57	0.03	0.13	0.19	0.24	0.30	0.38	0.36
NJ	0.43	0.29	0.40	0.48	0.28	-0.03	-0.49	-0.06	0.23	0.33	0.40	0.47	0.23
NY	0.49	0.33	0.43	0.61	0.50	0.27	0.08	0.14	0.26	0.35	0.50	0.47	0.37
PA	0.36	0.37	0.43	0.77	0.49	0.20	-0.48	-0.09	-0.26	-0.03	0.16	0.23	0.18
RI	0.67	0.45	0.48	0.51	0.58	0.38	0.38	0.67	0.61	0.61	0.62	0.64	0.55
VT	0.37	0.32	0.47	0.73	0.47	0.43	-0.12	-0.14	-0.01	0.19	0.33	0.26	0.28
Visibility Improvement State and Tribal Association of the Southeast (VISTAS)													
VISTAS	0.57	0.31	0.68	0.48	0.48	0.06	-0.26	-0.38	-0.42	-0.04	0.37	0.49	0.20
AL	0.46	0.36	0.76	0.58	0.54	0.32	0.08	-0.45	-0.58	0.00	0.37	0.57	0.25
GA	0.36	0.04	0.53	0.26	0.28	0.17	-0.37	-0.41	-0.44	-0.15	0.22	0.34	0.07
FL	1.21	0.95	1.15	0.89	0.91	0.55	0.74	0.40	0.19	0.67	1.02	0.98	0.81
KY	0.32	0.19	0.84	0.76	0.82	0.11	-0.24	-0.44	-0.66	-0.32	-0.03	0.26	0.13
MS	0.52	0.65	0.68	0.54	0.36	-0.19	-0.25	-0.62	-0.67	0.04	0.40	0.72	0.18
NC	0.53	0.07	0.59	0.37	0.43	0.11	-0.48	-0.54	-0.32	-0.13	0.31	0.48	0.12
SC	0.65	0.24	0.73	0.55	0.64	0.30	-0.19	-0.26	-0.37	0.04	0.41	0.55	0.27
TN	0.34	0.11	0.71	0.51	0.25	-0.59	-0.92	-0.94	-0.81	-0.54	-0.11	0.38	-0.13
VA	0.21	-0.02	0.22	-0.06	-0.05	-0.89	-1.19	-0.91	-0.91	-0.55	0.01	0.05	-0.34
WV	0.34	0.21	0.59	0.79	0.73	0.21	-0.44	-0.39	-0.61	-0.24	0.15	0.11	0.12
Midwest Regional Planning Organization (MRPO)													
MW	0.29	0.37	0.41	0.50	0.58	0.20	0.22	-0.09	-0.20	-0.05	0.14	0.24	0.22
IL	0.30	0.39	0.39	0.50	0.74	0.17	0.02	-0.56	-0.50	-0.23	0.00	0.18	0.12
IN	0.37	0.68	0.47	0.69	0.57	0.15	0.32	-0.10	-0.16	-0.16	0.06	0.26	0.26
MI	0.32	0.34	0.42	0.44	0.43	-0.09	0.26	0.47	0.43	0.35	0.38	0.38	0.34
OH	0.37	0.53	0.42	0.67	0.55	0.28	0.31	0.23	-0.28	0.04	0.15	0.19	0.29
WI	0.19	0.17	0.41	0.40	0.62	0.56	0.29	-0.53	-0.65	-0.40	-0.01	0.13	0.10
Central States Regional Air Partnership (CENRAP)													
CENRAP	0.31	0.37	0.31	0.34	0.20	-0.36	-0.77	-1.00	-0.74	-0.25	0.15	0.21	-0.10
AR	0.28	0.85	0.73	0.75	0.61	-0.29	-0.81	-1.04	-0.67	-0.27	0.18	0.51	0.07
IA	0.35	0.20	0.14	0.24	0.65	0.31	0.14	-0.59	-0.49	-0.19	0.06	0.18	0.08
KS	0.50	0.65	0.49	0.46	0.32	-0.73	-1.55	-1.36	-0.42	-0.13	0.22	0.26	-0.11
LA	0.66	0.72	0.51	0.59	0.42	0.17	0.05	0.15	-0.26	0.15	0.60	0.60	0.36
MN	0.15	0.10	0.30	0.40	0.47	0.36	0.06	-0.86	-0.71	-0.38	0.15	0.14	0.02
MO	0.43	0.56	0.65	0.75	1.04	0.00	-0.44	-0.78	-0.34	-0.10	0.23	0.31	0.19
NE	0.55	0.40	0.27	0.28	0.37	-0.01	-0.81	-0.64	-0.50	-0.10	0.16	0.32	0.02
OK	0.07	0.29	0.23	0.19	-0.38	-1.74	-2.53	-2.15	-1.38	-0.74	-0.02	-0.04	-0.68
TX	0.29	0.39	0.21	0.16	-0.32	-0.81	-1.13	-1.17	-0.97	-0.22	0.13	0.14	-0.28

Table 3-8. Mixing Ratio Bias (g/kg) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.20	0.20	0.17	0.24	0.07	-0.33	-0.69	-0.86	-0.72	-0.30	0.00	0.09	-0.16
Western Regional Air Partnership (WRAP)													
WRAP	0.14	-0.04	0.01	0.09	-0.13	-0.48	-0.84	-0.87	-0.82	-0.32	-0.13	-0.03	-0.29
AZ	-0.13	-0.44	-0.12	0.15	0.01	-0.45	-1.25	-0.71	-0.33	0.17	-0.05	-0.38	-0.29
CA	-0.24	-0.58	-0.40	-0.15	-0.56	-1.02	-1.20	-1.01	-1.35	-0.84	-0.68	-0.50	-0.71
CO	0.37	0.33	0.30	0.25	0.07	-0.20	-0.35	-0.83	-0.70	-0.31	-0.01	0.21	-0.07
ID	0.22	0.20	0.04	0.28	0.20	-0.16	-0.43	-0.63	-0.67	-0.34	-0.25	0.01	-0.13
MT	0.40	0.47	0.37	0.45	0.18	0.01	-0.01	-0.28	-0.58	-0.03	0.04	0.30	0.11
NM	0.26	0.16	0.16	0.02	-0.32	-0.57	-1.44	-1.38	-0.76	-0.18	0.10	0.12	-0.32
ND	0.25	0.18	0.25	0.17	0.13	-0.19	-0.76	-1.14	-0.55	-0.21	0.21	0.23	-0.12
NV	0.17	-0.02	0.19	0.22	-0.17	0.01	-0.67	-0.36	-0.25	0.04	-0.21	-0.01	-0.09
OR	0.17	0.18	-0.01	0.21	0.21	0.39	0.47	0.06	-0.29	-0.31	-0.26	0.02	0.07
SD	0.41	0.32	0.40	0.37	0.23	-0.14	-0.78	-0.88	-0.64	-0.08	0.29	0.36	-0.01
UT	0.38	0.24	0.26	0.23	-0.08	-0.40	-1.04	-0.57	-0.45	-0.27	-0.05	0.22	-0.13
WA	0.14	0.00	-0.03	0.11	0.16	0.23	0.39	-0.01	-0.30	-0.38	-0.18	0.01	0.01
WY	0.30	0.04	0.24	0.34	0.17	-0.12	-0.22	-0.35	-0.42	-0.03	0.13	0.26	0.03
Westjump DSAD Domains													
DJ_4km_rev	0.43	0.04	0.27	0.12	0.05	-0.17	-0.63	-1.08	-0.84	-0.38	-0.03	0.29	-0.16
FourCorners_4km	0.40	-0.07	0.23	0.24	0.00	-0.18	-0.95	-0.84	-0.25	-0.08	0.04	0.10	-0.11
MT_ND_4km_rev	0.42	0.34	0.40	0.27	0.08	-0.21	-0.59	-0.79	-0.61	-0.09	0.22	0.31	-0.02
NM_SE_4km	0.19	0.25	0.10	-0.04	-0.40	-0.83	-1.77	-1.90	-1.30	-0.28	0.21	0.21	-0.46
PowderRiver_4km	0.33	0.12	0.24	0.41	0.22	0.03	-0.23	-0.33	-0.42	-0.01	0.13	0.28	0.06
Uinta_Piceance_4km	0.27	0.43	0.29	0.33	0.06	-0.19	-0.49	-0.47	-0.55	-0.18	-0.05	0.12	-0.04
Westjump IAD Domains													
CO_UT	0.37	0.24	0.29	0.24	0.07	-0.18	-0.48	-0.70	-0.60	-0.23	0.00	0.22	-0.06
MT_ND_rev	0.38	0.34	0.34	0.38	0.14	-0.10	-0.33	-0.50	-0.57	-0.06	0.12	0.30	0.04
SanJuan_NM	0.34	0.21	0.25	0.24	-0.01	-0.19	-0.60	-0.80	-0.42	-0.12	0.04	0.12	-0.08
WY_rev	0.34	0.10	0.26	0.25	0.09	-0.17	-0.56	-0.65	-0.61	-0.15	0.02	0.24	-0.07
Central States Regional Air Partnership (CENRAP)													
CENRAP	0.28	0.40	0.29	0.29	0.14	-0.41	-0.85	-1.06	-0.75	-0.27	0.17	0.20	-0.13
AR	0.30	0.99	0.72	0.73	0.53	-0.36	-0.92	-1.13	-0.61	-0.23	0.22	0.54	0.07
IA	0.33	0.19	0.12	0.19	0.58	0.18	-0.05	-0.64	-0.51	-0.20	0.07	0.19	0.04
KS	0.47	0.67	0.43	0.40	0.24	-0.75	-1.60	-1.41	-0.48	-0.15	0.27	0.28	-0.14
LA	0.50	0.69	0.44	0.50	0.16	-0.25	-0.45	-0.46	-0.65	-0.29	0.30	0.47	0.08
MN	0.14	0.06	0.27	0.36	0.41	0.17	-0.11	-0.88	-0.69	-0.37	0.17	0.15	-0.03

Table 3-8. Mixing Ratio Bias (g/kg) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
MO	0.43	0.54	0.60	0.70	0.94	-0.13	-0.63	-0.91	-0.37	-0.12	0.24	0.32	0.13
NE	0.53	0.42	0.24	0.24	0.28	-0.03	-0.82	-0.68	-0.51	-0.13	0.15	0.32	0.00
OK	0.06	0.33	0.21	0.14	-0.43	-1.70	-2.47	-2.12	-1.36	-0.69	0.06	0.02	-0.66
TX	0.25	0.52	0.22	0.14	-0.29	-0.70	-1.05	-1.14	-0.92	-0.19	0.18	0.13	-0.24

(a) ALL in this case refers to those states within the area covered by the 36 km modeling domain.

Table 3-9. Mixing Ratio Bias (g/kg) for 2008 WRF by Month in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.24	0.14	0.18	0.14	0.04	-0.19	-0.30	-0.48	-0.38	-0.13	0.05	0.11	-0.05
Western Regional Air Partnership (WRAP)													
WRAP	0.23	0.11	0.19	0.23	0.17	-0.09	-0.17	-0.33	-0.32	-0.11	0.02	0.09	0.00
AZ	-0.22	-0.62	-0.18	0.08	0.11	-0.50	-0.70	-0.20	-0.15	0.24	-0.02	-0.43	-0.22
CO	0.34	0.32	0.32	0.24	0.10	0.08	0.65	-0.27	-0.15	-0.25	0.05	0.18	0.13
ID	0.28	0.24	0.11	0.31	0.42	-0.12	-0.40	-0.65	-0.67	-0.40	-0.26	0.05	-0.09
MT	0.34	0.39	0.38	0.50	0.40	0.15	0.29	-0.02	-0.40	-0.01	0.00	0.28	0.19
NM	0.19	0.04	0.13	-0.09	-0.30	-0.22	-0.64	-0.73	-0.34	-0.09	0.19	0.07	-0.15
UT	0.43	0.33	0.25	0.28	0.26	-0.13	-0.63	-0.54	-0.26	-0.29	-0.10	0.26	-0.01
WY	0.28	0.13	0.22	0.39	0.40	0.05	0.13	0.20	-0.23	0.03	0.15	0.31	0.17
Westjump DSAD Domains													
DJ_4km_rev	0.34	0.03	0.30	0.14	0.10	0.00	0.39	-0.36	-0.30	-0.25	0.04	0.25	0.06
FourCorners_4km	0.40	-0.05	0.32	0.21	0.09	0.04	0.15	-0.06	0.18	-0.05	0.16	0.10	0.12
MT_ND_4km_rev	0.31	0.30	0.39	0.36	0.32	0.11	0.01	-0.39	-0.30	-0.03	0.14	0.26	0.12
NM_SE_4km	0.09	0.17	0.02	-0.20	-0.48	-0.32	-1.25	-1.22	-0.87	-0.13	0.29	0.12	-0.32
PowderRiver_4km	0.31	0.17	0.25	0.42	0.44	0.12	0.07	0.11	-0.26	0.02	0.14	0.32	0.18
Uinta_Piceance_4km	0.34	0.48	0.34	0.38	0.30	0.09	0.12	-0.30	-0.30	-0.19	0.02	0.15	0.12
Westjump IAD Domains													
CO_UT	0.35	0.26	0.31	0.26	0.20	0.03	0.33	-0.22	-0.18	-0.17	0.06	0.22	0.12
MT_ND_rev	0.32	0.28	0.35	0.41	0.35	0.12	0.07	-0.20	-0.36	-0.03	0.09	0.28	0.14
SanJuan_NM	0.32	0.17	0.26	0.20	0.04	0.04	0.28	-0.23	0.01	-0.08	0.11	0.10	0.10
WY_rev	0.32	0.14	0.28	0.29	0.28	-0.04	-0.05	-0.20	-0.34	-0.08	0.08	0.28	0.08

Table 3-10. Mixing Ratio Error (g/kg) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.58	0.56	0.67	0.82	0.99	1.26	1.42	1.34	1.12	0.81	0.64	0.60	0.90
Western Regional Air Partnership (WRAP)													
WRAP	0.57	0.68	0.59	0.63	0.82	1.11	1.43	1.34	1.17	0.84	0.70	0.62	0.88
AZ	0.68	0.71	0.52	0.52	0.69	0.92	1.64	1.53	1.09	0.77	0.67	0.73	0.87
CA	0.77	0.98	0.86	0.85	1.08	1.61	1.78	1.62	1.78	1.30	1.20	0.98	1.23
CO	0.51	0.67	0.58	0.63	0.78	1.03	1.21	1.33	1.03	0.66	0.48	0.49	0.78
ID	0.43	0.62	0.46	0.57	0.77	0.90	1.22	1.18	0.96	0.69	0.53	0.41	0.73
MT	0.50	0.60	0.57	0.69	0.69	0.89	1.10	0.95	0.74	0.56	0.44	0.41	0.68
NM	0.53	0.47	0.51	0.50	0.86	1.13	1.76	1.72	1.20	0.78	0.47	0.52	0.87
ND	0.35	0.36	0.43	0.48	0.67	0.88	1.29	1.42	0.90	0.57	0.38	0.31	0.67
NV	0.48	0.59	0.54	0.49	0.62	0.50	1.12	0.97	0.67	0.55	0.57	0.51	0.63
OR	0.49	0.61	0.46	0.53	0.75	0.94	1.20	1.08	0.92	0.74	0.56	0.51	0.73
SD	0.48	0.49	0.49	0.56	0.71	1.01	1.57	1.31	0.99	0.53	0.46	0.39	0.75
UT	0.61	0.75	0.60	0.65	0.71	0.83	1.33	1.12	0.87	0.75	0.65	0.56	0.79
WA	0.42	0.47	0.38	0.46	0.69	0.76	1.03	0.96	0.80	0.68	0.51	0.45	0.63
WY	0.41	0.42	0.47	0.60	0.70	0.88	1.13	1.03	0.78	0.51	0.47	0.42	0.65
Westjump DSAD Domains													
DJ_4km_rev	0.53	0.46	0.57	0.60	0.79	1.14	1.46	1.63	1.15	0.64	0.42	0.48	0.82
FourCorners_4km	0.63	0.43	0.55	0.54	0.71	0.74	1.36	1.18	0.84	0.72	0.49	0.51	0.73
MT_ND_4km_rev	0.47	0.46	0.54	0.46	0.62	0.77	1.09	1.10	0.88	0.59	0.39	0.36	0.64
NM_SE_4km	0.55	0.49	0.52	0.54	0.96	1.28	1.97	2.11	1.54	0.88	0.59	0.62	1.00
PowderRiver_4km	0.45	0.48	0.48	0.65	0.70	0.91	1.15	0.96	0.76	0.52	0.48	0.42	0.66
Uinta_Piceance_4km	0.50	0.76	0.55	0.65	0.74	0.83	1.07	1.01	0.88	0.65	0.56	0.48	0.72
Westjump IAD Domains													
CO_UT	0.52	0.61	0.56	0.62	0.75	0.98	1.26	1.27	0.96	0.63	0.49	0.49	0.76
MT_ND_rev	0.46	0.52	0.53	0.61	0.68	0.89	1.19	1.06	0.82	0.55	0.43	0.39	0.68
SanJuan_NM	0.55	0.60	0.56	0.58	0.74	0.89	1.30	1.30	0.93	0.69	0.50	0.50	0.76
WY_rev	0.46	0.48	0.49	0.59	0.70	0.95	1.34	1.20	0.91	0.54	0.46	0.42	0.71
Mid-Atlantic/Northeast Visibility Union (MANE-VU)													
MANE_VU	0.54	0.36	0.55	0.79	0.78	1.11	1.16	0.99	0.92	0.69	0.53	0.53	0.75
CT	0.70	0.35	0.60	0.77	0.72	1.05	1.01	0.85	0.84	0.66	0.58	0.56	0.72
DE	0.49	0.31	0.53	0.66	0.70	1.13	1.25	1.02	0.91	0.64	0.44	0.54	0.72
MA	0.68	0.44	0.60	0.79	0.85	1.21	1.12	1.04	0.94	0.76	0.68	0.62	0.81
MD	0.50	0.30	0.58	0.71	0.84	1.35	1.55	1.25	1.17	0.86	0.57	0.59	0.86
ME	0.49	0.35	0.48	0.81	0.76	0.92	1.00	0.80	0.73	0.59	0.45	0.50	0.66
NH	0.52	0.38	0.52	0.76	0.78	1.12	1.03	0.88	0.81	0.56	0.45	0.50	0.69

Table 3-10. Mixing Ratio Error (g/kg) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NJ	0.53	0.32	0.54	0.72	0.71	1.08	1.25	1.01	0.95	0.79	0.52	0.59	0.75
NY	0.55	0.34	0.54	0.79	0.74	1.04	1.06	0.97	0.94	0.70	0.58	0.55	0.73
PA	0.47	0.38	0.56	0.89	0.82	1.11	1.22	1.00	0.94	0.63	0.43	0.44	0.74
RI	0.71	0.45	0.60	0.72	0.77	1.12	1.05	0.96	0.87	0.76	0.73	0.68	0.79
VT	0.45	0.32	0.54	0.81	0.71	1.10	1.01	0.89	0.83	0.48	0.42	0.37	0.66
Visibility Improvement State and Tribal Association of the Southeast (VISTAS)													
VISTAS	0.78	0.57	0.90	0.96	1.11	1.42	1.47	1.40	1.22	0.94	0.75	0.82	1.03
AL	0.62	0.54	0.89	0.95	1.09	1.30	1.33	1.38	1.10	0.85	0.74	0.85	0.97
GA	0.67	0.52	0.84	0.96	1.10	1.48	1.47	1.31	1.17	0.88	0.68	0.74	0.99
FL	1.40	1.13	1.34	1.27	1.40	1.39	1.37	1.27	1.13	1.16	1.26	1.19	1.28
KY	0.44	0.39	0.89	0.92	1.18	1.26	1.29	1.14	1.12	0.74	0.44	0.47	0.86
MS	0.67	0.71	0.87	0.94	1.08	1.32	1.41	1.46	1.21	0.85	0.77	0.90	1.02
NC	0.71	0.35	0.79	0.84	0.98	1.35	1.41	1.50	1.20	0.87	0.63	0.79	0.95
SC	0.78	0.48	0.88	0.93	1.05	1.44	1.29	1.27	1.11	0.85	0.69	0.87	0.97
TN	0.48	0.44	0.83	0.83	1.04	1.39	1.48	1.40	1.15	0.84	0.47	0.66	0.92
VA	0.53	0.27	0.65	0.78	0.96	1.74	1.94	1.66	1.59	1.08	0.60	0.66	1.04
WV	0.52	0.34	0.75	0.98	1.05	1.24	1.41	1.28	1.23	0.69	0.50	0.49	0.87
Midwest Regional Planning Organization (MRPO)													
MW	0.40	0.44	0.52	0.72	0.87	1.16	1.19	1.16	0.99	0.64	0.43	0.37	0.74
IL	0.42	0.52	0.56	0.73	1.03	1.25	1.32	1.27	1.00	0.65	0.40	0.40	0.80
IN	0.44	0.71	0.57	0.84	0.91	1.02	1.10	1.07	0.89	0.60	0.41	0.38	0.75
MI	0.40	0.36	0.49	0.69	0.75	1.15	1.02	1.06	0.93	0.63	0.50	0.44	0.70
OH	0.45	0.56	0.55	0.86	0.86	1.03	1.19	1.11	1.02	0.62	0.43	0.35	0.75
WI	0.32	0.31	0.49	0.63	0.86	1.25	1.34	1.27	1.07	0.67	0.39	0.28	0.74
Central States Regional Air Partnership (CENRAP)													
CENRAP	0.53	0.56	0.67	0.89	1.17	1.43	1.65	1.59	1.20	0.83	0.60	0.54	0.97
AR	0.45	0.90	0.85	1.02	1.14	1.34	1.48	1.54	1.13	0.74	0.56	0.68	0.99
IA	0.41	0.33	0.46	0.64	0.98	1.26	1.35	1.29	1.03	0.65	0.44	0.34	0.77
KS	0.57	0.66	0.62	0.78	1.22	1.66	2.02	1.76	0.95	0.63	0.47	0.39	0.98
LA	0.92	0.98	0.99	1.23	1.37	1.47	1.46	1.35	1.26	1.08	1.07	1.01	1.18
MN	0.29	0.34	0.41	0.63	0.78	1.08	1.28	1.43	1.06	0.72	0.40	0.24	0.72
MO	0.49	0.59	0.73	0.88	1.29	1.31	1.41	1.39	1.00	0.63	0.43	0.44	0.88
NE	0.57	0.51	0.46	0.62	0.89	1.20	1.69	1.41	0.95	0.59	0.44	0.40	0.81
OK	0.48	0.50	0.73	0.92	1.41	2.25	2.65	2.32	1.61	1.05	0.59	0.51	1.25
TX	0.69	0.67	0.86	1.16	1.45	1.51	1.70	1.69	1.39	1.00	0.80	0.79	1.14

(a) ALL in this case refers to those states within the area covered by the 36 km modeling domain.

Table 3-11. Mixing Ratio Error (g/kg) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.52	0.61	0.60	0.74	0.98	1.26	1.52	1.46	1.15	0.81	0.64	0.54	0.90
Western Regional Air Partnership (WRAP)													
WRAP	0.56	0.68	0.57	0.60	0.80	1.07	1.40	1.32	1.16	0.85	0.71	0.62	0.86
AZ	0.69	0.78	0.51	0.47	0.68	0.94	1.66	1.66	1.12	0.72	0.64	0.78	0.89
CA	0.76	0.97	0.84	0.82	1.02	1.48	1.67	1.53	1.71	1.30	1.22	0.95	1.19
CO	0.50	0.70	0.56	0.59	0.78	1.04	1.23	1.33	1.04	0.68	0.49	0.48	0.79
ID	0.44	0.61	0.46	0.55	0.75	0.90	1.23	1.21	0.98	0.71	0.56	0.42	0.74
MT	0.48	0.55	0.54	0.64	0.67	0.86	1.08	0.92	0.80	0.57	0.43	0.41	0.66
NM	0.51	0.45	0.49	0.49	0.85	1.13	1.76	1.71	1.18	0.78	0.48	0.50	0.86
ND	0.37	0.37	0.44	0.49	0.69	0.92	1.32	1.42	0.89	0.59	0.41	0.31	0.69
NV	0.46	0.52	0.48	0.45	0.63	0.51	1.16	0.97	0.68	0.51	0.60	0.55	0.63
OR	0.47	0.63	0.45	0.50	0.75	0.88	1.08	1.04	0.96	0.78	0.61	0.54	0.72
SD	0.45	0.48	0.48	0.56	0.70	0.99	1.62	1.35	0.94	0.51	0.46	0.39	0.74
UT	0.51	0.59	0.51	0.53	0.66	0.80	1.37	1.02	0.81	0.67	0.56	0.51	0.71
WA	0.42	0.55	0.39	0.44	0.67	0.72	0.96	0.94	0.82	0.71	0.53	0.46	0.63
WY	0.40	0.46	0.45	0.58	0.70	0.94	1.18	1.06	0.81	0.55	0.46	0.40	0.67
Westjump DSAD Domains													
DJ_4km_rev	0.49	0.53	0.54	0.57	0.81	1.17	1.44	1.60	1.13	0.66	0.43	0.44	0.82
FourCorners_4km	0.58	0.58	0.50	0.49	0.69	0.77	1.42	1.24	0.89	0.72	0.50	0.50	0.74
MT_ND_4km_rev	0.48	0.45	0.56	0.48	0.65	0.83	1.14	1.12	0.87	0.60	0.42	0.36	0.66
NM_SE_4km	0.53	0.40	0.51	0.54	0.96	1.28	1.96	2.11	1.53	0.89	0.58	0.58	0.99
PowderRiver_4km	0.43	0.50	0.45	0.62	0.68	0.95	1.21	1.00	0.80	0.55	0.47	0.41	0.67
Uinta_Piceance_4km	0.44	0.65	0.50	0.58	0.71	0.81	1.13	1.00	0.88	0.62	0.49	0.46	0.69
Westjump IAD Domains													
CO_UT	0.49	0.60	0.53	0.57	0.75	0.99	1.28	1.25	0.95	0.63	0.48	0.46	0.75
MT_ND_rev	0.46	0.49	0.52	0.60	0.68	0.90	1.22	1.05	0.85	0.57	0.45	0.39	0.68
SanJuan_NM	0.50	0.60	0.51	0.53	0.73	0.88	1.31	1.32	0.95	0.69	0.48	0.49	0.75
WY_rev	0.44	0.50	0.47	0.57	0.71	1.00	1.39	1.23	0.93	0.57	0.46	0.40	0.72
Central States Regional Air Partnership (CENRAP)													
CENRAP	0.51	0.58	0.64	0.86	1.16	1.46	1.67	1.62	1.19	0.81	0.60	0.52	0.97
AR	0.46	1.03	0.85	1.01	1.14	1.41	1.55	1.60	1.07	0.71	0.60	0.68	1.01
IA	0.40	0.33	0.46	0.63	0.97	1.32	1.40	1.32	1.03	0.66	0.45	0.34	0.78
KS	0.56	0.68	0.59	0.73	1.21	1.68	2.04	1.81	0.94	0.62	0.52	0.41	0.98
LA	0.79	0.91	0.95	1.20	1.37	1.51	1.54	1.36	1.29	1.01	0.93	0.91	1.15
MN	0.29	0.34	0.40	0.62	0.76	1.07	1.30	1.44	1.06	0.71	0.42	0.26	0.72

Table 3-11. Mixing Ratio Error (g/kg) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
MO	0.49	0.57	0.69	0.84	1.22	1.36	1.47	1.44	0.94	0.61	0.44	0.43	0.88
NE	0.56	0.53	0.45	0.61	0.88	1.26	1.68	1.43	0.95	0.61	0.46	0.40	0.82
OK	0.50	0.54	0.72	0.89	1.40	2.22	2.60	2.28	1.59	1.00	0.61	0.51	1.24
TX	0.65	0.72	0.83	1.13	1.46	1.54	1.72	1.75	1.39	1.01	0.81	0.74	1.15

Table 3-12. Mixing Ratio Error (g/kg) for 2008 WRF by Month in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	0.50	0.55	0.55	0.61	0.87	1.05	1.36	1.26	1.00	0.70	0.56	0.51	0.79
Western Regional Air Partnership (WRAP)													
WRAP	0.49	0.59	0.52	0.55	0.75	0.92	1.29	1.16	0.97	0.68	0.54	0.51	0.75
AZ	0.75	0.90	0.57	0.50	0.69	1.05	1.51	1.58	1.25	0.80	0.76	0.85	0.93
CO	0.48	0.63	0.59	0.58	0.83	1.00	1.36	1.13	0.97	0.70	0.49	0.49	0.77
ID	0.43	0.63	0.47	0.56	0.74	0.87	1.18	1.15	0.93	0.69	0.55	0.44	0.72
MT	0.42	0.48	0.52	0.64	0.71	0.77	0.99	0.79	0.75	0.54	0.40	0.38	0.62
NM	0.52	0.42	0.53	0.52	0.86	1.07	1.59	1.41	1.17	0.87	0.55	0.51	0.84
UT	0.56	0.69	0.54	0.54	0.71	0.83	1.37	1.13	0.92	0.72	0.59	0.57	0.76
WY	0.37	0.44	0.44	0.59	0.72	0.81	1.00	0.86	0.74	0.53	0.46	0.41	0.61
Westjump DSAD Domains													
DJ_4km_rev	0.44	0.36	0.56	0.54	0.83	0.99	1.33	1.17	0.94	0.65	0.45	0.42	0.72
FourCorners_4km	0.62	0.60	0.56	0.50	0.72	0.77	1.27	1.21	0.97	0.80	0.55	0.54	0.76
MT_ND_4km_rev	0.36	0.41	0.51	0.53	0.71	0.75	1.01	0.94	0.73	0.54	0.38	0.29	0.60
NM_SE_4km	0.54	0.33	0.53	0.57	1.01	1.18	1.81	1.67	1.41	0.97	0.65	0.57	0.94
PowderRiver_4km	0.40	0.47	0.45	0.62	0.71	0.83	1.04	0.87	0.78	0.55	0.47	0.42	0.63
Uinta_Piceance_4km	0.48	0.79	0.55	0.61	0.76	0.84	1.22	1.04	0.93	0.63	0.49	0.52	0.74
Westjump IAD Domains													
CO_UT	0.47	0.57	0.55	0.57	0.79	0.92	1.27	1.09	0.90	0.64	0.49	0.48	0.73
MT_ND_rev	0.39	0.44	0.49	0.59	0.72	0.80	1.04	0.89	0.78	0.54	0.42	0.36	0.62
SanJuan_NM	0.51	0.57	0.54	0.51	0.75	0.90	1.33	1.17	0.98	0.74	0.52	0.50	0.75
WY_rev	0.41	0.47	0.48	0.57	0.72	0.86	1.16	1.00	0.85	0.57	0.46	0.41	0.66

Table 3-13. Wind Direction Bias (deg.) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	7.80	4.28	6.61	4.24	5.43	5.18	4.72	5.30	3.69	7.01	7.05	4.67	5.50
Western Regional Air Partnership (WRAP)													
WRAP	13.19	4.17	5.94	8.62	3.47	2.64	2.28	5.88	4.74	3.62	8.17	7.76	5.87
AZ	8.29	-4.82	4.39	10.02	-7.23	-1.48	6.82	12.84	5.89	-5.68	-1.51	-16.22	0.94
CA	13.79	3.78	5.15	9.19	1.41	-3.05	0.79	1.56	2.13	-1.99	5.26	0.45	3.21
CO	8.26	0.41	-4.28	15.76	0.29	1.20	-4.50	5.35	-0.92	-8.69	3.78	4.22	1.74
ID	17.70	0.01	0.38	10.07	16.21	15.11	8.36	5.88	20.43	24.76	17.39	27.78	13.67
MT	30.62	10.39	16.54	10.09	7.40	11.48	8.33	-0.15	2.00	17.39	12.82	17.02	11.99
NM	3.20	-6.22	6.65	15.55	7.28	3.64	-11.77	4.74	2.22	-1.69	7.44	2.55	2.80
ND	11.43	6.39	13.19	-2.94	5.65	2.64	2.06	8.90	3.50	12.14	4.14	12.07	6.60
NV	7.57	14.56	7.86	-0.97	0.27	6.00	5.94	10.93	7.05	6.41	12.97	21.28	8.32
OR	16.02	15.18	15.37	6.34	4.54	-1.25	5.82	4.71	12.05	7.70	28.48	13.67	10.72
SD	11.07	6.42	1.94	5.66	6.68	5.92	4.49	8.63	-2.25	5.93	2.72	13.08	5.86
UT	10.67	13.84	7.22	1.47	-0.24	8.17	9.63	23.51	-8.60	-1.70	15.82	2.91	6.89
WA	12.88	8.44	12.67	9.27	1.65	3.14	4.51	6.19	15.20	17.64	21.54	14.44	10.63
WY	17.67	3.40	0.64	-1.35	13.20	13.93	8.72	11.01	11.87	8.70	-2.40	12.41	8.15
Westjump DSAD Domains													
DJ_4km_rev	10.62	1.82	-6.73	18.40	-3.23	4.57	-0.52	8.85	4.13	-14.00	5.16	10.42	3.29
FourCorners_4km	1.38	-0.79	11.18	19.54	15.66	13.34	-4.04	11.30	6.56	14.33	1.21	2.09	7.65
MT_ND_4km_rev	25.69	5.16	12.91	3.58	6.47	7.15	3.03	3.18	1.04	20.69	2.45	21.03	9.37
NM_SE_4km	4.62	4.15	5.66	7.37	12.85	-0.86	-10.44	10.13	2.16	1.78	10.96	0.37	4.06
PowderRiver_4km	14.49	2.55	-0.29	-1.85	15.79	5.72	5.65	0.38	6.42	4.91	1.76	11.33	5.57
Uinta_Piceance_4km	14.87	8.65	2.44	6.50	-6.99	4.54	-1.09	10.64	-15.73	-2.62	11.24	-9.74	1.89
Westjump IAD Domains													
CO_UT	10.66	2.64	-0.34	9.30	0.22	7.51	-1.85	8.87	2.99	-3.98	5.59	5.26	3.91
MT_ND_rev	22.73	6.37	12.14	4.64	9.81	9.32	4.23	3.63	3.98	10.98	5.01	14.18	8.92
SanJuan_NM	6.81	-3.29	-0.88	18.59	2.95	5.08	-5.14	6.62	3.21	-4.10	2.92	4.71	3.12
WY_rev	18.00	6.27	2.82	5.27	5.65	11.19	4.82	7.49	7.65	2.36	5.68	9.47	7.22
Mid-Atlantic/Northeast Visibility Union (MANE-VU)													
MANE_VU	6.31	1.97	9.79	4.35	5.67	5.18	3.74	5.81	-0.51	13.82	16.92	2.30	6.28
CT	-0.60	-6.91	1.19	-0.54	0.23	-6.07	11.48	-2.95	0.52	11.85	31.93	-0.47	3.31
DE	12.38	0.02	24.74	18.54	3.72	18.14	-4.21	5.50	14.16	11.03	20.71	-4.10	10.05
MA	5.64	7.75	6.51	2.01	-1.97	-6.31	-16.01	3.51	-5.27	14.80	16.69	0.82	2.35
MD	2.88	-2.11	12.16	10.70	6.02	11.28	6.36	1.31	-13.54	16.88	9.13	-1.40	4.97
ME	11.30	0.05	5.35	5.55	19.77	-7.25	9.26	10.08	-0.34	16.52	24.54	-1.22	7.80
NH	15.18	5.86	12.33	11.31	12.31	2.16	-10.61	9.50	-4.81	23.52	33.69	-0.64	9.15

Table 3-13. Wind Direction Bias (deg.) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NJ	5.45	-7.07	7.80	-3.68	1.76	-2.46	-1.44	8.96	-4.05	13.06	12.12	13.53	3.67
NY	4.96	5.57	7.82	3.20	9.90	14.31	8.33	8.57	10.55	14.40	15.12	-0.04	8.56
PA	8.98	4.68	18.31	3.84	5.12	11.49	13.49	5.76	4.14	8.59	16.61	7.78	9.07
RI	-2.19	0.06	-7.86	-0.65	-4.71	-5.30	-8.46	-0.11	-17.64	4.62	15.12	1.02	-2.18
VT	0.31	-7.93	9.21	6.08	3.71	16.63	1.14	7.57	-21.15	21.10	3.77	5.53	3.83
Visibility Improvement State and Tribal Association of the Southeast (VISTAS)													
VISTAS	5.67	3.12	7.73	2.97	3.15	7.20	5.92	6.23	2.53	7.53	6.75	4.59	5.28
AL	8.40	-0.84	7.03	4.30	-2.98	6.00	2.25	11.89	0.30	7.81	6.35	0.85	4.28
GA	6.00	-1.38	1.72	-0.19	-3.40	4.00	-1.02	8.29	-5.40	8.65	-0.81	1.33	1.48
FL	4.08	-7.13	4.49	5.92	3.57	5.56	7.38	1.47	8.01	5.14	-0.90	0.45	3.17
KY	2.56	0.95	-3.76	1.60	6.57	1.97	-1.92	4.60	-6.84	2.05	-7.11	-1.87	-0.10
MS	11.78	2.77	4.37	4.09	6.70	-0.51	1.04	15.36	-8.47	-4.49	3.65	3.38	3.31
NC	6.16	9.90	14.08	0.04	4.49	10.16	7.18	7.03	-3.11	4.88	11.40	9.70	6.83
SC	5.88	15.69	12.29	-9.87	1.34	13.15	9.47	11.18	15.01	7.93	4.68	6.79	7.80
TN	15.25	14.54	5.20	4.03	13.56	8.31	-0.72	14.85	11.01	10.86	18.57	7.48	10.25
VA	-0.89	6.68	16.68	3.53	7.53	9.47	15.60	-0.31	10.11	23.13	23.48	10.02	10.42
WV	12.35	2.97	6.30	14.32	-6.94	10.33	11.49	3.88	-1.22	2.79	16.69	3.12	6.34
Midwest Regional Planning Organization (MRPO)													
MW	4.09	3.32	5.84	-1.45	5.17	6.00	6.25	1.53	4.03	7.79	5.03	1.00	4.05
IL	3.44	-0.59	9.87	2.91	7.68	7.59	8.73	0.99	4.29	13.80	4.74	0.69	5.35
IN	1.94	10.09	3.07	-3.01	7.51	5.48	1.37	-1.41	5.83	3.18	0.84	-0.81	2.84
MI	1.95	-0.39	3.45	-7.95	1.46	2.25	4.32	-0.52	2.01	5.15	7.81	-3.91	1.30
OH	-0.92	6.69	2.62	-0.59	0.87	6.88	4.39	-2.15	2.15	0.88	6.35	1.73	2.41
WI	12.43	7.54	7.46	0.89	8.60	9.69	12.25	7.85	6.60	10.92	2.61	8.27	7.93
Central States Regional Air Partnership (CENRAP)													
CENRAP	6.77	5.12	5.33	4.98	7.98	4.68	2.98	6.96	2.58	7.88	6.24	4.98	5.54
AR	15.02	6.00	11.15	7.75	7.97	8.31	6.73	14.00	-3.23	8.20	10.42	0.26	7.72
IA	3.20	1.45	9.06	2.58	11.43	3.64	9.25	2.03	-0.62	5.26	-2.47	0.57	3.78
KS	4.65	2.36	-0.08	11.18	0.51	-2.29	-5.38	6.94	1.14	2.54	3.82	6.39	2.65
LA	3.48	-2.43	7.92	7.56	10.31	6.86	4.55	6.27	-4.33	1.39	5.88	3.98	4.29
MN	5.70	6.12	5.75	0.26	9.26	6.07	1.63	12.99	6.35	9.80	0.53	6.17	5.89
MO	6.42	3.62	6.60	2.70	2.29	8.38	-8.80	5.32	9.82	13.27	5.32	4.02	4.91
NE	8.47	1.79	5.17	4.54	10.02	5.02	0.19	6.27	8.83	1.15	4.17	4.51	5.01
OK	8.20	0.48	-0.26	6.00	11.34	-5.33	-8.38	2.35	-0.06	12.24	4.77	4.97	3.03
TX	7.28	10.07	4.60	6.85	6.20	6.47	6.61	5.03	1.64	8.71	13.34	7.14	7.00

Table 3-14. Wind Direction Bias (deg.) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	9.62	4.50	4.91	5.54	6.10	3.81	4.20	5.31	2.93	6.34	4.50	4.12	5.16
Western Regional Air Partnership (WRAP)													
WRAP	10.91	2.18	5.04	7.45	4.84	2.27	2.28	3.51	3.03	1.80	3.28	4.30	4.24
AZ	6.20	-8.55	1.89	9.38	-2.97	1.77	3.18	8.93	6.27	1.33	-0.28	-13.03	1.18
CA	11.61	1.38	6.06	7.27	3.69	-4.04	-0.64	-1.60	-1.94	-2.86	-7.44	-7.46	0.34
CO	6.31	0.47	-2.96	12.64	3.21	-3.63	-1.64	1.29	-0.07	-16.21	2.21	0.17	0.15
ID	12.18	-7.38	-0.64	11.06	17.87	20.13	2.75	4.24	11.42	19.81	11.62	15.13	9.85
MT	25.68	6.53	10.56	8.10	5.67	9.54	8.23	-1.92	-2.67	10.86	11.97	8.69	8.44
NM	3.95	-4.03	4.51	8.52	10.46	4.12	-6.40	5.06	6.83	3.88	12.05	7.05	4.67
ND	10.13	5.88	12.51	-2.29	6.33	0.73	1.62	10.20	3.02	11.25	4.42	9.67	6.12
NV	0.24	6.23	7.63	0.09	-7.46	1.15	4.16	3.16	7.62	11.43	8.59	-1.10	3.48
OR	16.44	9.31	10.99	5.68	5.76	5.83	10.69	1.48	10.60	5.66	13.26	16.91	9.38
SD	7.63	5.69	1.52	5.01	7.01	3.19	4.92	8.81	-2.50	3.55	4.25	10.21	4.94
UT	0.02	3.87	5.87	5.62	7.19	9.39	6.61	13.11	-5.30	-4.82	8.14	6.33	4.67
WA	11.47	9.67	12.06	10.49	1.45	5.21	7.23	6.54	13.36	12.87	12.75	12.14	9.60
WY	16.55	2.02	-0.86	-0.36	2.19	5.80	4.89	9.54	6.36	7.32	-5.29	11.92	5.01
Westjump DSAD Domains													
DJ_4km_rev	8.79	-2.55	-3.43	12.42	-3.39	1.95	-1.63	7.28	-1.99	-19.87	7.29	7.53	1.03
FourCorners_4km	-0.05	1.66	9.00	12.89	20.32	7.11	9.37	3.03	7.78	12.20	2.70	3.21	7.44
MT_ND_4km_rev	20.04	1.51	12.29	1.73	8.03	4.49	4.36	4.61	1.63	14.21	4.51	15.07	7.71
NM_SE_4km	6.53	4.81	3.17	3.37	16.55	1.18	-4.81	10.32	7.29	5.45	14.20	3.71	5.98
PowderRiver_4km	13.90	0.72	-1.13	0.16	5.98	3.45	4.77	0.97	3.70	5.56	-7.20	13.73	3.72
Uinta_Piceance_4km	7.43	-0.39	1.79	7.26	-2.44	0.25	2.85	1.81	-5.47	-8.27	-3.33	-14.05	-1.05
Westjump IAD Domains													
CO_UT	7.03	0.29	1.31	8.30	2.02	3.79	0.53	5.23	3.17	-7.78	0.37	3.42	2.31
MT_ND_rev	20.04	5.49	10.00	3.77	8.80	7.25	3.87	5.08	0.23	8.52	6.71	11.26	7.59
SanJuan_NM	4.12	-2.29	-0.25	14.59	4.48	3.32	-1.53	4.90	3.20	-7.02	1.81	3.73	2.42
WY_rev	15.89	2.69	2.65	3.74	2.00	6.16	4.68	5.40	6.30	1.23	-0.53	4.12	4.53
Central States Regional Air Partnership (CENRAP)													
CENRAP	7.32	4.28	6.05	5.14	8.53	4.60	3.99	7.46	2.44	8.56	7.22	5.70	5.94
AR	14.97	6.79	12.75	8.39	7.57	8.22	2.73	10.87	-4.48	10.95	11.59	1.50	7.65
IA	4.66	-0.40	7.15	3.31	11.71	4.38	8.82	2.81	-0.98	6.87	-1.19	1.91	4.09
KS	6.96	3.24	-0.16	11.43	-0.94	-2.75	-3.94	7.98	0.33	2.64	5.69	7.16	3.14
LA	6.50	-5.17	10.41	6.09	11.06	3.63	9.46	3.56	-3.31	-3.39	7.04	2.09	4.00
MN	4.86	3.78	6.23	0.30	10.11	6.35	5.02	13.78	6.94	10.13	0.89	7.00	6.28

Table 3-14. Wind Direction Bias (deg.) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
MO	8.62	1.89	7.30	4.23	2.66	8.44	-10.04	6.08	9.05	15.81	4.80	4.94	5.32
NE	8.76	1.43	6.05	4.41	10.93	4.91	0.42	7.19	7.35	1.45	5.69	4.12	5.23
OK	9.33	-1.12	1.48	6.99	12.04	-5.52	-4.55	3.12	-0.46	12.95	6.06	6.31	3.89
TX	7.29	10.39	6.08	6.74	7.00	6.60	7.32	5.84	1.55	9.18	14.74	7.82	7.55

Table 3-15. Wind Direction Bias (deg.) for 2008 WRF by Month in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	4.07	2.59	4.11	5.76	4.31	1.05	1.86	3.28	3.19	2.05	3.72	4.26	3.35
Western Regional Air Partnership (WRAP)													
WRAP	2.68	1.03	4.55	4.18	4.55	3.36	2.87	3.21	3.59	1.70	5.45	2.15	3.28
AZ	1.83	-8.60	2.71	5.65	-3.82	7.17	4.99	-8.11	9.63	2.80	6.08	-11.62	0.73
CO	-2.16	2.88	-2.70	4.60	-1.24	0.01	-2.48	1.67	2.10	-4.52	0.80	-2.59	-0.30
ID	8.30	-1.34	3.00	9.17	5.46	2.65	11.22	6.90	8.65	8.42	9.10	6.23	6.48
MT	0.77	1.47	5.84	6.75	7.16	0.57	6.24	1.30	-0.15	-1.21	5.99	6.66	3.45
NM	4.28	-3.30	4.68	5.03	8.47	3.69	-2.88	1.30	3.06	-0.59	9.60	7.03	3.36
UT	-5.17	3.58	12.96	0.82	2.09	15.34	2.64	6.53	2.85	0.15	0.57	-2.08	3.36
WY	-0.38	-0.16	4.15	-5.96	6.67	4.05	3.15	7.22	3.33	1.12	-0.30	-8.18	1.23
Westjump DSAD Domains													
DJ_4km_rev	0.69	-0.16	-1.33	7.57	-3.32	2.41	-3.73	6.94	2.26	-3.10	1.05	-0.39	0.74
FourCorners_4km	9.74	14.25	3.53	7.74	16.42	14.24	-0.29	1.76	10.92	10.28	9.03	4.42	8.50
MT_ND_4km_rev	6.30	6.86	4.87	3.34	5.43	0.42	-2.57	2.33	1.14	-1.26	2.95	5.88	2.97
NM_SE_4km	8.77	-3.10	7.28	5.15	8.70	2.21	-1.56	1.70	3.42	1.06	7.75	9.36	4.23
PowderRiver_4km	-5.54	-1.56	-1.01	-10.24	7.26	-0.19	-0.66	3.80	2.19	-1.87	-1.19	-3.22	-1.02
Uinta_Piceance_4km	-2.63	2.52	11.47	-4.03	-3.47	3.80	2.32	0.14	-4.36	-10.22	-0.09	-14.35	-1.58
Westjump IAD Domains													
CO_UT	-1.02	2.49	3.07	2.60	0.85	2.74	-0.84	3.77	2.85	-2.36	0.73	-4.12	0.90
MT_ND_rev	5.59	3.80	5.42	3.60	5.00	3.32	1.72	5.12	1.30	0.31	4.36	5.09	3.72
SanJuan_NM	-1.27	0.14	2.00	5.94	2.12	1.15	-4.56	2.01	0.57	-3.03	2.74	2.17	0.83
WY_rev	1.10	-0.46	4.47	-1.44	3.59	2.46	1.55	4.01	3.61	0.26	2.88	-3.00	1.59

Table 3-16. Wind Direction Error (deg.) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	24.55	29.17	26.56	24.95	28.57	31.70	34.99	27.75	32.80	28.52	27.48	24.23	28.44
Western Regional Air Partnership (WRAP)													
WRAP	36.31	48.29	38.96	31.78	44.17	48.78	46.15	38.09	48.52	47.32	44.04	47.92	43.36
AZ	40.86	51.45	35.79	24.45	48.06	48.38	45.37	47.51	34.72	52.78	50.07	51.15	44.22
CA	43.12	55.90	44.51	31.33	39.60	42.22	45.44	42.93	49.53	47.79	56.06	62.01	46.70
CO	43.73	53.99	48.69	42.90	38.40	51.53	46.75	43.17	51.36	46.49	36.07	47.12	45.85
ID	36.10	61.15	38.52	34.93	62.68	72.99	55.91	46.09	60.00	65.76	52.77	58.99	53.82
MT	39.02	37.23	36.04	37.31	39.22	44.39	36.60	37.65	52.18	46.75	32.98	41.78	40.10
NM	25.45	45.69	20.67	29.32	40.77	52.88	55.14	22.78	48.53	41.00	41.48	45.33	39.09
ND	19.37	21.07	20.57	14.99	23.52	20.31	42.94	18.55	27.99	23.85	17.46	22.58	22.77
NV	56.37	65.81	42.57	31.01	43.72	51.20	55.17	46.16	69.81	35.59	68.91	66.90	52.77
OR	32.64	55.94	55.88	31.95	55.37	64.22	48.15	31.73	61.47	58.02	59.14	41.62	49.68
SD	21.97	19.97	17.02	15.58	25.79	23.78	33.74	13.53	24.90	24.32	10.24	29.89	21.73
UT	46.22	70.15	44.13	34.10	57.71	62.62	52.97	55.04	65.83	51.88	64.06	71.55	56.36
WA	29.07	52.16	39.64	32.41	58.67	57.95	46.13	39.33	49.95	53.50	59.09	37.38	46.27
WY	38.73	40.25	39.86	41.92	65.08	52.97	47.98	41.93	53.47	53.43	35.90	58.35	47.49
Westjump DSAD Domains													
DJ_4km_rev	29.80	39.38	42.67	47.32	41.76	36.72	34.28	30.92	44.95	42.49	21.55	39.81	37.64
FourCorners_4km	38.94	51.70	24.28	36.15	41.43	75.08	49.57	35.63	52.61	42.38	39.12	51.25	44.85
MT_ND_4km_rev	34.52	36.32	29.18	25.91	23.07	29.88	30.70	18.78	40.47	34.96	11.56	36.40	29.31
NM_SE_4km	20.01	41.74	19.58	23.98	36.48	46.94	58.68	24.25	43.36	35.53	40.32	39.37	35.85
PowderRiver_4km	39.80	48.17	37.10	40.44	65.42	50.94	50.31	44.49	54.26	56.62	42.28	64.74	49.55
Uinta_Piceance_4km	47.91	63.42	49.80	36.79	55.96	62.86	57.74	52.26	58.35	53.07	52.73	56.87	53.98
Westjump IAD Domains													
CO_UT	37.60	48.41	42.06	39.01	45.98	49.36	43.93	38.97	50.15	46.27	35.31	49.30	43.86
MT_ND_rev	32.63	33.58	33.81	28.62	33.89	36.79	35.07	29.65	41.39	36.59	23.93	37.01	33.58
SanJuan_NM	42.99	53.65	38.04	36.87	43.08	59.57	52.46	43.61	54.70	49.12	43.12	51.41	47.39
WY_rev	33.99	39.60	35.71	39.74	50.94	44.08	43.19	36.22	47.44	47.63	30.79	51.52	41.74
Mid-Atlantic/Northeast Visibility Union (MANE-VU)													
MANE_VU	22.53	17.26	24.28	24.62	23.53	27.72	31.35	25.51	30.53	26.01	29.22	22.11	25.39
CT	24.55	14.00	16.56	20.47	16.04	23.62	38.01	20.83	27.42	28.66	39.91	15.17	23.77
DE	21.00	9.73	29.40	26.95	15.17	32.28	18.28	22.83	29.54	23.36	26.06	19.10	22.81
MA	20.79	17.04	21.61	29.17	15.18	20.00	34.40	18.57	27.95	22.47	33.23	18.28	23.22
MD	21.00	13.20	28.28	29.09	22.71	31.50	27.51	37.00	37.30	35.32	30.68	25.05	28.22
ME	19.52	16.11	21.28	20.46	39.27	27.39	42.56	18.78	21.59	23.55	34.62	16.84	25.16

Table 3-16. Wind Direction Error (deg.) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NH	26.05	22.53	22.32	24.95	52.85	30.78	55.04	23.48	42.03	45.33	58.12	26.01	35.79
NJ	21.86	15.52	25.24	20.71	17.82	28.24	22.73	26.42	30.94	22.82	18.55	21.35	22.68
NY	24.25	23.02	23.97	21.66	25.25	30.07	27.89	28.91	28.96	24.63	26.52	23.33	25.71
PA	22.48	14.68	28.38	26.55	19.97	29.01	27.21	28.36	33.88	21.62	23.87	26.91	25.24
RI	19.94	11.87	15.45	17.53	14.02	15.47	31.33	14.94	29.48	15.37	24.12	12.80	18.53
VT	27.91	28.03	24.09	29.40	38.58	37.35	39.94	29.16	34.84	43.18	39.84	27.35	33.31
Visibility Improvement State and Tribal Association of the Southeast (VISTAS)													
VISTAS	21.55	21.90	20.60	27.49	19.18	24.66	29.61	21.83	41.81	26.06	27.34	16.85	24.91
AL	23.25	32.79	13.87	23.48	19.83	26.83	22.84	19.54	29.38	33.10	28.62	14.62	24.01
GA	18.83	23.13	16.93	37.22	21.33	17.49	21.35	18.81	37.59	27.10	29.31	14.83	23.66
FL	21.77	20.43	18.47	21.00	21.36	33.06	30.63	12.30	58.07	18.24	22.09	19.84	24.77
KY	19.77	27.59	12.74	25.80	13.41	17.26	45.33	20.47	33.03	17.08	20.03	13.21	22.14
MS	28.14	18.21	12.75	18.84	22.06	23.20	23.86	23.36	22.38	22.68	19.69	15.85	20.92
NC	17.60	20.04	25.88	31.05	14.99	22.92	32.33	29.60	37.83	33.62	30.26	16.92	26.09
SC	17.64	30.48	18.29	30.93	16.73	17.23	19.51	30.95	56.01	33.25	24.58	15.17	25.90
TN	30.91	24.41	27.57	25.60	20.93	21.02	40.34	26.53	37.41	27.11	30.42	17.08	27.44
VA	23.10	18.42	31.84	30.42	20.82	28.62	38.32	29.55	41.10	37.73	36.41	21.65	29.83
WV	28.28	20.05	22.50	34.88	21.76	28.08	31.82	27.14	31.26	24.33	27.42	13.29	25.90
Midwest Regional Planning Organization (MRPO)													
MW	18.40	29.47	18.61	23.17	17.17	18.98	27.51	24.24	17.83	16.81	18.00	13.34	20.29
IL	12.84	24.08	19.20	12.96	16.41	19.82	34.35	19.03	16.12	18.57	19.05	11.10	18.63
IN	15.45	28.11	11.20	17.89	16.31	14.62	26.97	23.65	17.89	11.36	13.94	12.75	17.51
MI	19.96	40.73	20.12	34.22	19.09	16.76	22.65	33.56	20.71	14.55	17.05	13.71	22.76
OH	20.54	26.84	13.96	32.73	14.03	18.08	19.47	22.07	19.16	11.95	20.44	14.48	19.48
WI	23.77	23.02	22.27	19.55	17.64	24.20	38.48	21.97	15.36	23.65	18.03	14.93	21.91
Central States Regional Air Partnership (CENRAP)													
CENRAP	18.68	20.04	16.60	14.52	22.56	28.15	30.67	18.90	21.86	21.96	16.64	17.06	20.64
AR	20.44	27.00	19.35	19.15	24.20	27.11	50.64	20.39	21.05	22.59	18.49	14.24	23.72
IA	12.48	17.30	19.94	10.47	18.38	15.57	26.85	10.98	13.48	25.70	10.09	13.46	16.23
KS	14.57	19.25	17.66	18.20	32.07	27.49	23.36	14.29	23.82	16.95	10.67	14.99	19.44
LA	22.00	18.52	13.89	17.94	21.00	44.05	19.09	18.95	20.51	24.14	20.18	17.28	21.46
MN	19.61	21.68	16.89	16.00	26.74	20.31	46.38	16.53	19.04	21.52	16.12	16.48	21.44
MO	12.47	19.16	18.19	13.68	29.49	24.06	46.03	15.70	17.71	22.71	16.05	13.19	20.70
NE	19.31	17.85	15.05	13.73	42.45	26.68	17.70	10.26	21.90	24.70	8.96	18.84	19.79
OK	20.64	20.08	20.12	13.06	19.50	40.04	35.46	26.73	19.28	21.17	14.86	13.87	22.07

Table 3-16. Wind Direction Error (deg.) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
TX	20.77	20.01	14.05	13.91	16.15	34.76	27.06	26.36	30.17	21.25	21.98	21.25	22.31

Table 3-17. Wind Direction Error (deg.) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	26.35	31.80	27.58	22.64	31.47	36.28	37.38	27.10	31.67	31.88	27.87	27.89	29.99
Western Regional Air Partnership (WRAP)													
WRAP	33.22	44.49	36.65	29.75	40.38	44.97	42.29	35.21	43.65	44.61	41.11	47.84	40.35
AZ	38.62	45.44	33.73	22.01	40.51	47.57	37.45	46.47	32.10	41.29	41.50	44.37	39.26
CA	37.87	50.38	39.45	27.49	34.46	35.88	39.22	37.96	44.61	44.40	52.04	57.77	41.79
CO	40.37	48.22	43.52	41.02	36.81	46.90	42.83	38.64	45.32	44.48	33.68	46.08	42.32
ID	29.37	60.30	38.72	34.53	59.86	69.35	50.50	42.46	52.65	61.36	50.76	52.62	50.21
MT	34.95	33.44	34.23	37.45	35.88	41.67	35.39	36.32	41.83	39.84	29.99	37.21	36.52
NM	24.04	43.38	20.92	24.58	37.42	48.77	51.53	22.12	43.04	37.74	39.54	42.08	36.26
ND	18.78	20.23	20.38	14.84	24.04	19.21	43.29	20.24	26.47	22.57	16.36	21.48	22.32
NV	50.33	56.26	41.01	30.72	39.51	53.32	49.21	43.83	69.74	34.76	66.83	57.81	49.44
OR	31.14	53.99	52.13	31.18	50.90	63.05	44.15	30.61	52.70	58.07	51.95	45.93	47.15
SD	20.35	19.41	17.09	13.83	25.99	23.72	33.18	13.22	23.43	24.75	10.40	27.97	21.11
UT	48.15	66.19	44.45	35.92	58.41	61.43	50.86	52.32	64.33	46.80	66.52	67.02	55.20
WA	26.61	48.02	40.85	30.38	53.40	55.08	45.56	35.66	48.33	56.43	56.58	41.85	44.90
WY	37.29	37.40	38.14	42.37	57.36	46.58	45.06	39.07	48.07	52.28	34.23	52.47	44.19
Westjump DSAD Domains													
DJ_4km_rev	26.43	35.27	38.20	45.04	44.06	32.60	31.92	27.19	38.03	38.53	20.95	36.10	34.53
FourCorners_4km	35.47	43.37	22.40	31.04	39.64	72.97	45.63	34.54	46.57	44.22	35.14	48.57	41.63
MT_ND_4km_rev	29.56	33.09	27.95	26.25	23.15	27.18	30.91	20.11	37.49	30.75	11.75	32.91	27.59
NM_SE_4km	19.23	40.79	21.98	20.74	36.42	42.59	56.79	23.11	39.06	38.20	38.78	37.88	34.63
PowderRiver_4km	38.92	44.60	35.63	40.72	57.11	45.71	46.20	41.35	50.44	56.37	38.54	60.71	46.36
Uinta_Piceance_4km	47.66	58.25	48.97	37.85	52.71	57.11	53.08	49.09	52.17	49.62	50.48	55.89	51.07
Westjump IAD Domains													
CO_UT	35.49	44.58	39.39	38.16	43.87	45.29	41.22	35.60	45.32	43.18	34.09	47.25	41.12
MT_ND_rev	29.59	30.91	33.25	29.10	32.72	35.84	34.02	29.95	36.53	33.57	22.74	33.79	31.83
SanJuan_NM	38.88	49.08	34.71	33.67	38.76	55.37	47.77	39.43	48.57	45.51	41.38	47.41	43.38
WY_rev	32.43	37.08	35.33	39.33	48.09	40.02	40.34	34.08	41.44	46.22	28.16	48.85	39.28

Table 3-17. Wind Direction Error (deg.) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Central States Regional Air Partnership (CENRAP)													
CENRAP	18.73	19.71	17.10	14.19	22.77	27.90	31.45	18.86	20.85	22.09	16.94	16.65	20.60
AR	20.35	27.35	20.42	18.44	24.91	27.54	53.22	18.64	20.97	23.78	18.61	13.88	24.01
IA	12.98	17.38	19.78	10.75	18.57	15.79	26.41	11.12	13.72	26.20	10.21	13.11	16.34
KS	14.84	18.88	18.60	17.77	32.17	26.80	23.67	14.63	22.94	17.07	11.21	14.75	19.44
LA	23.67	17.92	15.43	14.54	20.18	43.24	21.37	19.23	20.61	23.91	18.26	15.82	21.18
MN	18.90	20.72	17.13	15.85	26.65	20.48	46.84	17.17	19.07	21.27	16.62	16.21	21.41
MO	13.06	17.88	18.66	13.15	28.25	24.28	43.81	15.49	17.47	24.20	16.32	13.16	20.48
NE	19.07	18.03	15.85	13.73	41.85	26.52	17.74	10.56	20.58	24.04	9.67	18.50	19.68
OK	20.89	18.54	19.51	12.83	19.46	36.44	34.98	26.60	19.14	21.38	15.32	14.13	21.60
TX	21.02	20.37	14.65	13.69	16.67	35.95	28.35	26.22	27.17	21.39	22.86	20.62	22.41

Table 3-18. Wind Direction Error (deg.) for 2008 WRF by Month in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	28.12	35.06	34.05	28.80	37.55	40.22	37.18	30.60	35.45	35.53	29.73	35.23	33.96
Western Regional Air Partnership (WRAP)													
WRAP	30.17	39.33	34.27	31.76	39.99	44.53	39.82	35.49	37.65	38.40	32.46	39.79	36.97
AZ	40.08	47.54	34.59	21.73	38.29	50.61	34.96	58.02	32.94	43.02	35.91	39.90	39.80
CO	35.89	46.45	41.56	37.77	36.38	46.94	42.95	36.30	40.02	36.24	31.91	42.46	39.57
ID	25.81	43.73	39.90	34.59	51.97	59.59	38.32	36.95	44.41	50.95	35.67	40.73	41.89
MT	30.60	29.10	34.88	38.53	36.56	32.93	27.10	34.19	33.60	33.05	26.82	32.59	32.50
NM	23.96	40.68	21.74	23.18	33.69	47.24	57.52	24.84	39.86	33.39	38.01	38.16	35.19
UT	38.09	62.93	45.68	33.81	53.38	58.51	41.71	44.29	52.63	34.48	56.31	59.90	48.48
WY	29.67	31.71	34.98	40.67	54.75	38.60	37.80	36.43	34.74	41.02	26.98	43.86	37.60
Westjump DSAD Domains													
DJ_4km_rev	21.06	30.46	37.83	39.21	43.23	28.22	30.69	25.37	29.71	25.45	18.24	29.80	29.94
FourCorners_4km	36.37	57.39	20.69	27.67	37.63	73.53	51.20	34.46	45.07	44.70	35.86	48.61	42.77
MT_ND_4km_rev	20.08	34.99	25.22	31.90	21.52	21.77	28.67	19.83	23.53	22.16	10.56	26.98	23.93
NM_SE_4km	20.58	39.88	23.40	22.87	33.91	45.28	61.75	26.03	34.34	34.03	36.65	39.11	34.82
PowderRiver_4km	31.15	35.78	31.28	40.76	52.66	37.19	34.30	36.70	36.85	44.15	26.88	49.79	38.12
Uinta_Piceance_4km	37.89	55.80	47.42	39.52	48.41	58.33	45.25	44.75	43.94	38.97	43.31	53.76	46.45
Westjump IAD Domains													
CO_UT	30.89	41.23	39.17	35.80	42.17	42.89	37.95	32.52	38.02	34.82	29.95	41.23	37.22

Table 3-18. Wind Direction Error (deg.) for 2008 WRF by Month in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
MT_ND_rev	25.46	28.55	31.90	31.97	32.88	29.41	27.85	28.07	28.49	28.97	20.89	28.12	28.55
SanJuan_NM	35.96	46.75	31.75	29.81	36.18	54.15	47.20	37.14	43.11	37.38	39.42	41.02	39.99
WY_rev	26.10	32.10	33.11	38.92	44.33	33.45	31.78	30.38	31.91	36.19	21.34	40.95	33.38

Table 3-19. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	1.97	1.79	1.80	1.89	1.76	1.64	1.62	1.67	1.51	1.93	1.85	1.94	1.78
Western Regional Air Partnership (WRAP)													
WRAP	2.44	2.01	1.97	2.21	1.84	1.87	1.79	1.96	1.75	1.88	2.07	2.07	1.99
AZ	2.21	1.71	1.91	2.31	1.68	2.22	1.55	1.84	1.85	1.58	1.48	1.76	1.84
CA	2.18	1.79	1.88	2.02	1.58	1.66	1.45	1.78	1.72	2.13	1.83	1.45	1.79
CO	2.38	2.60	2.44	2.44	2.58	2.40	2.20	2.08	2.22	2.18	2.43	2.59	2.38
ID	2.80	1.63	2.08	2.43	1.65	2.02	1.66	1.88	1.82	2.01	2.66	2.35	2.08
MT	2.96	2.54	1.68	2.54	1.74	1.77	1.87	2.41	1.60	1.49	2.38	2.65	2.14
NM	2.64	2.05	2.61	2.58	1.97	1.77	1.98	1.70	1.69	1.51	2.19	1.94	2.05
ND	1.53	1.41	1.27	1.93	1.76	1.27	1.98	2.49	1.62	1.38	1.70	1.38	1.64
NV	2.29	1.66	1.88	2.41	1.87	1.88	1.83	1.88	1.99	2.47	2.19	1.71	2.01
OR	3.24	1.63	1.79	1.73	1.91	1.88	1.50	1.94	1.79	1.95	1.71	2.40	1.96
SD	1.63	2.01	1.30	2.53	1.64	1.43	2.48	2.30	1.51	1.51	2.06	1.53	1.83
UT	2.07	1.79	2.23	2.22	1.82	2.35	1.53	2.07	1.62	1.72	2.60	1.48	1.96
WA	2.22	1.61	1.69	1.88	1.61	1.86	1.49	1.77	1.43	1.63	1.29	2.21	1.72
WY	3.04	2.47	2.18	2.28	1.87	1.66	1.99	2.02	1.57	1.88	2.54	2.69	2.18
Westjump DSAD Domains													
DJ_4km_rev	2.50	2.90	2.11	2.20	2.50	2.00	2.25	2.13	2.00	1.91	2.96	2.61	2.34
FourCorners_4km	2.51	1.61	2.96	2.85	2.51	2.51	1.75	1.72	2.07	1.88	2.34	2.32	2.25
MT_ND_4km_rev	1.62	1.97	1.30	2.30	1.67	1.42	1.92	2.30	1.38	1.48	2.36	1.91	1.80
NM_SE_4km	2.51	2.24	2.77	2.67	1.99	1.65	2.33	2.01	1.57	1.63	2.11	1.82	2.11
PowderRiver_4km	2.88	2.35	1.96	2.62	1.91	1.75	1.96	2.15	1.76	1.86	2.52	2.49	2.18
Uinta_Piceance_4km	2.22	1.88	2.29	2.23	1.85	2.07	1.71	2.00	1.58	1.88	2.36	2.18	2.02
Westjump IAD Domains													
CO_UT	2.42	2.46	2.30	2.44	2.28	2.18	2.04	2.07	1.94	1.96	2.62	2.41	2.26
MT_ND_rev	2.60	2.35	1.62	2.49	1.76	1.58	1.91	2.25	1.56	1.57	2.29	2.36	2.03
SanJuan_NM	2.61	2.47	2.54	2.53	2.42	2.44	2.05	1.94	2.17	2.08	2.40	2.43	2.34
WY_rev	2.58	2.33	1.87	2.67	1.81	1.74	1.97	2.20	1.60	1.75	2.62	2.29	2.12
Mid-Atlantic/Northeast Visibility Union (MANE-VU)													

Table 3-19. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
MANE_VU	1.67	1.72	1.64	1.94	2.03	1.60	1.55	1.50	1.25	1.75	1.89	1.87	1.70
CT	1.39	1.43	1.73	1.89	1.53	1.18	1.73	1.59	0.97	1.34	1.63	1.37	1.48
DE	1.57	1.71	1.64	1.49	1.54	1.63	1.46	1.42	1.28	1.24	1.45	2.12	1.55
MA	2.20	2.21	1.82	2.16	1.92	1.76	1.50	1.57	1.34	2.67	2.34	2.06	1.96
MD	1.38	1.70	1.73	1.55	2.32	1.56	1.36	1.15	1.37	1.59	1.74	2.43	1.66
ME	1.89	1.77	1.45	1.99	1.62	1.12	1.17	1.48	1.14	1.68	1.42	1.78	1.54
NH	1.71	1.84	1.56	3.34	3.54	3.60	3.31	2.55	1.42	1.76	3.47	1.57	2.47
NJ	1.65	1.43	1.63	1.74	2.02	1.54	1.58	1.49	1.25	1.42	1.86	1.82	1.62
NY	1.74	1.71	1.74	1.69	2.02	1.40	1.54	1.44	1.34	1.69	2.04	1.81	1.68
PA	1.17	1.43	1.38	1.55	1.73	1.15	1.17	1.22	1.20	1.38	1.40	1.88	1.39
RI	1.69	1.97	1.42	2.25	1.98	1.29	1.69	1.58	0.85	1.73	2.03	1.50	1.67
VT	1.51	1.39	1.96	1.69	1.87	1.12	1.11	1.15	1.04	1.47	1.58	1.52	1.45
Visibility Improvement State and Tribal Association of the Southeast (VISTAS)													
VISTAS	1.53	1.74	1.60	1.37	1.61	1.59	1.49	1.44	1.38	1.62	1.79	2.14	1.61
AL	1.38	1.44	1.21	1.16	1.13	1.32	1.34	1.54	1.19	1.23	1.36	1.48	1.32
GA	1.46	1.64	1.27	1.26	1.22	1.79	1.65	1.34	1.27	1.26	1.82	1.83	1.48
FL	1.46	1.83	1.49	1.35	1.60	1.78	1.65	1.93	1.65	1.97	2.48	1.37	1.71
KY	1.21	1.36	1.81	1.17	2.02	1.31	1.38	0.96	1.25	1.11	1.19	1.55	1.36
MS	1.53	1.32	1.73	1.19	1.24	1.25	1.40	0.96	1.28	1.07	1.47	1.50	1.33
NC	1.81	1.92	1.80	1.29	1.56	1.58	1.50	1.28	1.14	1.73	1.53	2.76	1.66
SC	1.34	1.88	1.45	1.54	1.42	1.35	1.52	1.27	1.79	1.38	1.77	1.84	1.55
TN	1.52	1.23	1.62	1.24	1.57	1.17	1.32	0.95	1.45	1.22	1.24	1.68	1.35
VA	1.48	1.83	1.68	1.70	1.96	1.74	1.34	1.18	1.25	1.55	1.42	3.13	1.69
WV	1.55	1.58	2.11	1.23	1.97	1.23	1.16	1.02	1.18	1.22	1.60	2.42	1.52
Midwest Regional Planning Organization (MRPO)													
MW	1.47	1.28	1.78	1.39	1.72	1.59	1.31	1.14	1.45	2.28	1.39	1.92	1.56
IL	1.20	1.19	1.75	1.25	1.62	1.51	1.26	0.99	1.39	1.81	1.17	1.73	1.41
IN	1.23	1.27	2.20	1.32	1.88	1.39	1.22	1.09	1.31	1.83	1.29	1.57	1.47
MI	1.84	1.38	1.81	1.62	1.78	1.71	1.27	1.18	1.55	2.74	1.70	1.93	1.71
OH	1.08	1.39	1.87	1.61	2.20	1.23	1.23	1.14	1.19	1.50	1.24	1.76	1.45
WI	1.50	1.15	1.48	1.16	1.37	1.77	1.57	1.26	1.57	2.56	1.34	2.28	1.58
Central States Regional Air Partnership (CENRAP)													
CENRAP	1.75	1.68	1.86	1.85	1.67	1.32	1.61	1.74	1.33	1.77	1.85	1.61	1.67
AR	1.52	1.45	2.18	1.58	1.37	1.19	1.42	0.95	1.24	1.50	1.35	1.62	1.45
IA	1.09	1.30	1.62	1.50	1.59	1.27	1.31	1.54	1.38	1.93	1.18	1.49	1.43
KS	1.61	1.59	2.01	1.82	1.62	1.26	1.18	1.71	1.30	1.60	2.13	1.67	1.63

Table 3-19. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 36 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
LA	2.11	1.61	1.92	1.33	1.27	1.28	1.81	1.55	1.15	1.24	2.03	1.57	1.57
MN	1.21	1.36	1.62	1.44	1.54	1.24	2.03	2.58	1.49	1.59	1.21	1.65	1.58
MO	1.49	1.33	1.88	1.46	1.48	1.28	1.49	1.20	1.33	1.93	1.18	1.54	1.47
NE	1.37	1.46	1.47	1.92	1.58	1.29	1.79	1.86	1.16	1.26	2.32	1.54	1.59
OK	2.32	2.03	2.32	2.35	1.63	1.55	1.29	1.20	1.26	2.28	2.30	1.66	1.85
TX	2.12	1.98	1.91	2.14	1.92	1.39	1.60	1.24	1.30	1.83	2.09	1.64	1.76

Table 3-20. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	1.98	1.87	1.85	1.99	1.73	1.60	1.68	1.80	1.53	1.86	1.92	1.94	1.81
Western Regional Air Partnership (WRAP)													
WRAP	2.28	2.00	1.95	2.19	1.80	1.84	1.77	1.94	1.72	1.89	2.08	1.87	1.94
AZ	2.10	1.59	1.93	2.26	1.72	2.23	1.60	1.94	1.80	1.54	1.65	1.65	1.83
CA	1.89	1.76	1.76	2.02	1.58	1.57	1.43	1.74	1.57	2.15	1.71	1.57	1.73
CO	2.35	2.67	2.47	2.47	2.47	2.25	2.14	2.21	2.23	2.00	2.53	2.56	2.36
ID	2.66	1.64	2.09	2.35	1.65	2.08	1.64	1.84	1.87	1.99	2.53	2.25	2.05
MT	2.67	2.53	1.89	2.54	1.85	1.74	1.91	2.46	1.62	1.71	2.32	2.65	2.16
NM	2.41	2.06	2.44	2.40	1.94	1.80	1.93	1.70	1.68	1.40	2.08	1.92	1.98
ND	1.48	1.48	1.27	1.85	1.76	1.28	2.04	2.42	1.63	1.38	1.75	1.26	1.63
NV	2.16	1.71	1.84	2.33	1.85	1.86	1.71	1.96	1.84	2.59	2.02	1.66	1.96
OR	3.19	1.54	1.72	1.77	1.70	1.88	1.47	1.75	1.72	2.09	1.64	2.21	1.89
SD	1.73	2.06	1.38	2.40	1.62	1.48	2.46	2.20	1.55	1.58	2.17	1.43	1.84
UT	2.11	1.87	2.16	2.62	1.75	2.31	1.64	2.22	1.58	1.71	3.21	1.63	2.07
WA	2.04	1.51	1.69	1.76	1.46	1.85	1.46	1.53	1.53	1.83	1.35	2.06	1.67
WY	2.64	2.40	2.31	2.36	1.90	1.75	1.93	1.98	1.60	1.83	2.43	2.47	2.13
Westjump DSAD Domains													
DJ_4km_rev	2.46	2.75	2.15	2.15	2.22	1.90	2.15	2.14	1.95	1.77	2.86	2.26	2.23
FourCorners_4km	2.47	2.16	2.74	2.92	2.68	2.37	1.78	1.84	2.27	1.74	2.44	2.74	2.35
MT_ND_4km_rev	1.66	2.02	1.31	2.29	1.69	1.32	1.88	2.35	1.44	1.53	2.38	1.90	1.81
NM_SE_4km	2.35	2.27	2.65	2.57	2.03	1.68	2.18	2.01	1.55	1.50	2.12	1.80	2.06
PowderRiver_4km	2.44	2.28	2.13	2.64	1.95	1.75	1.94	2.07	1.78	1.94	2.51	2.16	2.13
Uinta_Piceance_4km	2.26	2.27	2.24	2.60	1.89	2.10	1.82	2.16	1.59	1.83	2.70	2.43	2.16
Westjump IAD Domains													
CO_UT	2.31	2.49	2.33	2.54	2.22	2.11	2.00	2.17	1.95	1.85	2.75	2.34	2.26
MT_ND_rev	2.46	2.40	1.73	2.45	1.77	1.59	1.91	2.24	1.56	1.69	2.28	2.32	2.03

Table 3-20. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 12 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
SanJuan_NM	2.57	2.55	2.54	2.54	2.29	2.29	2.02	2.02	2.17	1.86	2.54	2.44	2.32
WY_rev	2.32	2.35	1.97	2.63	1.86	1.79	1.93	2.16	1.65	1.81	2.65	2.15	2.11
Central States Regional Air Partnership (CENRAP)													
CENRAP	1.73	1.69	1.86	1.84	1.68	1.34	1.60	1.75	1.35	1.83	1.89	1.63	1.68
AR	1.48	1.52	2.34	1.70	1.36	1.20	1.45	0.99	1.25	1.62	1.44	1.66	1.50
IA	1.10	1.39	1.60	1.49	1.57	1.30	1.32	1.56	1.38	2.02	1.25	1.46	1.45
KS	1.61	1.55	2.11	1.79	1.70	1.26	1.20	1.67	1.35	1.65	2.23	1.69	1.65
LA	1.90	1.47	1.86	1.34	1.25	1.15	1.56	1.13	1.07	1.13	1.87	1.53	1.44
MN	1.25	1.42	1.57	1.43	1.59	1.27	1.97	2.58	1.47	1.67	1.22	1.69	1.59
MO	1.45	1.34	1.89	1.44	1.49	1.25	1.54	1.25	1.34	1.92	1.13	1.44	1.46
NE	1.39	1.48	1.51	1.89	1.58	1.31	1.75	1.83	1.21	1.31	2.37	1.52	1.60
OK	2.28	2.01	2.17	2.35	1.64	1.55	1.33	1.24	1.31	2.34	2.36	1.70	1.86
TX	2.13	1.98	1.95	2.12	1.90	1.41	1.63	1.29	1.34	1.87	2.17	1.66	1.79

(a) ALL in this case refers to those states within the area covered by the 12 km modeling domain.

Table 3-21. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ALL	2.31	2.28	2.13	2.53	2.02	1.91	1.95	2.09	1.68	1.76	2.33	2.12	2.09
Western Regional Air Partnership (WRAP)													
WRAP	2.27	2.22	2.17	2.61	2.04	2.07	2.05	2.21	1.81	1.78	2.40	2.19	2.15
AZ	2.27	1.93	1.99	2.40	1.87	2.61	1.82	2.36	2.26	1.59	1.81	1.75	2.06
CO	2.46	2.86	2.55	2.48	2.56	2.19	2.37	2.15	2.07	2.00	2.72	2.73	2.43
ID	2.10	1.66	2.09	2.38	2.05	2.23	1.55	1.77	1.74	1.92	1.90	2.11	1.96
MT	2.27	2.22	1.69	2.76	1.84	1.82	1.92	2.34	1.54	1.78	2.19	2.30	2.06
NM	2.61	2.04	2.56	2.70	1.93	2.04	2.40	2.05	1.73	1.44	2.99	1.85	2.20
UT	1.93	1.52	2.37	2.39	1.75	2.12	1.67	2.62	1.55	1.69	2.45	1.67	1.98
WY	2.50	2.30	2.43	2.71	1.86	1.80	1.93	2.34	1.44	1.71	2.48	2.68	2.18
Westjump DSAD Domains													
DJ_4km_rev	2.33	2.58	2.49	2.38	2.45	1.62	2.35	1.96	1.68	1.72	2.64	2.38	2.22
FourCorners_4km	2.58	2.20	2.75	2.64	2.32	2.36	2.01	2.06	2.11	1.55	3.50	2.54	2.39
MT_ND_4km_rev	1.42	1.96	1.18	2.62	1.60	1.34	1.96	2.35	1.24	1.45	2.20	1.67	1.75
NM_SE_4km	2.74	2.11	2.74	2.72	1.99	1.82	2.53	2.25	1.61	1.57	2.71	1.86	2.22
PowderRiver_4km	2.33	2.15	2.00	2.97	1.94	1.96	1.99	2.14	1.58	1.86	2.39	2.52	2.15
Uinta_Piceance_4km	2.51	2.57	2.42	2.57	1.86	2.12	1.82	2.46	1.53	1.74	2.38	2.31	2.19
Westjump IAD Domains													

Table 3-21. Wind Speed RMSE (m/s) for 2008 WRF by Month and by State and Region in the 4 km Domain.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
CO_UT	2.34	2.54	2.44	2.54	2.29	2.05	2.14	2.27	1.78	1.84	2.59	2.43	2.27
MT_ND_rev	2.17	2.29	1.59	2.79	1.77	1.55	1.92	2.19	1.39	1.69	2.17	2.10	1.97
SanJuan_NM	2.66	2.55	2.64	2.58	2.24	2.27	2.25	2.13	2.03	1.83	2.96	2.52	2.39
WY_rev	2.27	2.29	2.06	2.89	1.80	1.79	1.96	2.23	1.49	1.73	2.36	2.36	2.10

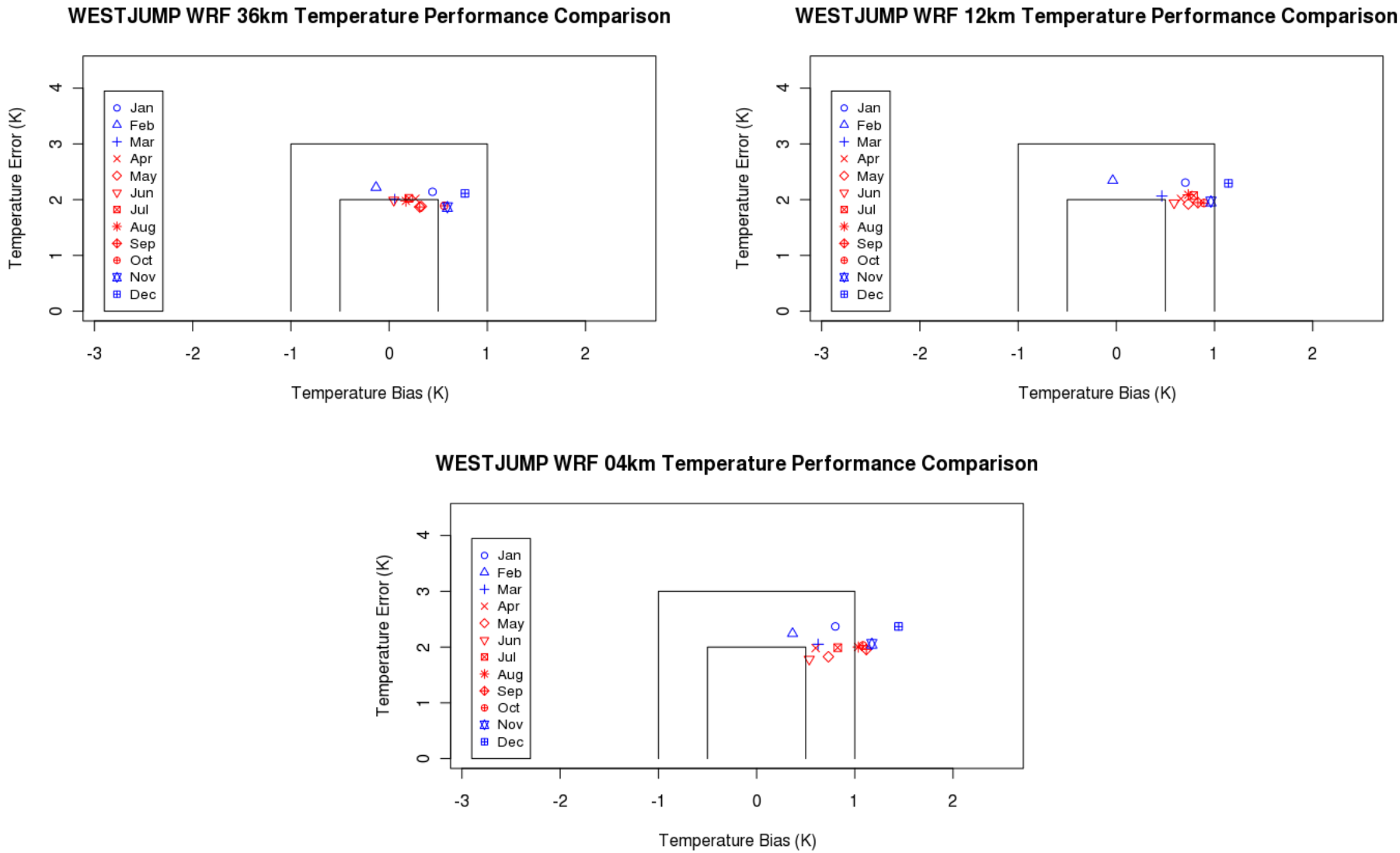


Figure 3-4: Monthly Temperature Bias and Error Soccerplot by Month for All Stations in the 36 km domain (top left), 12 km domain (top right) and 4 km domain (bottom).

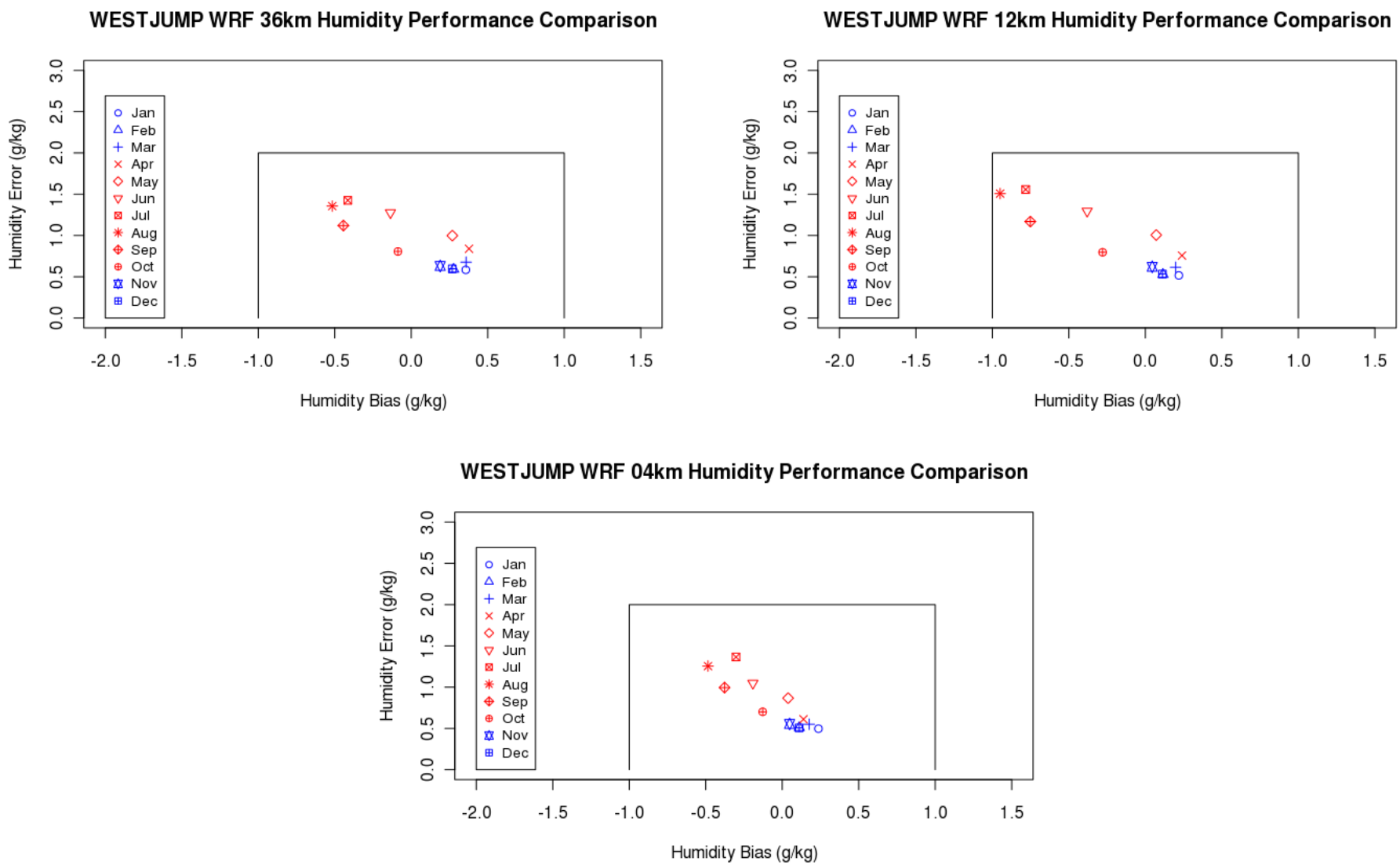


Figure 3-5: Monthly Mixing Ratio Bias and Error Soccerplot by Month for All Stations in the 36 km domain (top left), 12 km domain (top right) and 4 km domain (bottom).

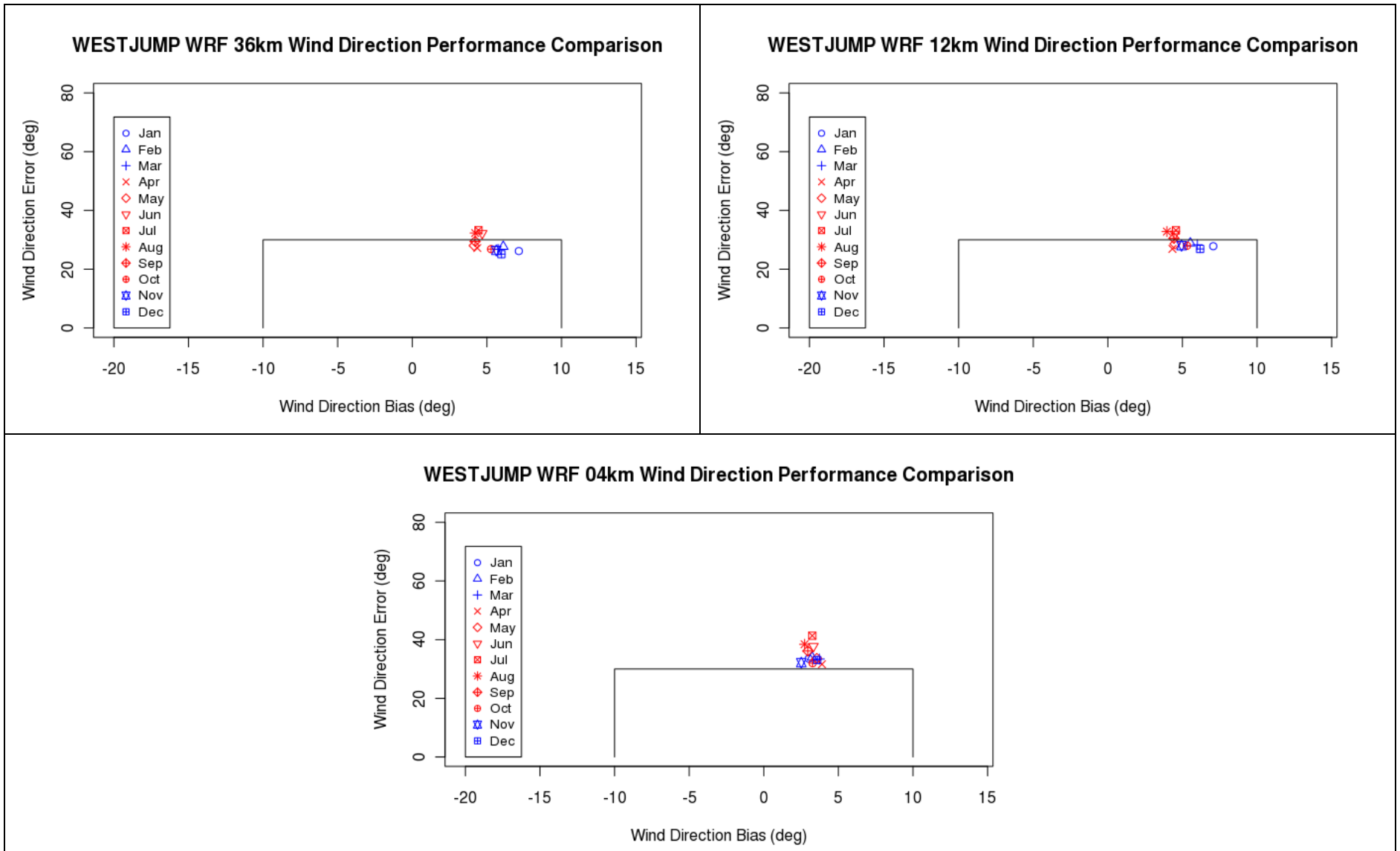


Figure 3-6: Monthly Wind Direction Bias and Error Soccerplot by Month for All Stations in the 36 km domain (top left), 12 km domain (top right) and 4 km domain (bottom).

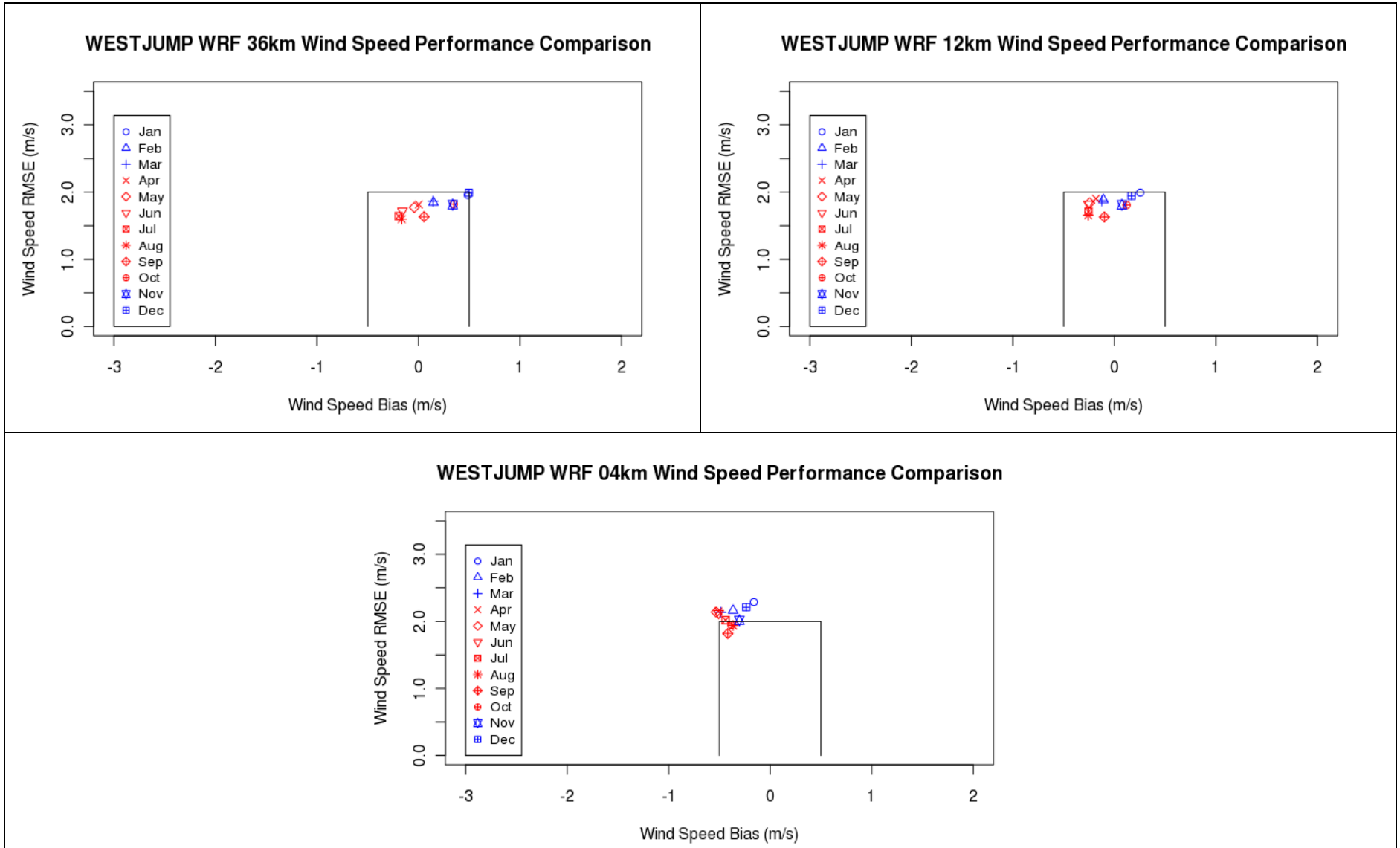


Figure 3-7: Wind Speed Bias and RMSE Soccerplot by Month for All Stations in the 36 km domain (top left), 12 km domain (top right) and 4 km domain (bottom).

3.2 Qualitative Monthly Precipitation Analysis

This section presents a qualitative comparison of WRF estimated precipitation with the Climate Prediction Center (CPC) retrospective analysis data. When comparing the CPC and WRF precipitation data, note should be taken that the CPC analysis covers only the Continental U.S. and does not extend offshore or into Canada or Mexico. The WRF fields, on the other hand, cover the entire 36 km domain. Also note that the CPC analysis is based on a 0.25 x 0.25 degree (~25 km resolution[18]) grid that is based on an analysis of precipitation measurements at monitoring sites and the WRF is based on either a 36 x 36 km, 12 x 12 km grid, or 4 x 4 km. As the precipitation monitoring sites tend to be located at lower elevations (e.g., air ports), the CPC analysis fields may not capture the enhanced precipitation at high elevations due to orographic effects that could be present in the WRF simulations.

Monthly total precipitation comparisons for the 36 km domain are presented in Figure 3-8 through 3-29. For each month, the first plot presents the CPC analysis data (e.g., Figure 3-8 for January) and the second plot represents the WRF total precipitation (e.g., Figure 3-9 for January). If the CPC analysis data are considered to be the standard for precipitation, WRF provides a reasonable representation of the spatial distribution of precipitation over the contiguous U.S. for all months of 2008. However, the magnitude and spatial extent of the precipitation is occasionally higher in WRF simulations than in the CPC analysis fields, particularly for June and July in the southeast.

Monthly total precipitation comparisons for the 12 km domain are presented in Figures 3-32 through 3-55. As with the 36 km WRF results, the WRF 12 km simulation tends to accurately represent the spatial extent of the CPC precipitation fields. The refinement of the 12 km grid size is obvious when comparing to the 36 km results as the 12 km results have somewhat more structure. The tendency is for the WRF precipitation data to have a smaller, better defined footprint than the CPC data, which are at the 40 km by 40 km spacing. Features that influence precipitation events, like terrain, appear better defined in the WRF data where terrain elevations are considered. As with the 36 km results, the WRF model is tending to overestimate precipitation during the summer months (i.e. June in central Montana; July and August in Colorado)

Monthly total precipitation comparisons for the 4 km domain are presented in Figure 3-56 through Figure 3-79. The 4 km WRF results are again showing greater structure than the ~25 km CPC analysis fields. WRF is tending to overestimate somewhat both the spatial extent of the precipitation in March and April and overestimate the precipitation amount in June, but on the whole, the model is doing a reasonable job estimating the precipitation.

3.3 Summary of Model Performance Evaluation

Temperature bias and error statistics, mixing ratio bias and error statistics, wind direction bias and error, and wind speed bias and RMSE statistics were estimated for the WRF model predictions on the 36 km, 12 km, and 4 km modeling domains and numerous subdomains, including RPOs, individual states and the various 4 km DSAD and IAD 4 km modeling domains that will be used in the WestJumpAQMS

18 Latitude/longitude coordinate system is an irregular grid with a 0.25 by 0.25 degree grid corresponding to a grid resolution of 18 to 28 km over the U.S.

modeling study. Further, a qualitative examination of model predicted precipitation was performed for the 36, 12 and 4 km modeling domains.

The temperature bias and error met the complex (long term) temperature bias and error goals for each of the 36 km, 12 km, and 4 km domains as a whole and for each of the RPO subregions.

Likewise, the model also showed skill in accurately estimating water vapor mixing ratio. Averaged by month for all the model grids the model was within the simple (episodic) benchmarks for all domains and months.

The model showed skill in regards to the wind direction. On the 36 km, 12 km and 4 km grids the model was well within the wind direction bias benchmark and exceeded, or was very close to the wind direction error benchmark. The model was tending to overestimate the wind speeds and exceeded the wind speed RMSE and benchmarks.

Finally, from a qualitative perspective, the model does a reasonable job of replicating the areal extent and the amount of rainfall in the 36 km, 12 km, and 4 km grids, with a tendency to perhaps overestimate the precipitation in the summer months.

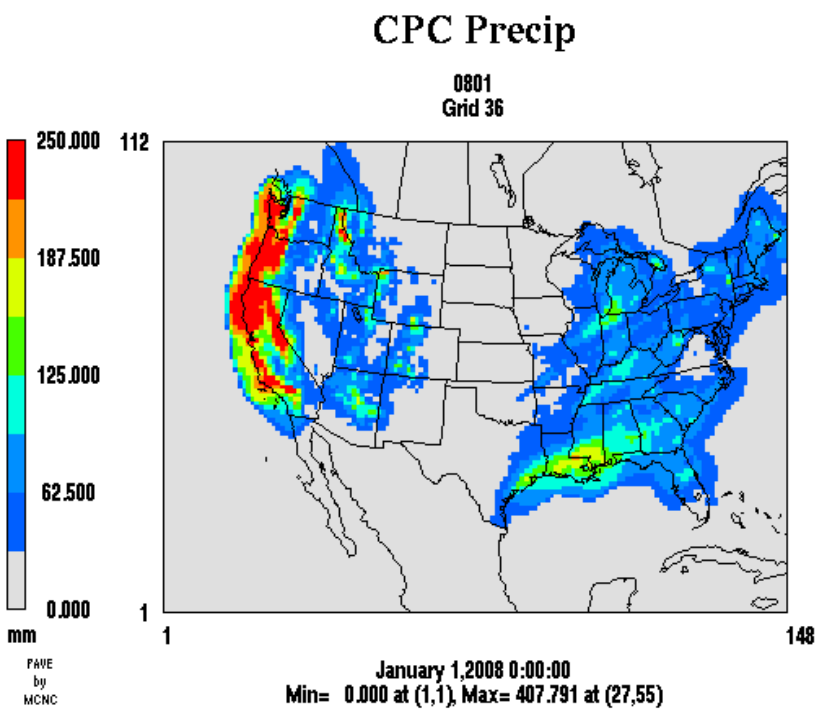


Figure 3-8. CPC Analyzed Precipitation for January 2008 over the 36 km Domain.

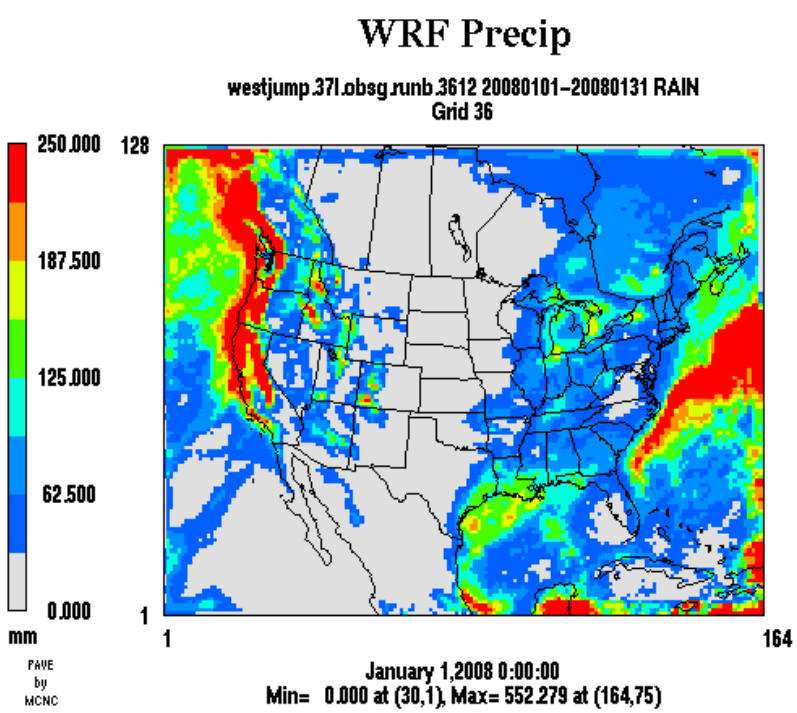


Figure 3-9. WRF Estimated Precipitation for January 2008 over the 36 km Domain.

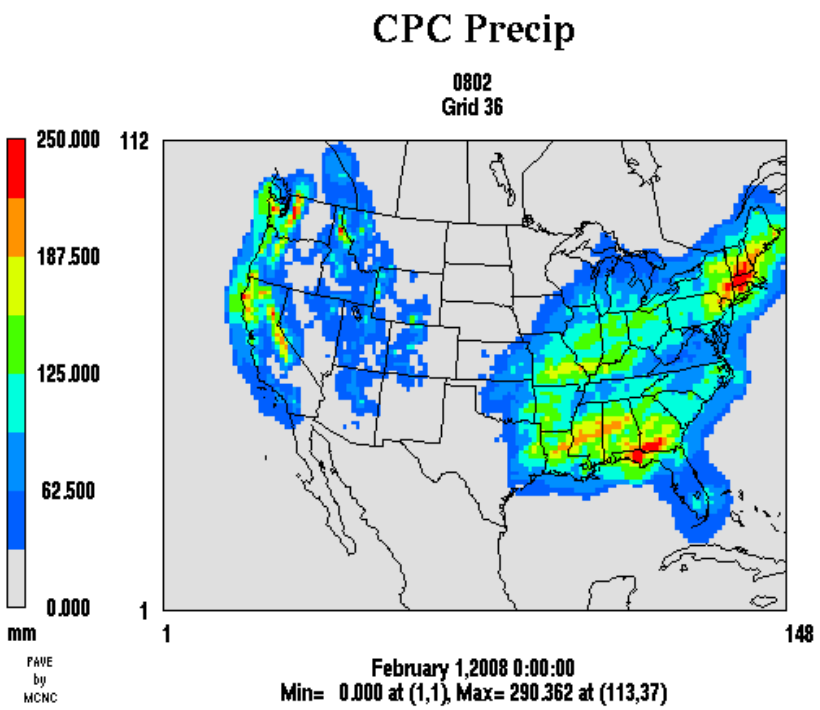


Figure 3-10. CPC Analyzed Precipitation for February 2008 over the 36 km Domain.

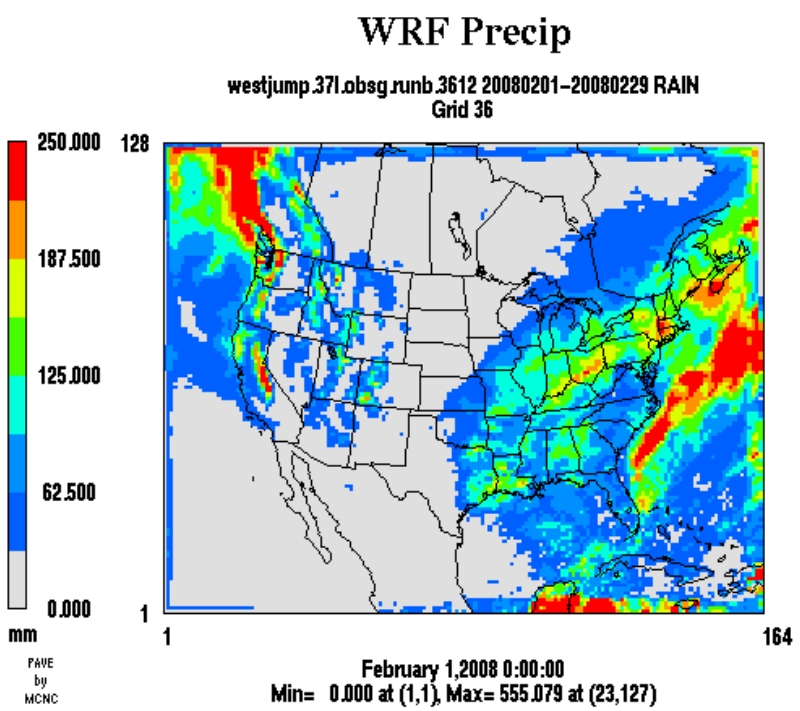


Figure 3-11. WRF Estimated Precipitation for February 2008 over the 36 km Domain.

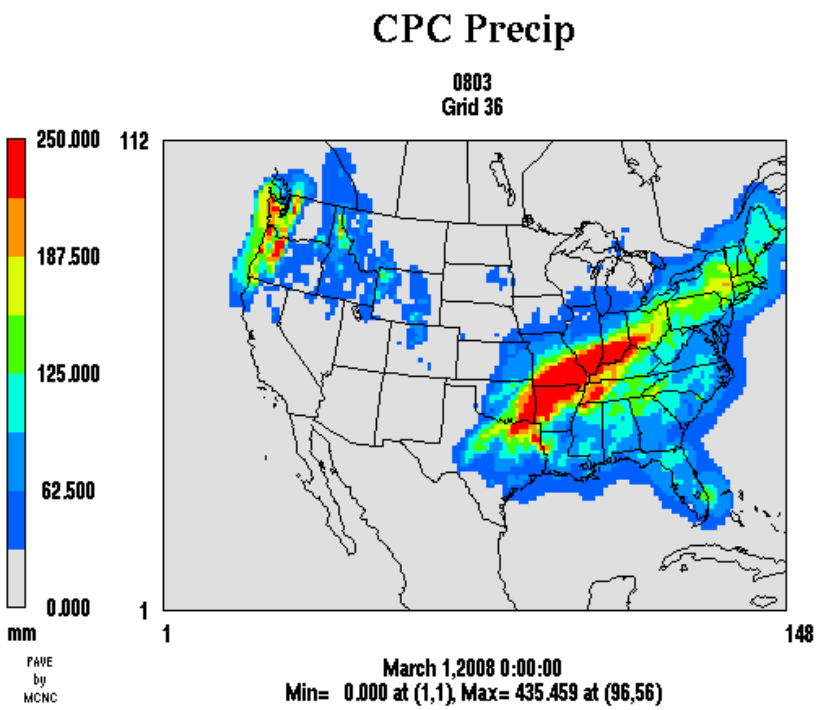


Figure 3-12. CPC Analyzed Precipitation for March 2008 over the 36 km Domain.

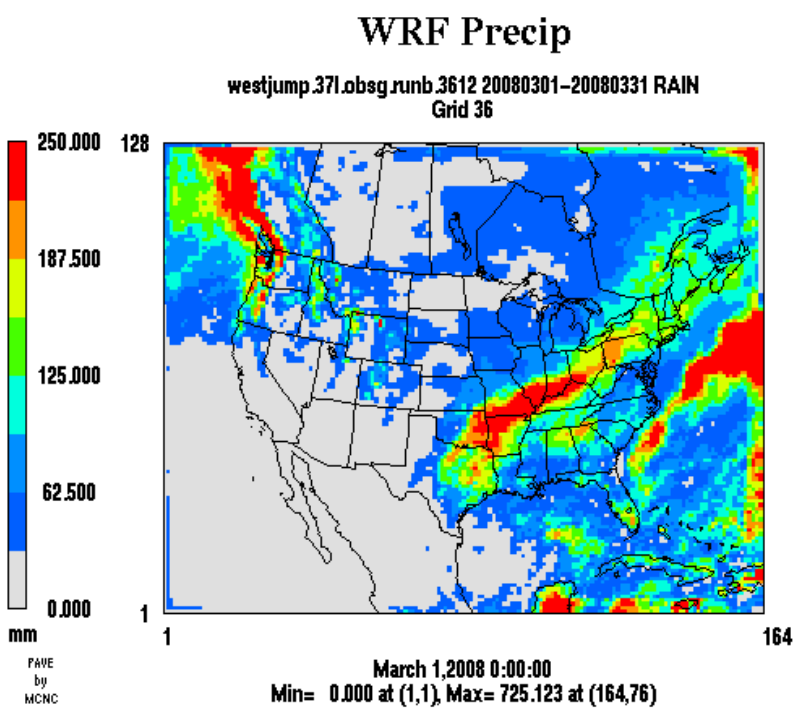


Figure 3-13. WRF Estimated Precipitation for March 2008 over the 36 km Domain.

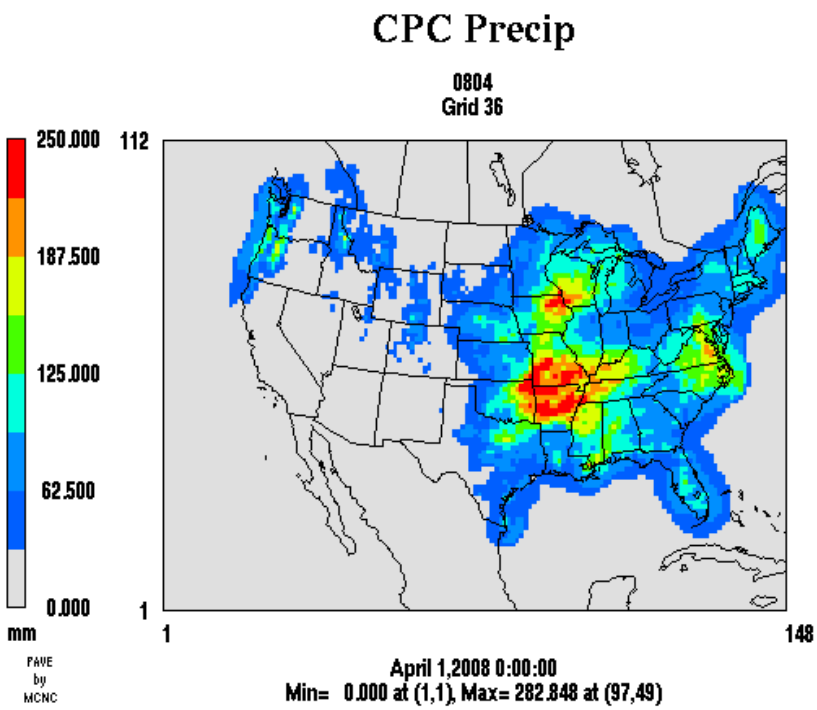


Figure 3-14. CPC Analyzed Precipitation for April 2008 over the 36 km Domain.

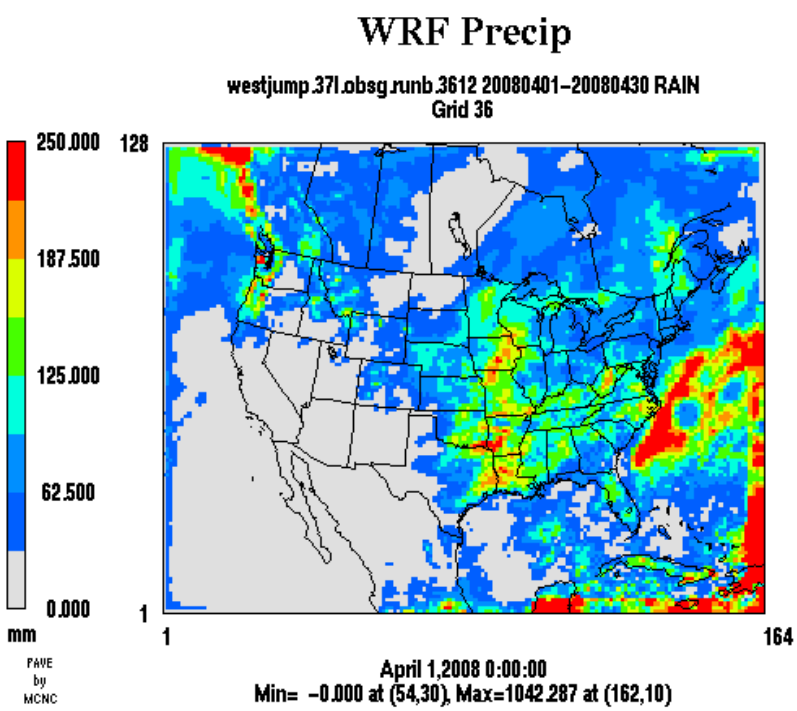


Figure 3-15. WRF Estimated Precipitation for April 2008 over the 36 km Domain.

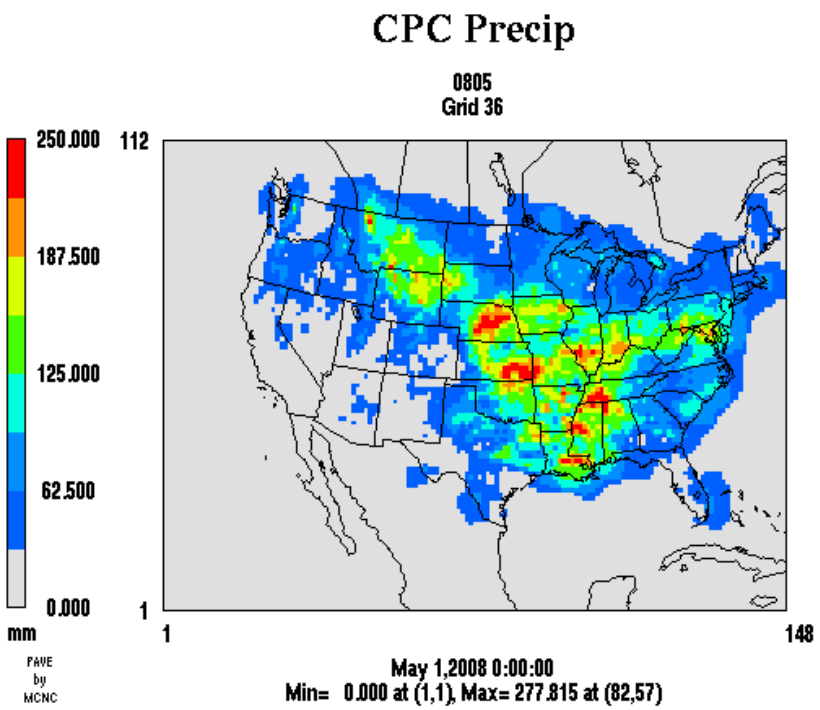


Figure 3-16. CPC Analyzed Precipitation for May 2008 over the 36 km Domain.

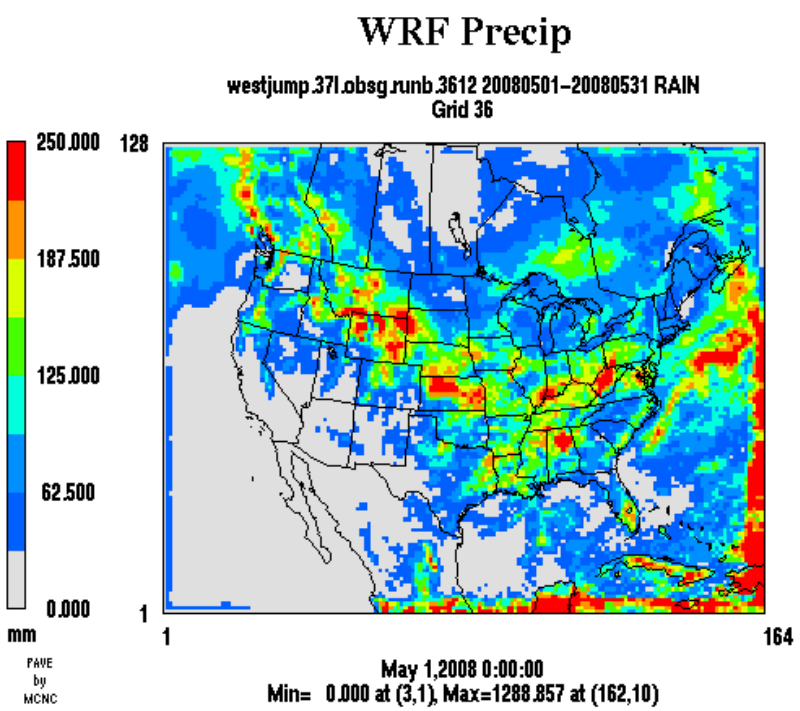


Figure 3-17. WRF Estimated Precipitation for May 2008 over the 36 km Domain.

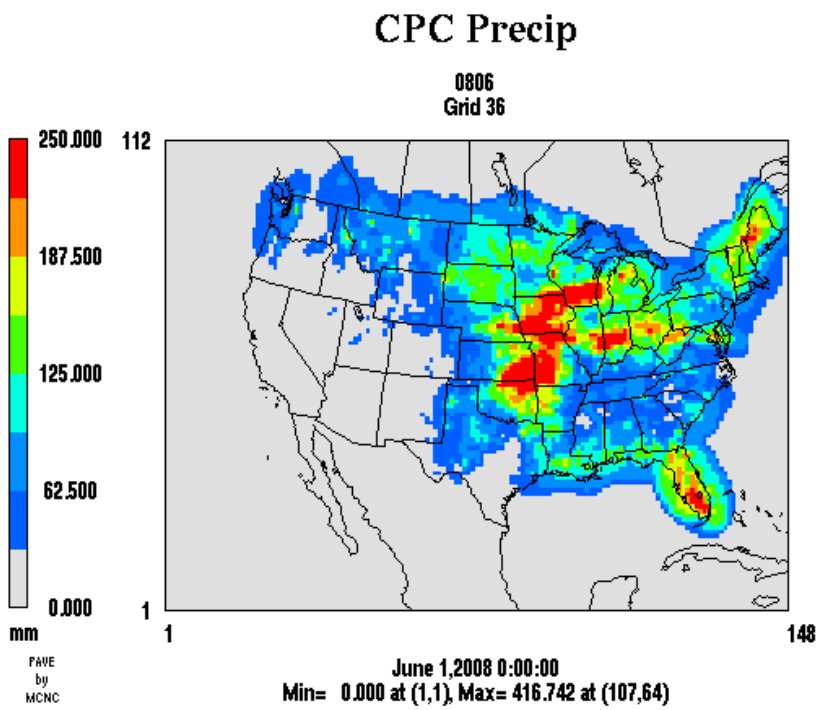


Figure 3-18. CPC Analyzed Precipitation for June 2008 over the 36 km Domain.

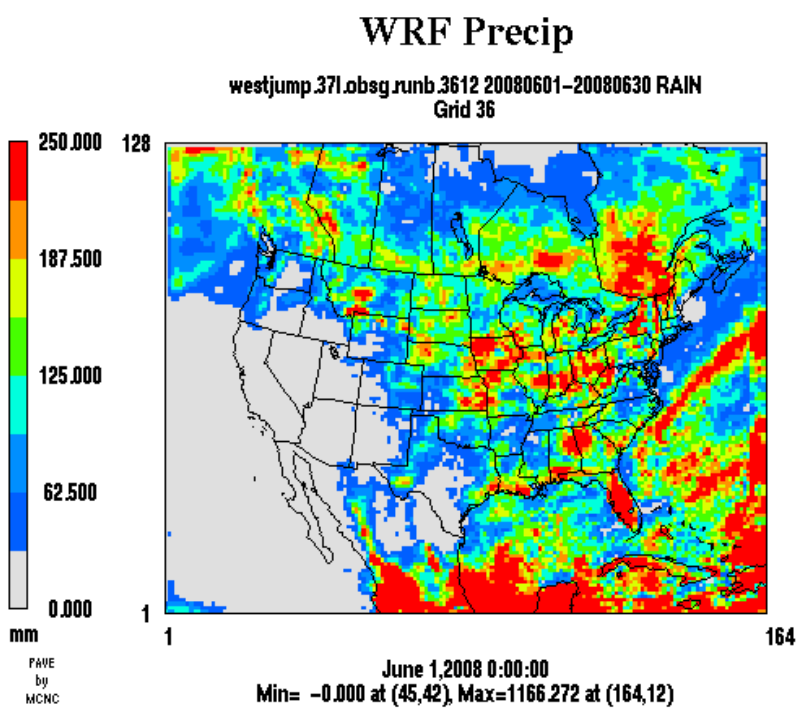


Figure 3-19. WRF Estimated Precipitation for June 2008 over the 36 km Domain.

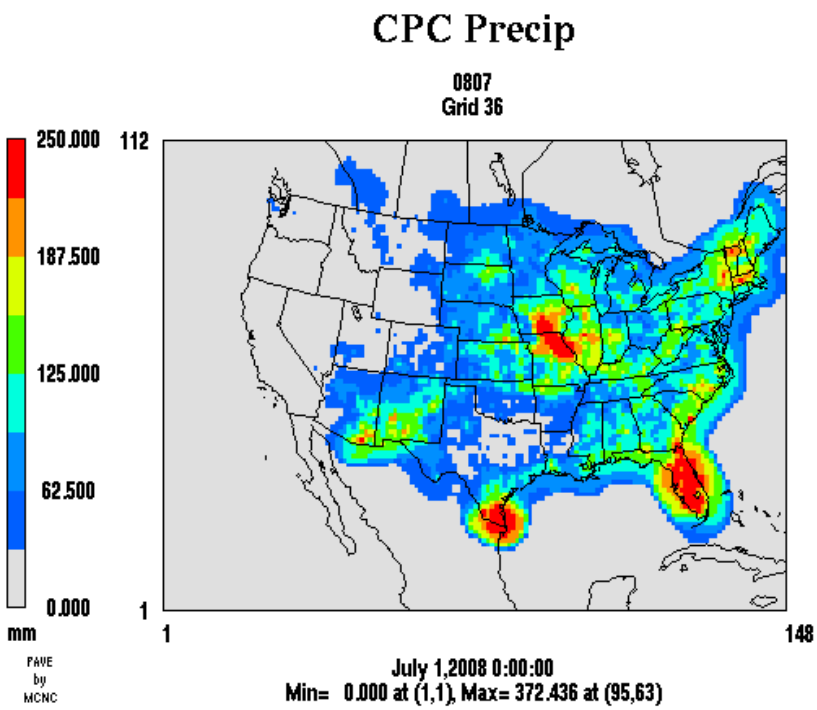


Figure 3-20. CPC Analyzed Precipitation for July 2008 over the 36 km Domain.

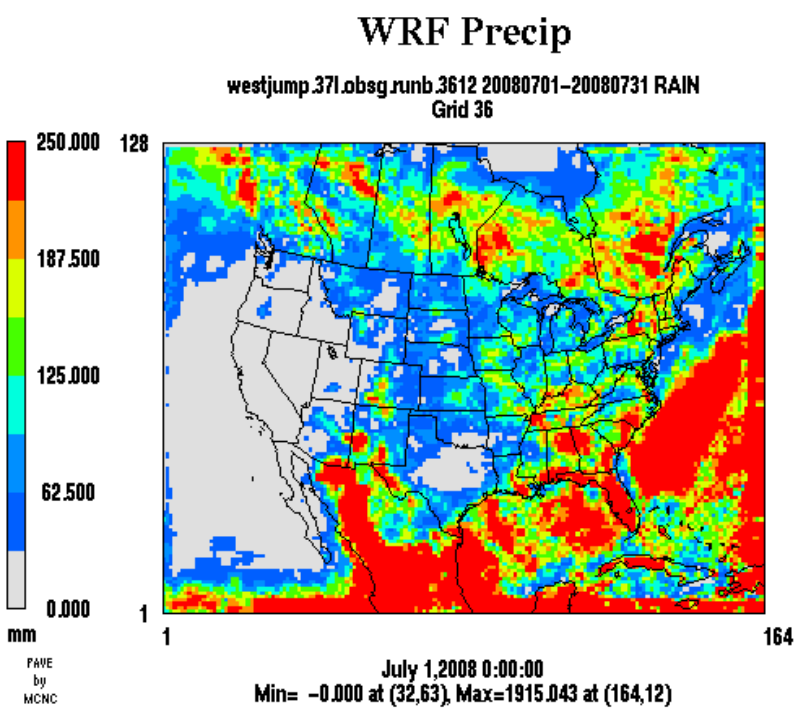


Figure 3-21. WRF Estimated Precipitation for July 2008 over the 36 km Domain.

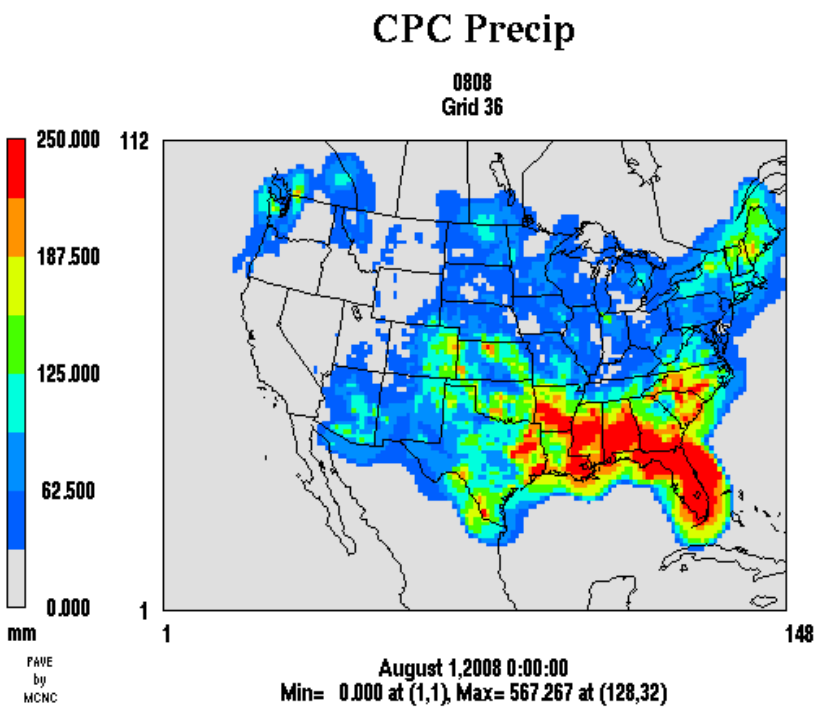


Figure 3-22. CPC Analyzed Precipitation for August 2008 over the 36 km Domain.

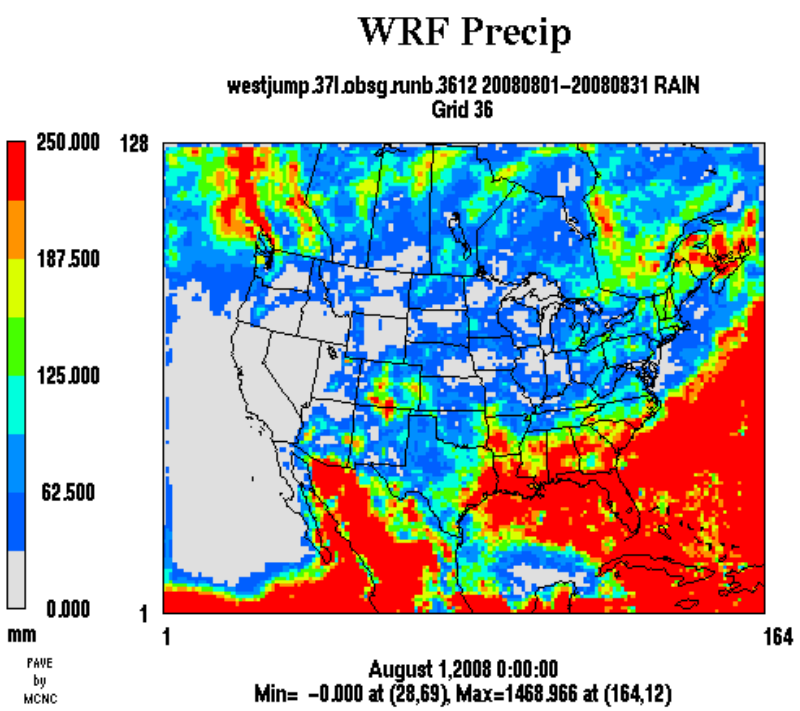


Figure 3-23. WRF Estimated Precipitation for August 2008 over the 36 km Domain.

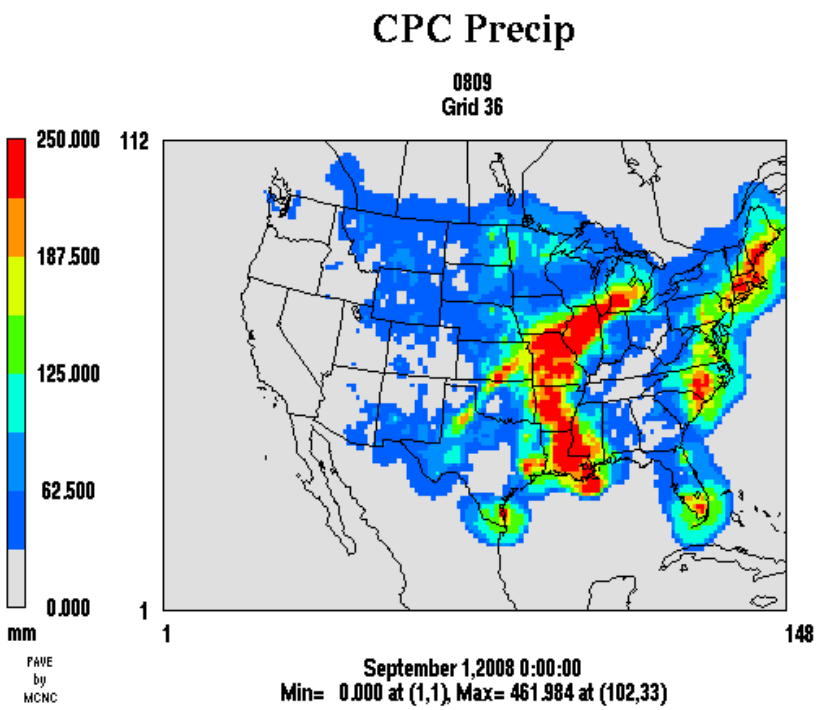


Figure 3-24. CPC Analyzed Precipitation for September 2008 over the 36 km Domain.

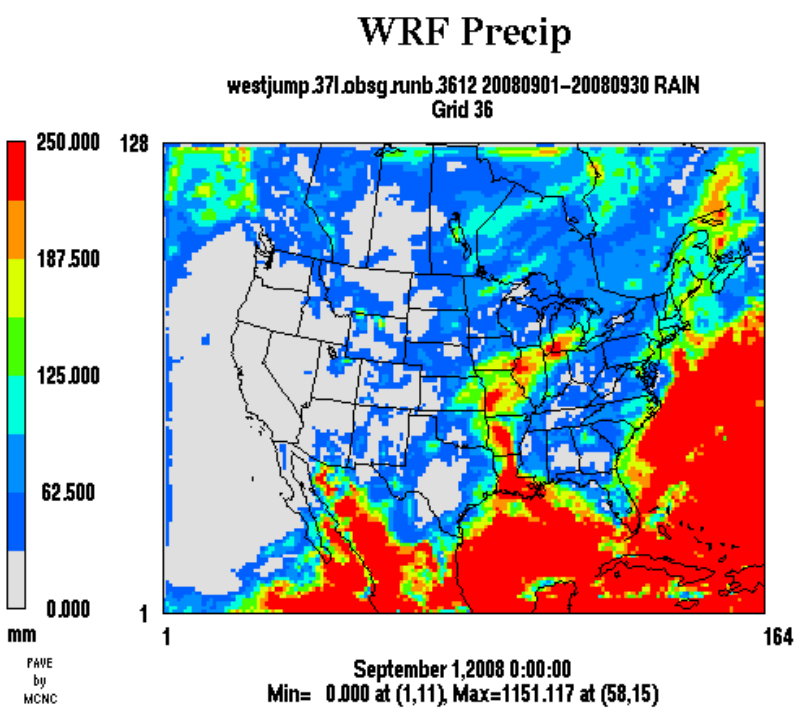


Figure 3-25. WRF Estimated Precipitation for September 2008 over the 36 km Domain.

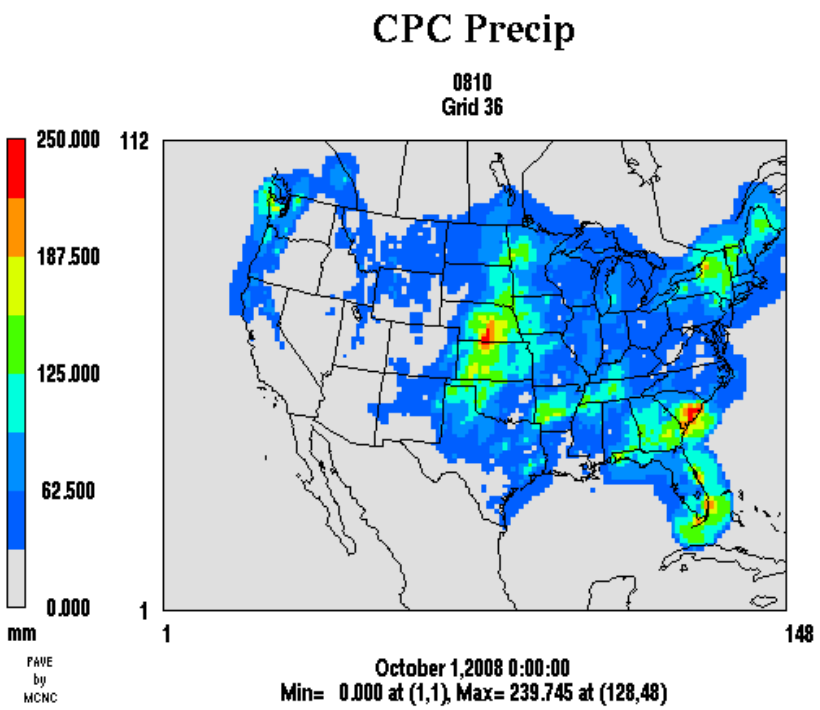


Figure 3-26. CPC Analyzed Precipitation for October 2008 over the 36 km Domain.

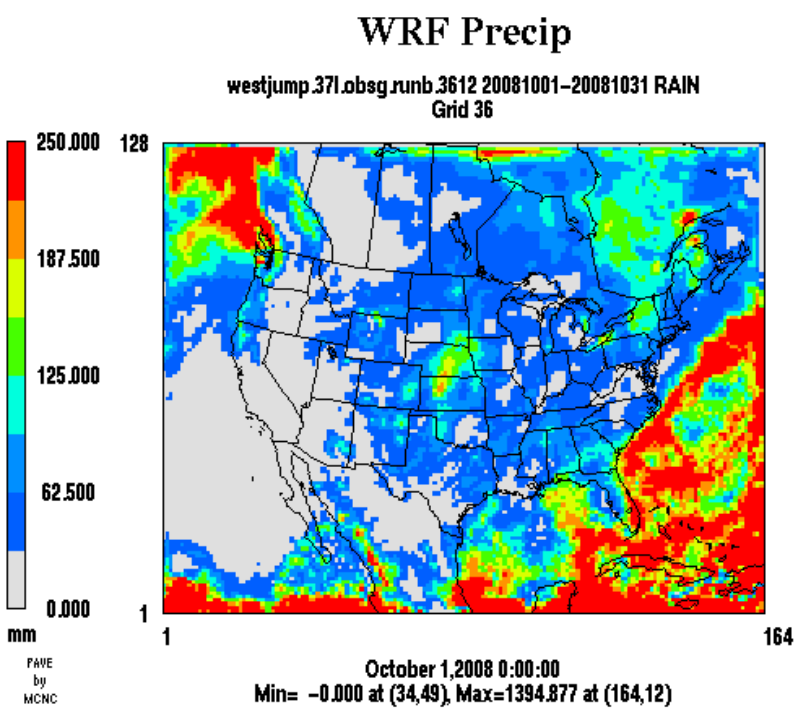


Figure 3-27. WRF Estimated Precipitation for October 2008 over the 36 km Domain.

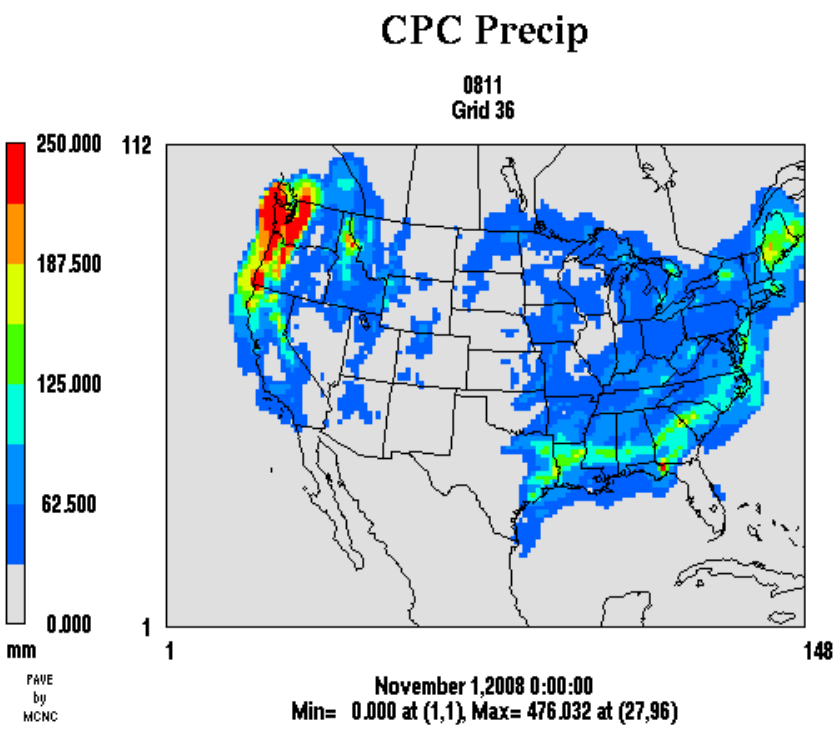


Figure 3-28. CPC Analyzed Precipitation for November 2008 over the 36 km Domain.

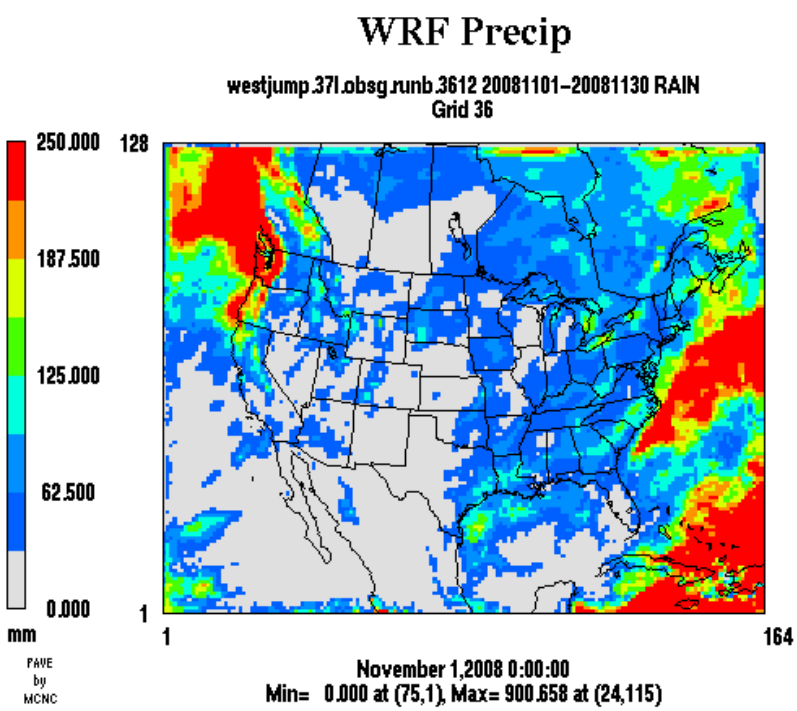


Figure 3-29. WRF Estimated Precipitation for November 2008 over the 36 km Domain.

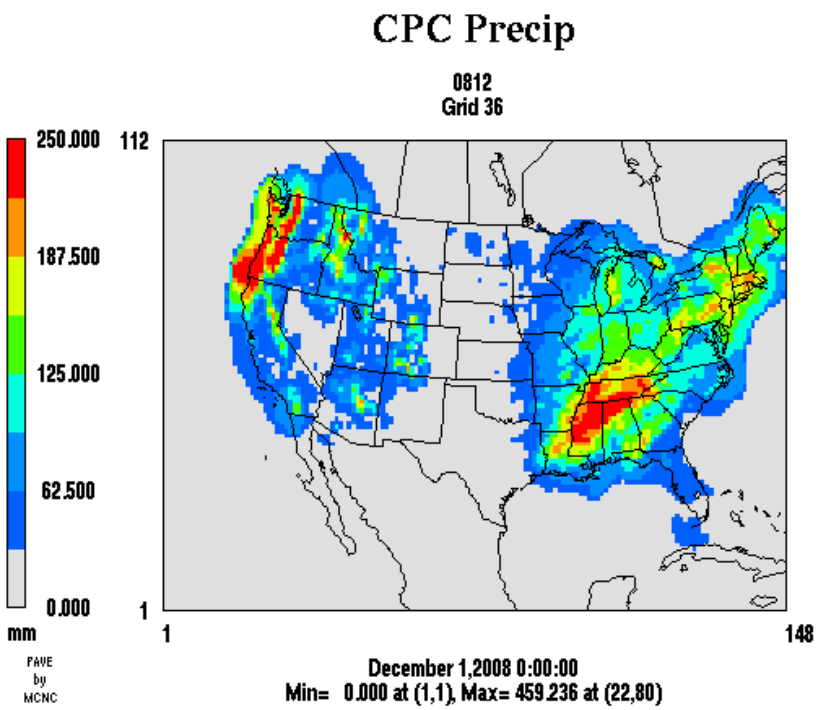


Figure 3-30. CPC Analyzed Precipitation for December 2008 over the 36 km Domain.

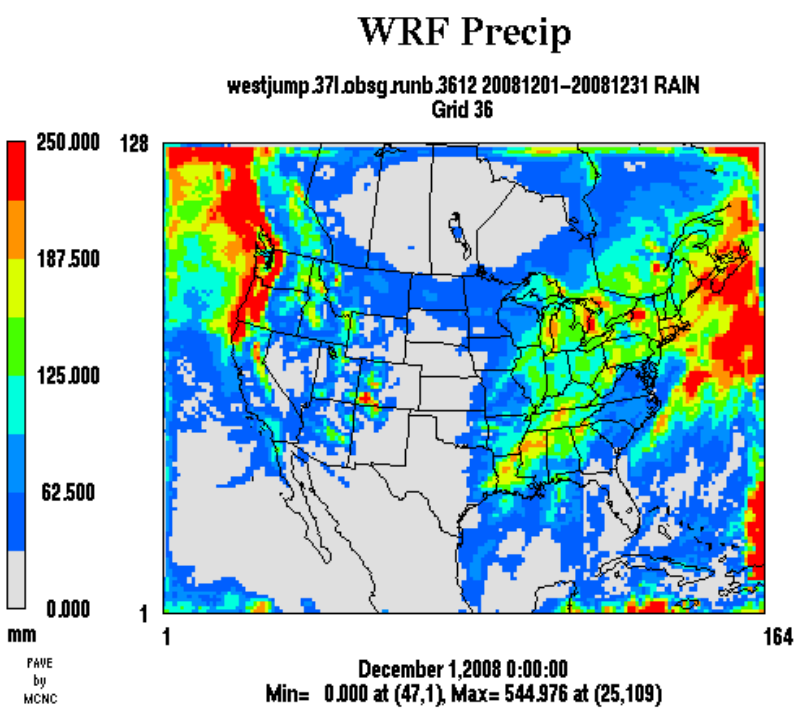


Figure 3-31. WRF Estimated Precipitation for December 2008 over the 36 km Domain.

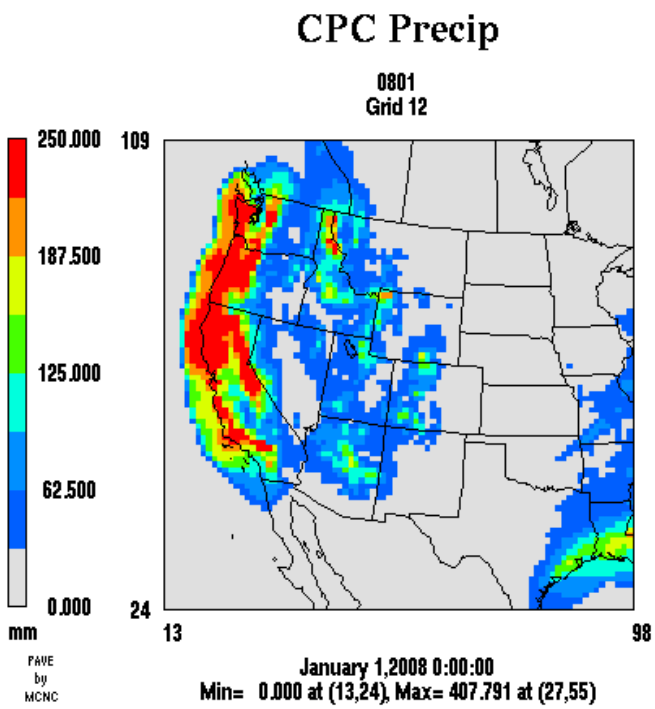


Figure 3-32. CPC Analyzed Precipitation for January 2008 over the 12 km Domain.

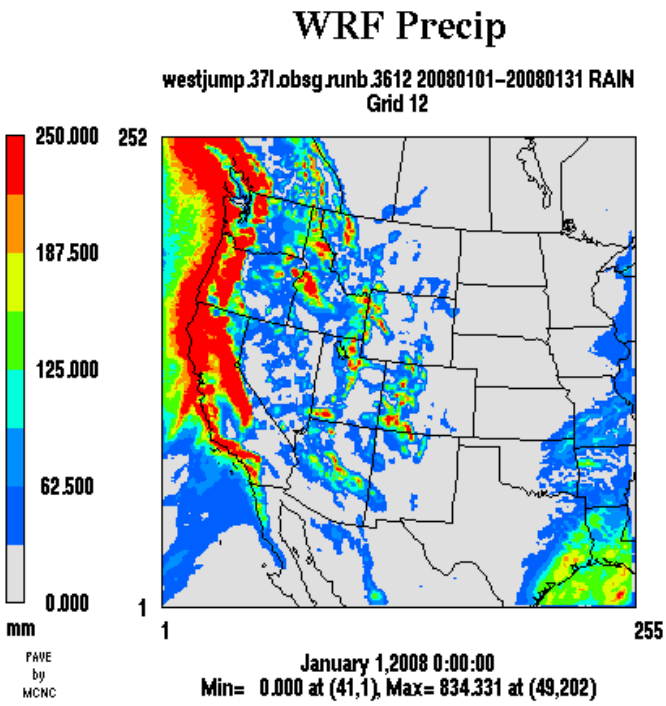


Figure 3-33. WRF Estimated Precipitation for January 2008 over the 12 km Domain.

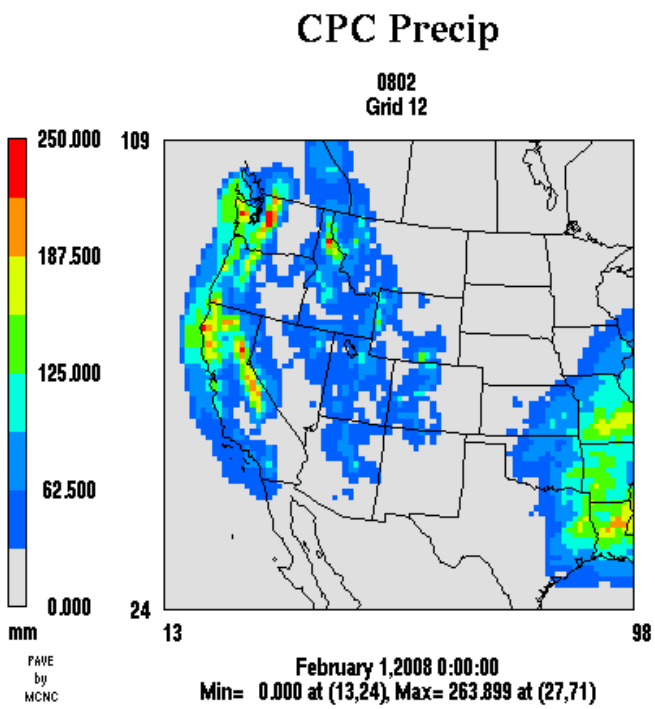


Figure 3-34. CPC Analyzed Precipitation for February 2008 over the 12 km Domain.

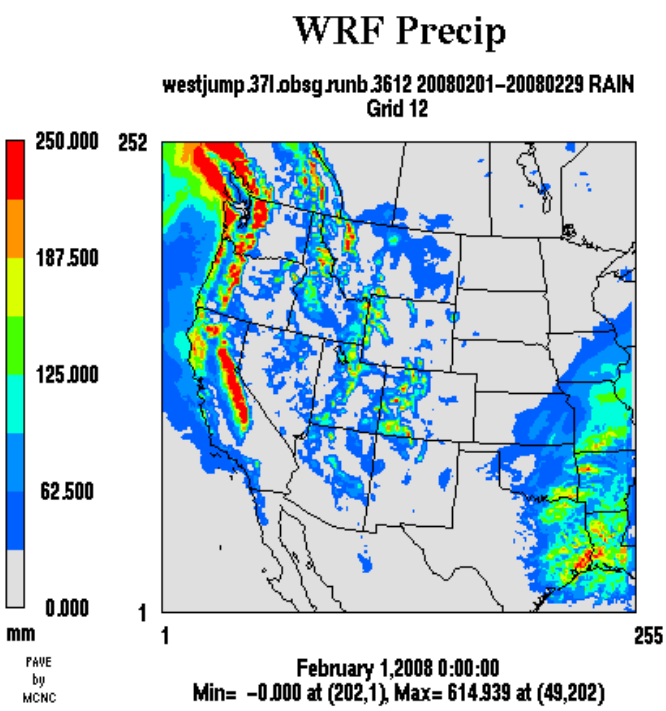
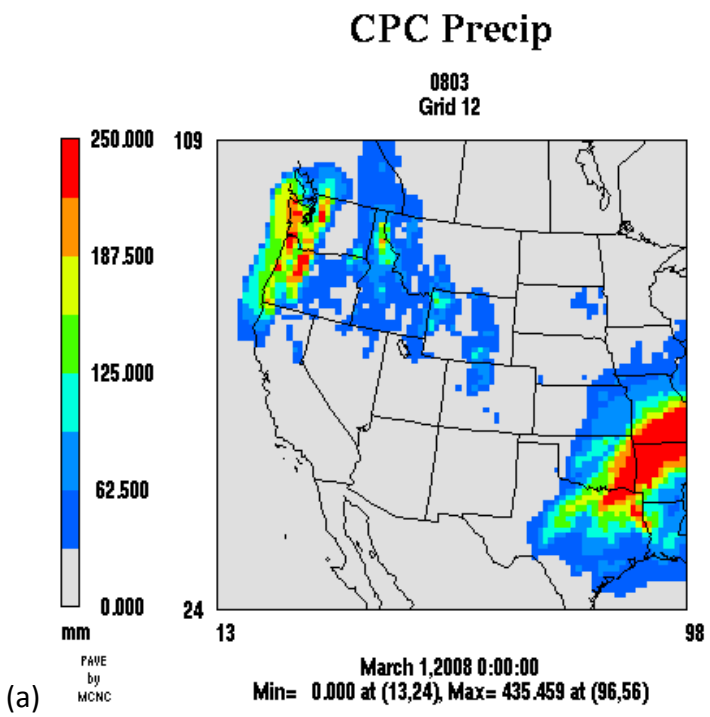


Figure 3-35. WRF Estimated Precipitation for February 2008 over the 12 km Domain.



(a)

Figure 3-36. CPC Analyzed Precipitation for March 2008 over the 12 km Domain.

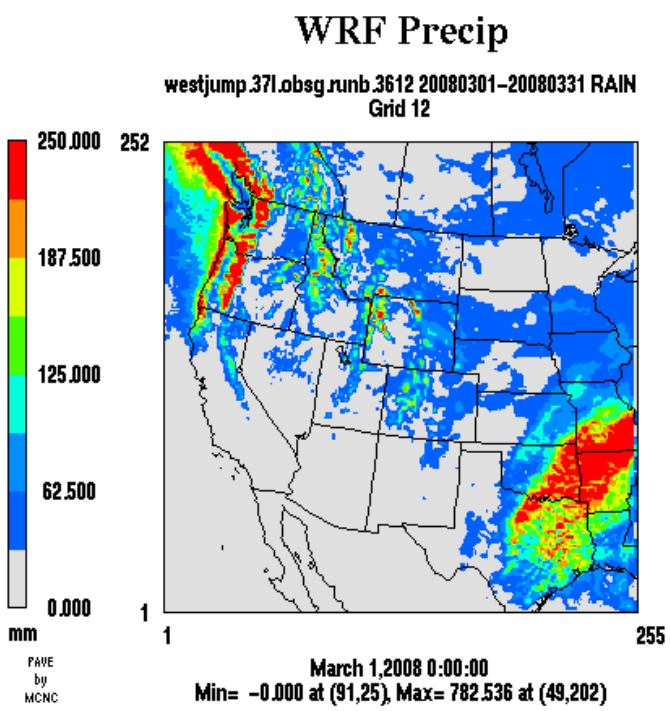


Figure 3-37. WRF Estimated Precipitation for March 2008 over the 12 km Domain.

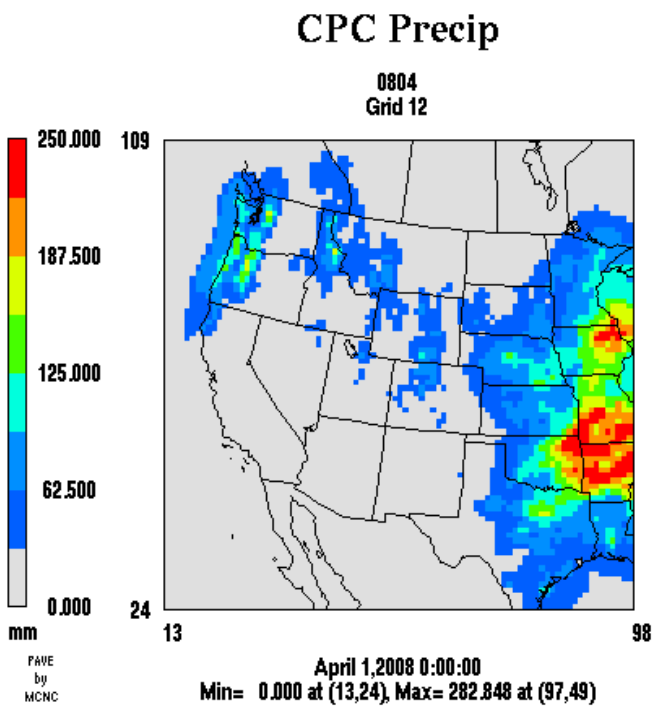


Figure 3-38. CPC Analyzed Precipitation for April 2008 over the 12 km Domain.

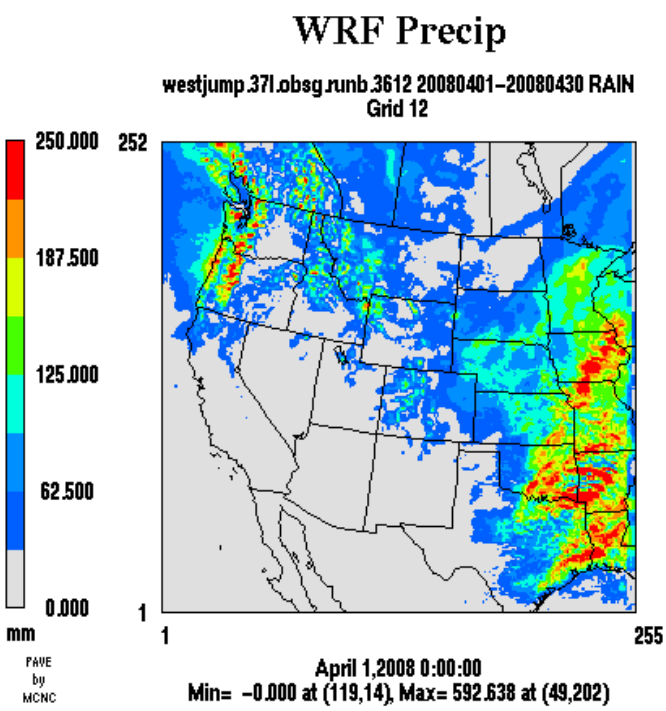


Figure 3-39. WRF Estimated Precipitation for April 2008 over the 12 km Domain.

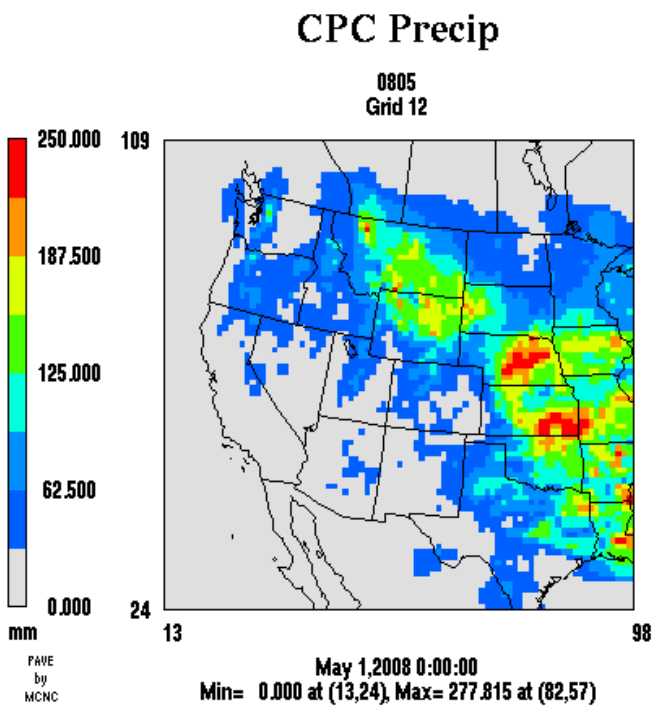


Figure 3-40. CPC Analyzed Precipitation for May 2008 over the 12 km Domain.

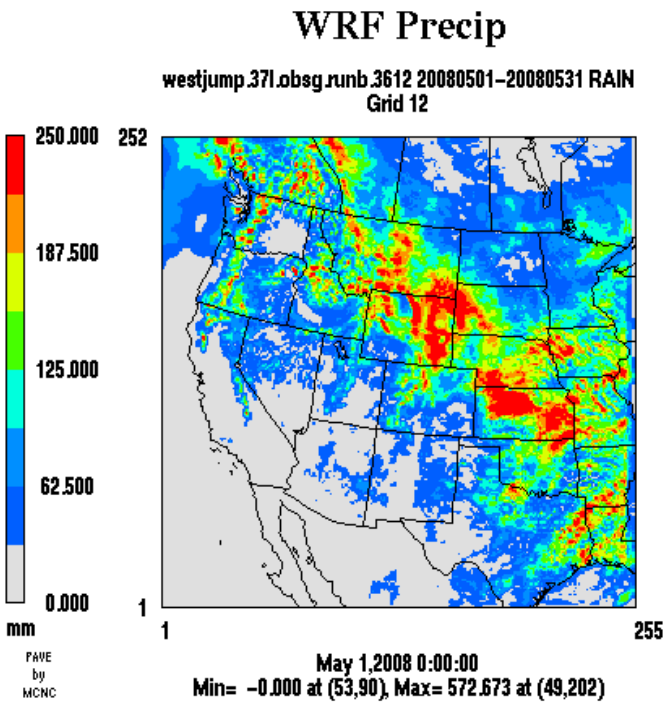


Figure 3-41. WFF Estimated Precipitation for May 2008 over the 12 km Domain.

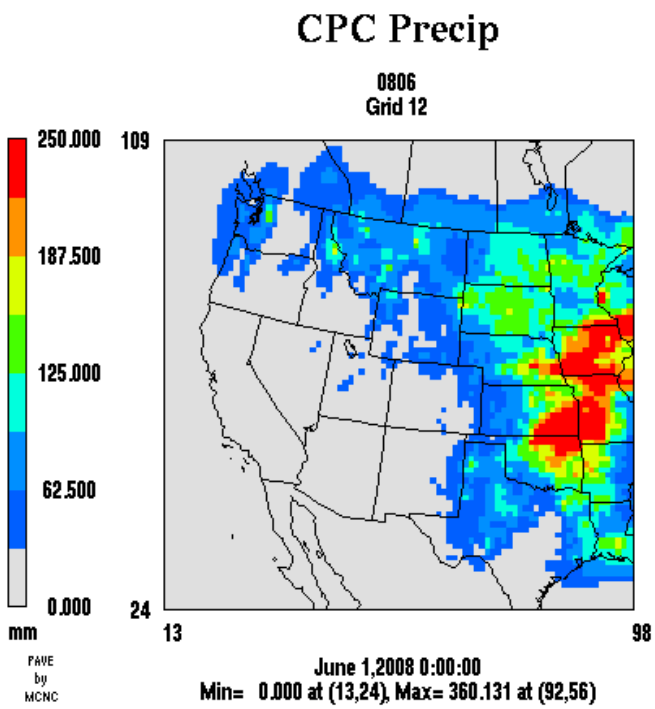


Figure 3-42. CPC Analyzed Precipitation for June 2008 over the 12 km Domain.

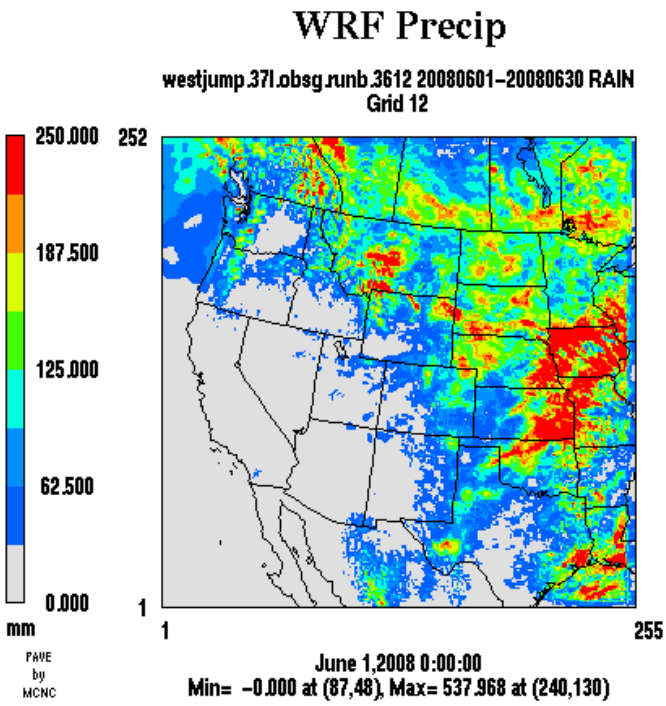


Figure 3-43. WRF Estimated Precipitation for June 2008 over the 12 km Domain.

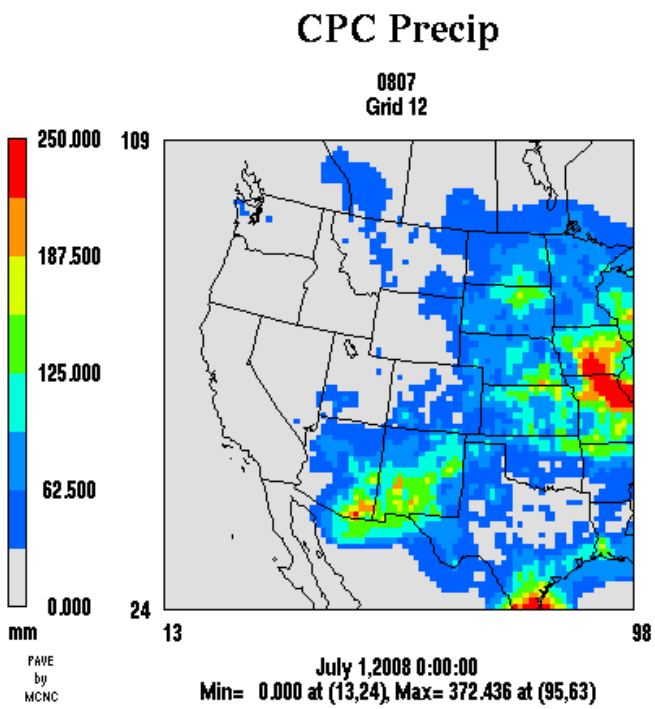


Figure 3-44. CPC Analyzed Precipitation for July 2008 over the 12 km Domain.

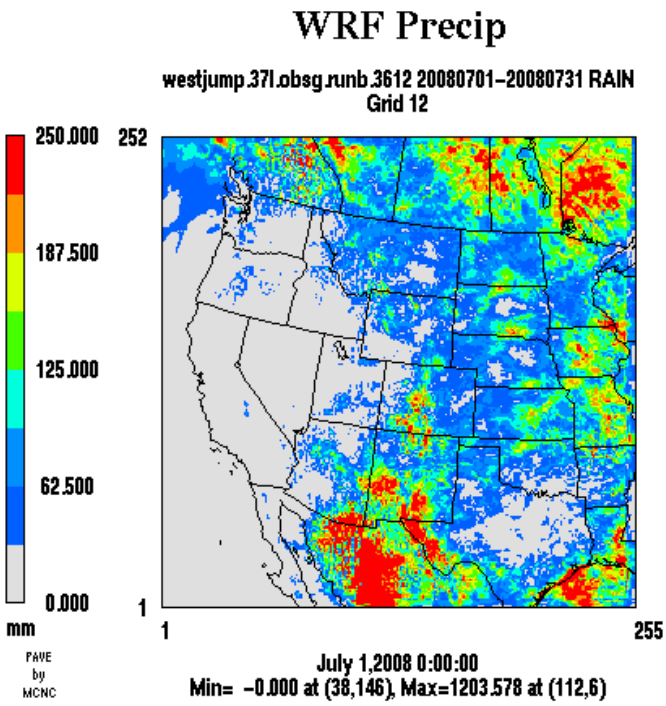


Figure 3-45. WRF Estimated Precipitation for July 2008 over the 12 km Domain.

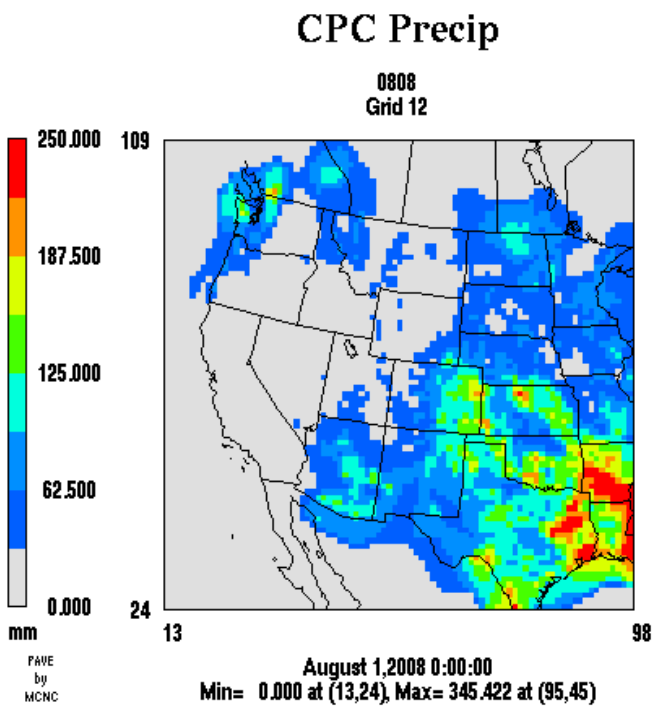


Figure 3-46. CPC Analyzed Precipitation for August 2008 over the 12 km Domain.

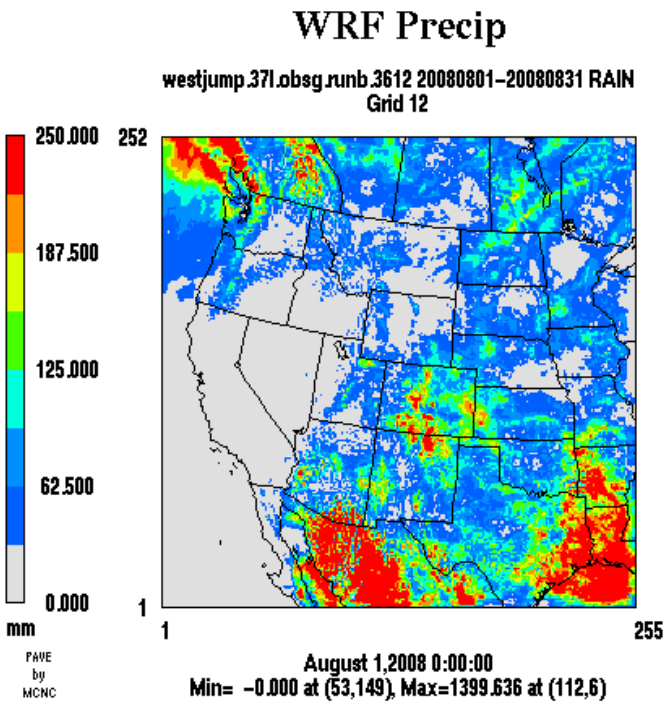


Figure 3-47. WRF Estimated Precipitation for August 2008 over the 12 km Domain.

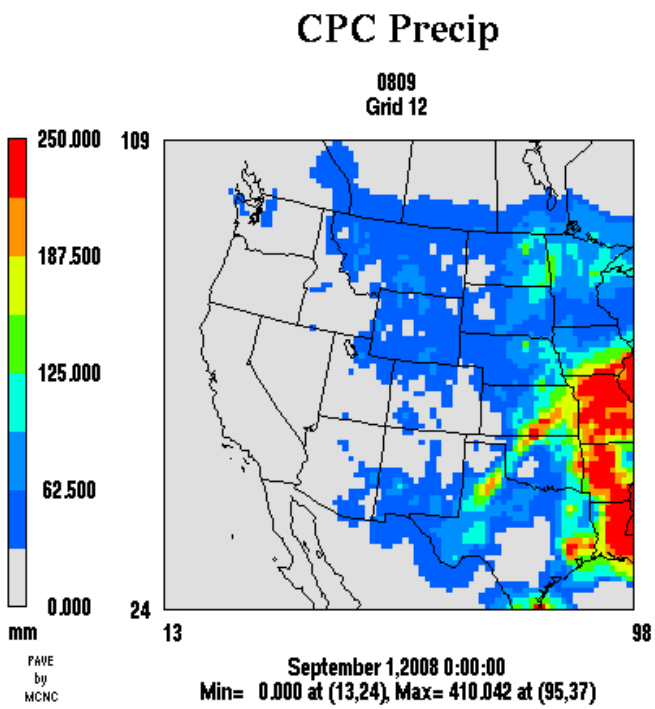


Figure 3-48. CPC Analyzed Precipitation for September 2008 over the 12 km Domain.

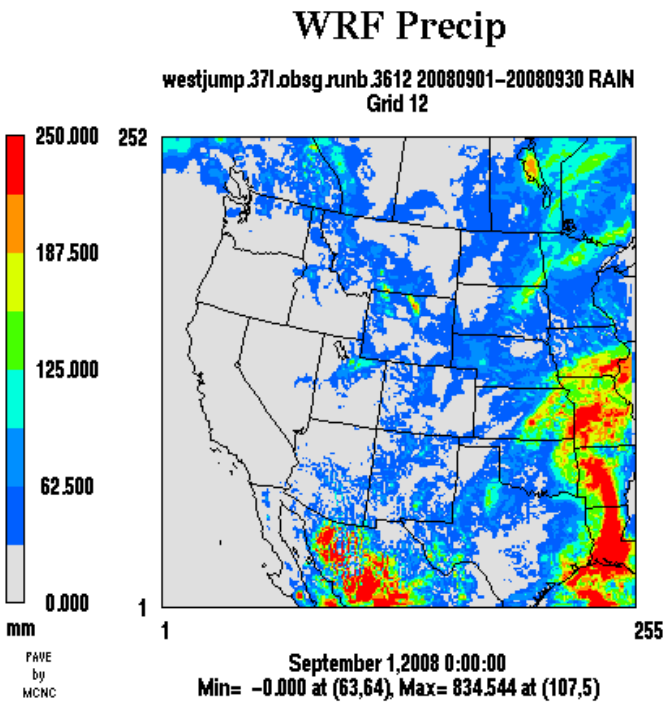


Figure 3-49. WRF Estimated Precipitation for September 2008 over the 12 km Domain.

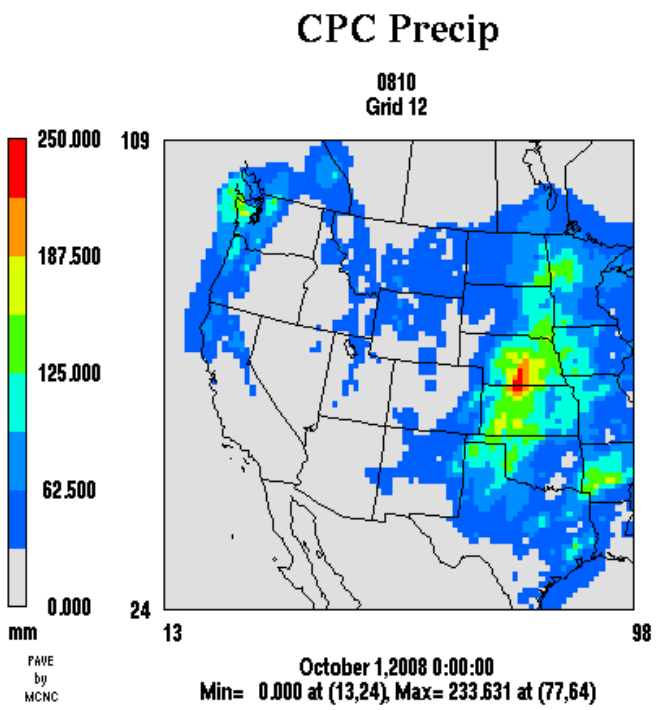


Figure 3-50. CPC Analyzed Precipitation for October 2008 over the 12 km Domain.

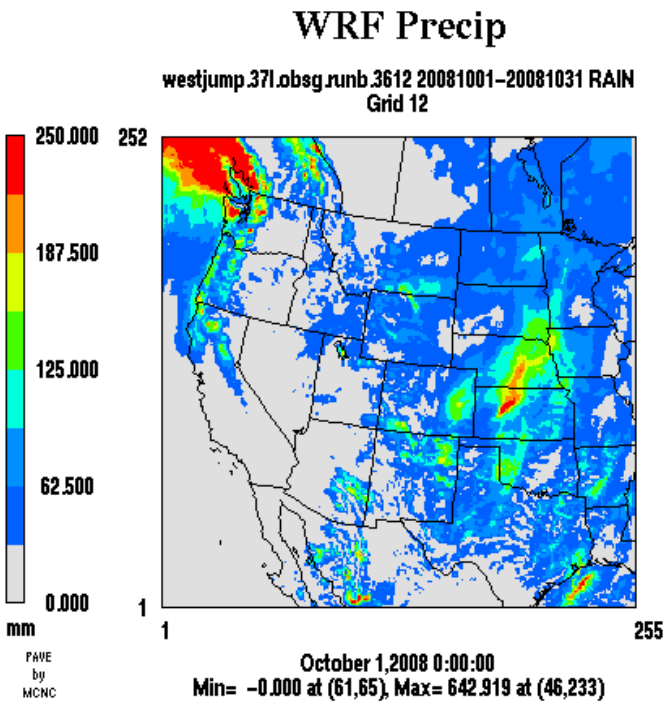


Figure 3-51. WRF Estimated Precipitation for October 2008 over the 12 km Domain.

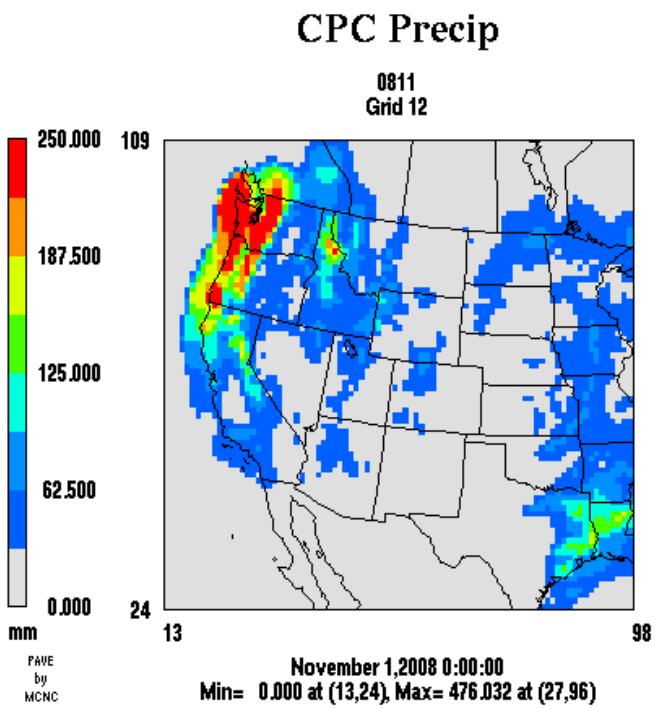


Figure 3-52. CPC Analyzed Precipitation for November 2008 over the 12 km Domain.

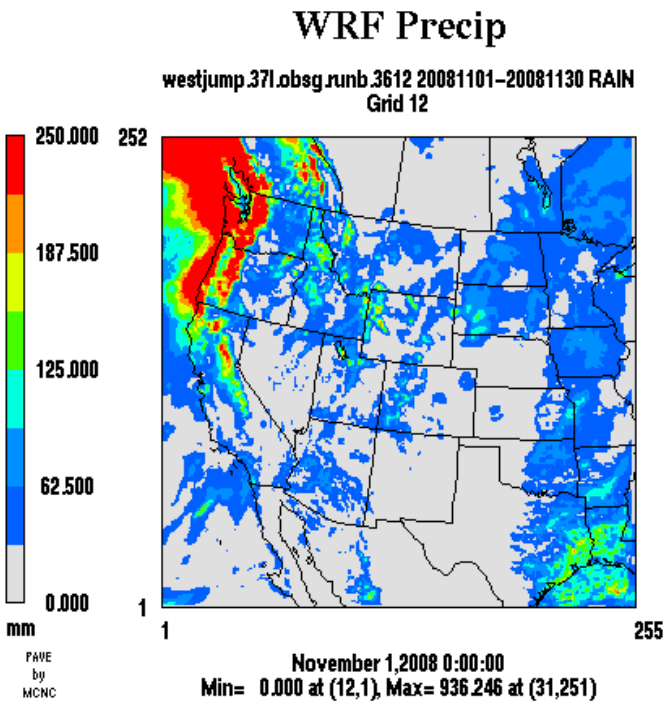


Figure 3-53. WRF Estimated Precipitation for November 2008 over the 12 km Domain.

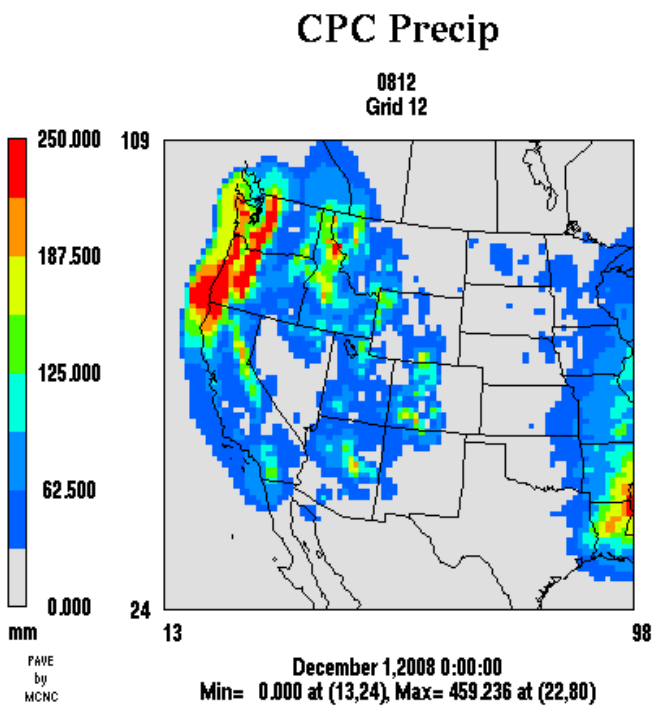


Figure 3-54. CPC Analyzed Precipitation for December 2008 over the 12 km Domain.

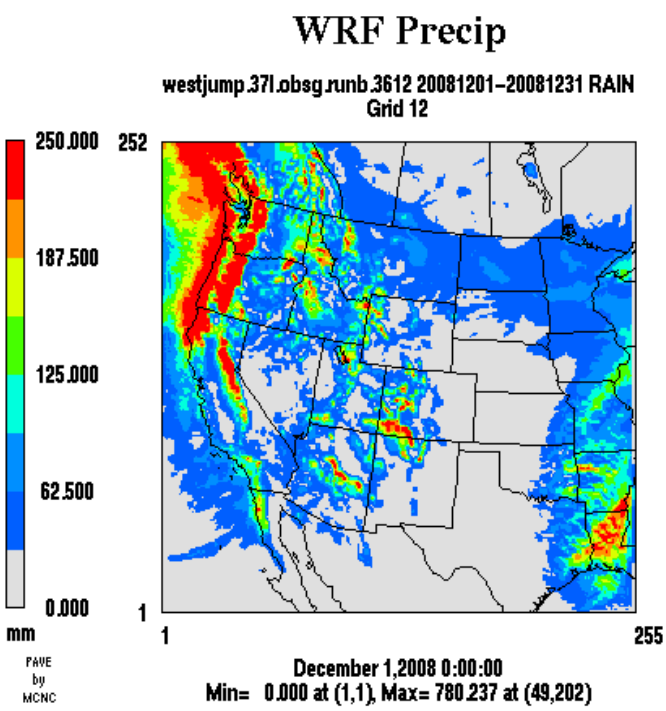


Figure 3-55. WRF Estimated Precipitation for December 2008 over the 12 km Domain.

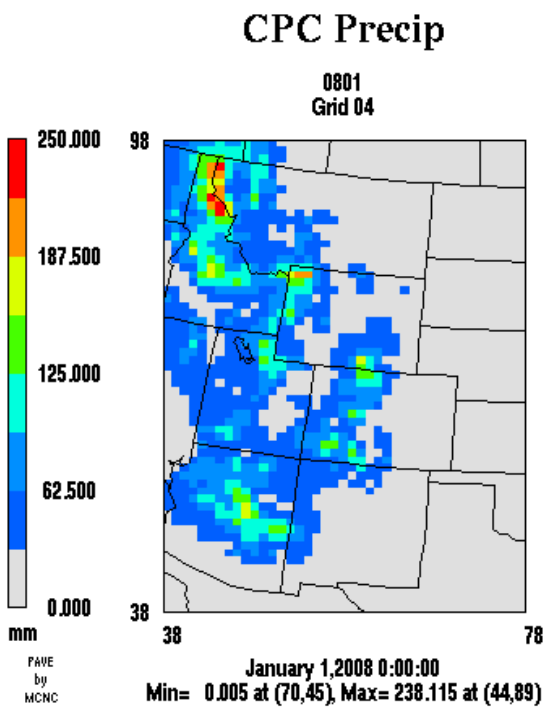


Figure 3-56. CPC Analyzed Precipitation for January 2008 over the 4 km Domain.

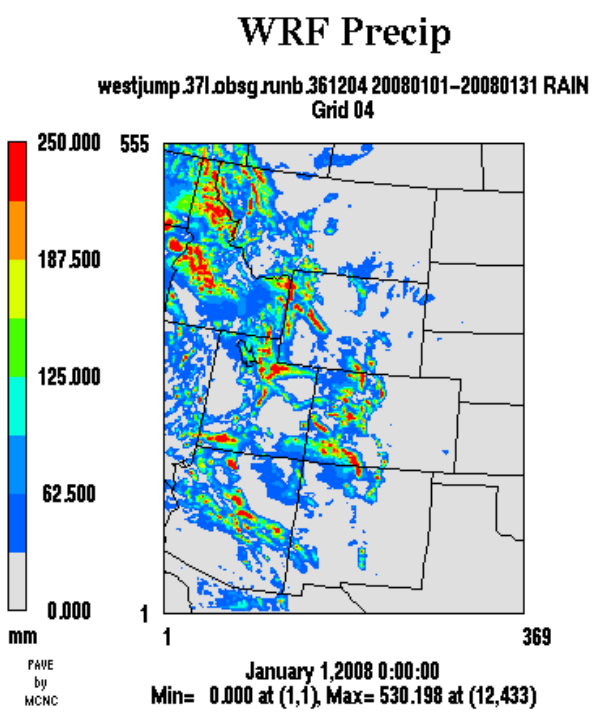


Figure 3-57. WRF Estimated Precipitation for January 2008 over the 4 km Domain.

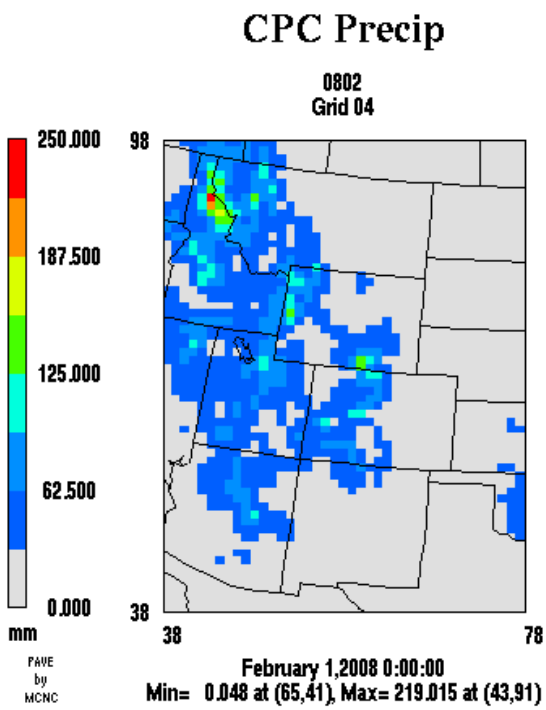


Figure 3-58. CPC Analyzed Precipitation for February 2008 over the 4 km Domain.

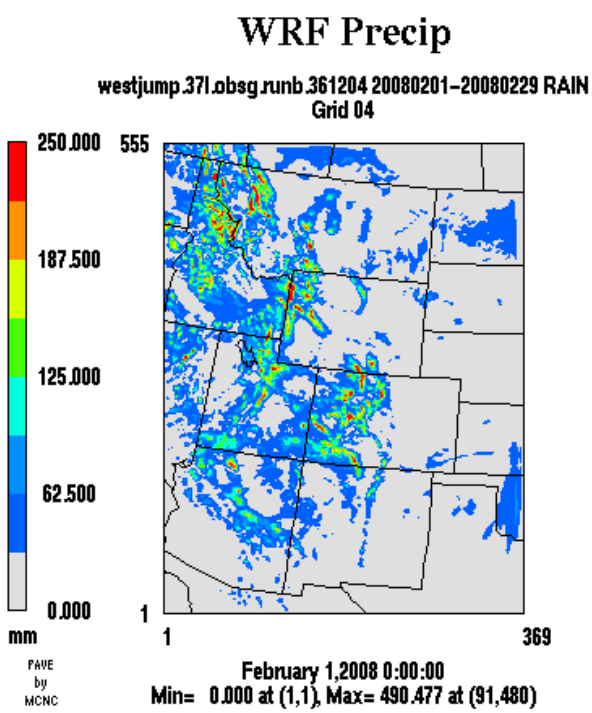


Figure 3-59. WRF Estimated Precipitation for February 2008 over the 4 km Domain.

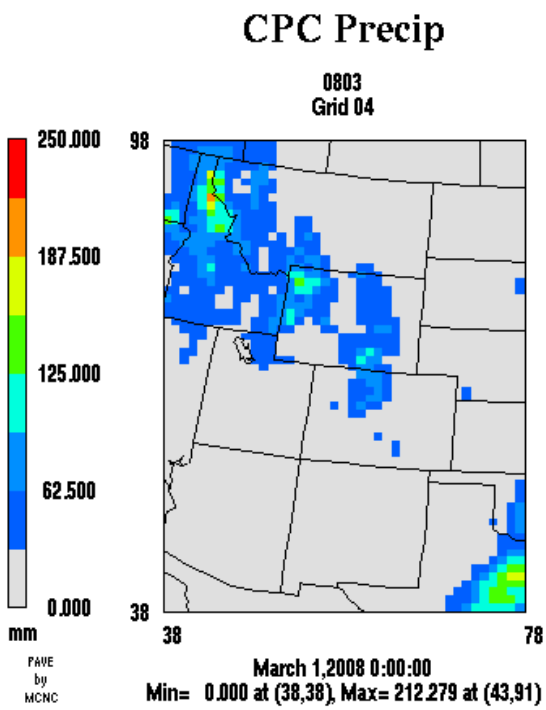


Figure 3-60. CPC Analyzed Precipitation for March 2008 over the 4 km Domain.

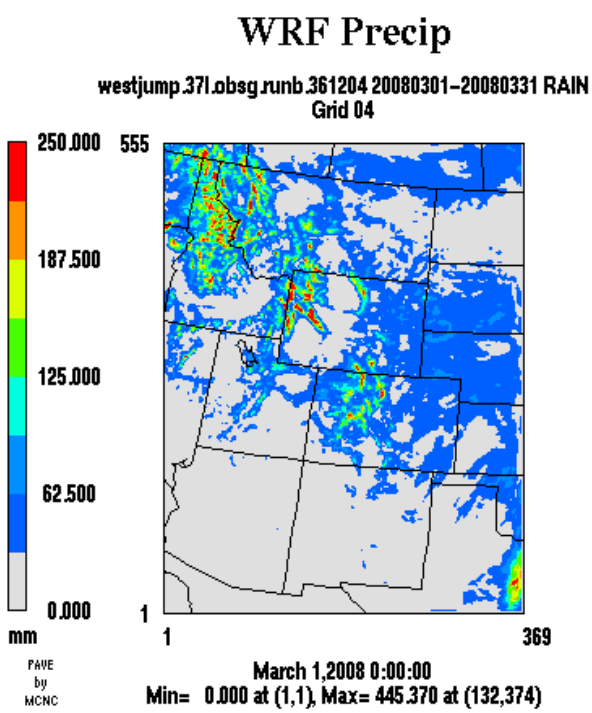


Figure 3-61. WRF Estimated Precipitation for March 2008 over the 4 km Domain.

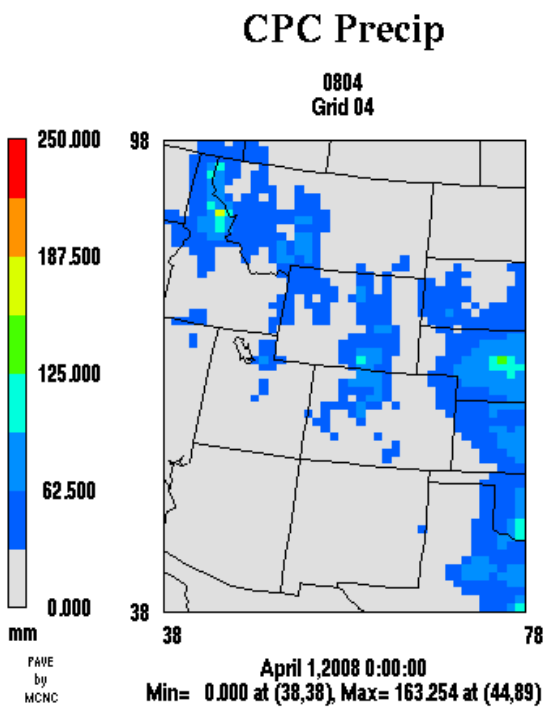


Figure 3-62. CPC Analyzed Precipitation for April 2008 over the 4 km Domain.

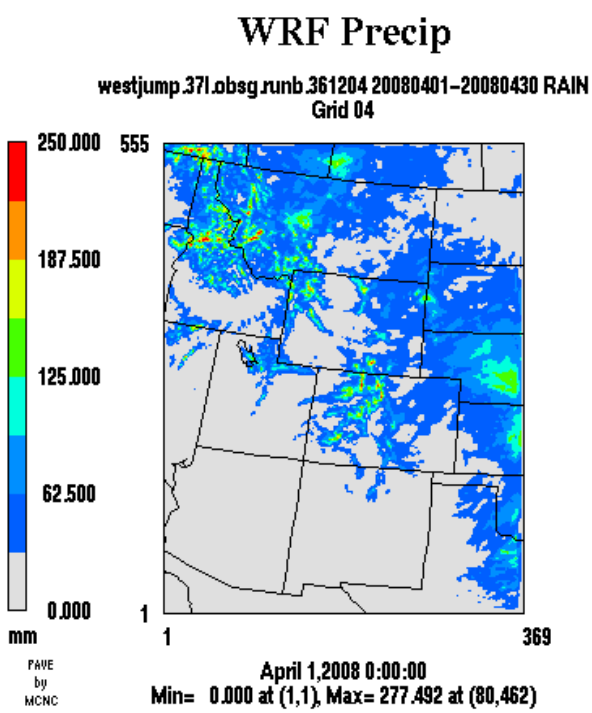


Figure 3-63. WRF Estimated Precipitation for April 2008 over the 4 km Domain.

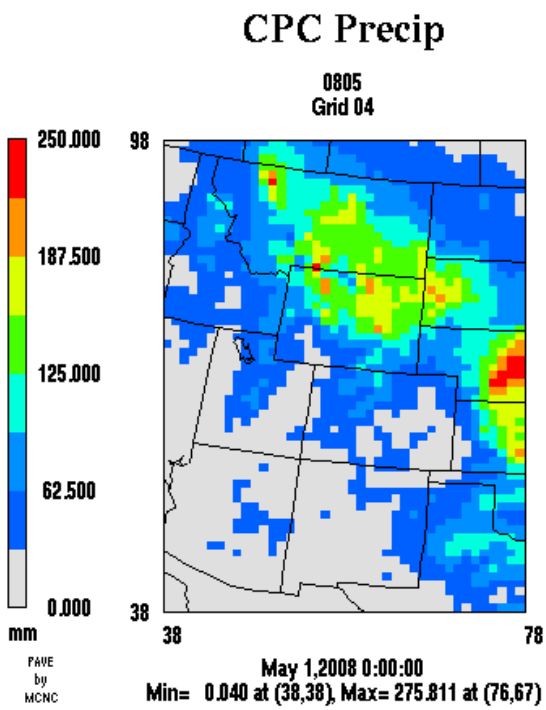


Figure 3-64. CPC Analyzed Precipitation for May 2008 over the 4 km Domain.

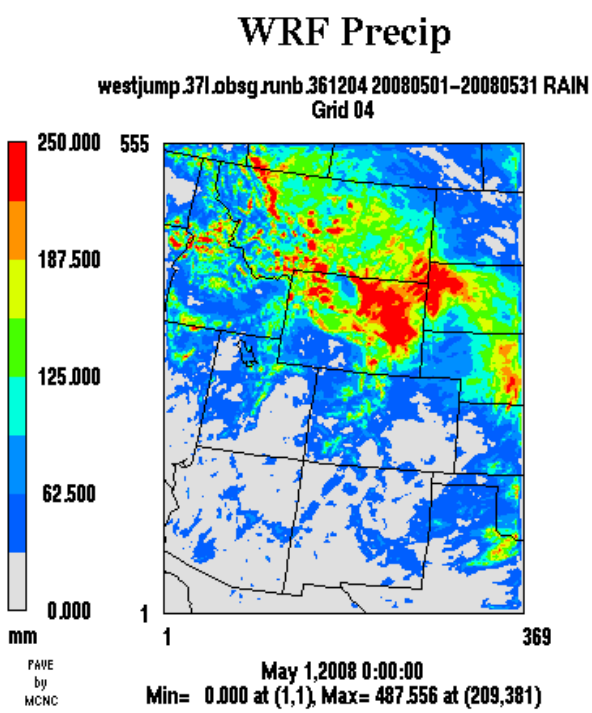


Figure 3-65. WFF Estimated Precipitation for May 2008 over the 4 km Domain.

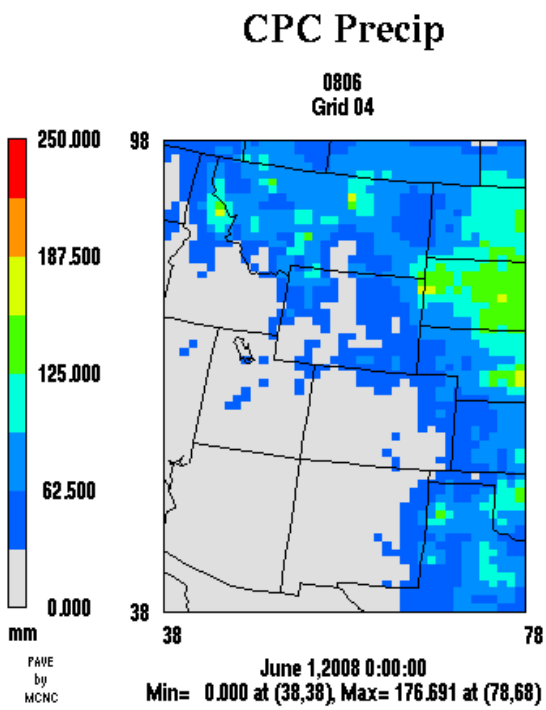


Figure 3-66. CPC Analyzed Precipitation for June 2008 over the 4 km Domain.

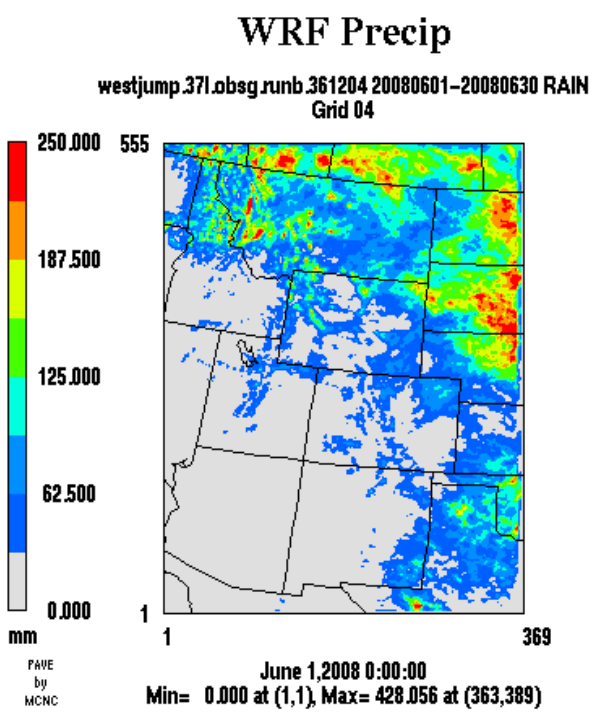


Figure 3-67. WRF Estimated Precipitation for June 2008 over the 4 km Domain.

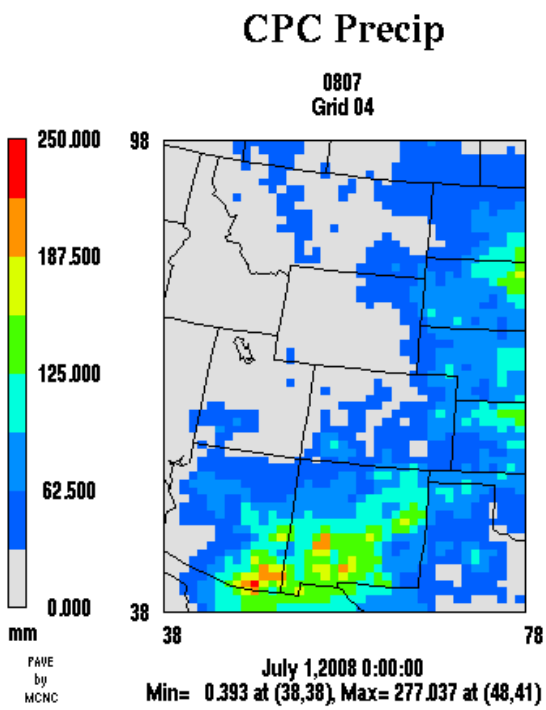


Figure 3-68. CPC Analyzed Precipitation for July 2008 over the 4 km Domain.

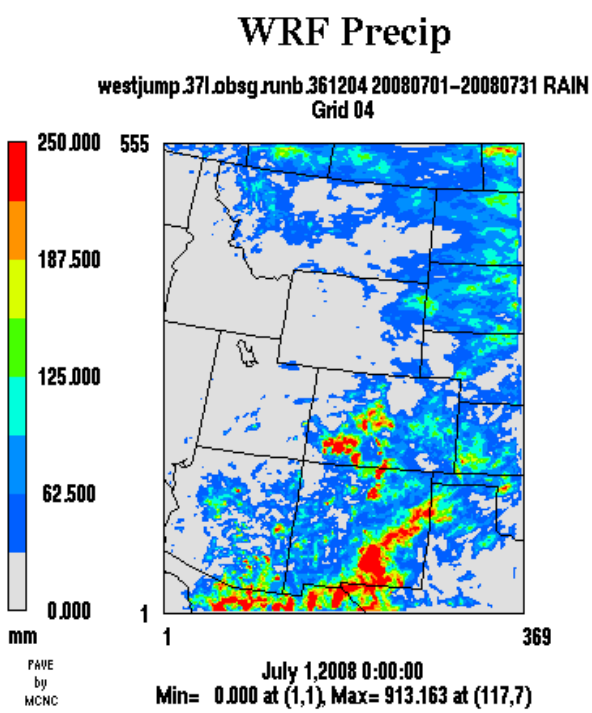


Figure 3-69. WRF Estimated Precipitation for July 2008 over the 4 km Domain.

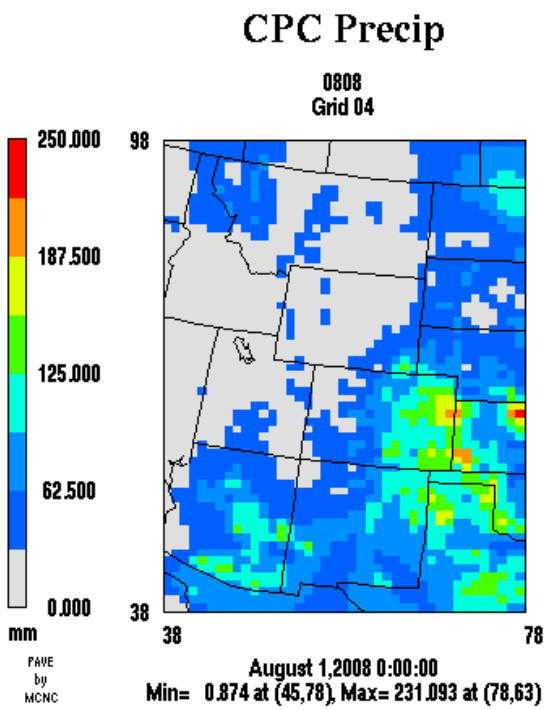


Figure 3-70. CPC Analyzed Precipitation for August 2008 over the 4 km Domain.

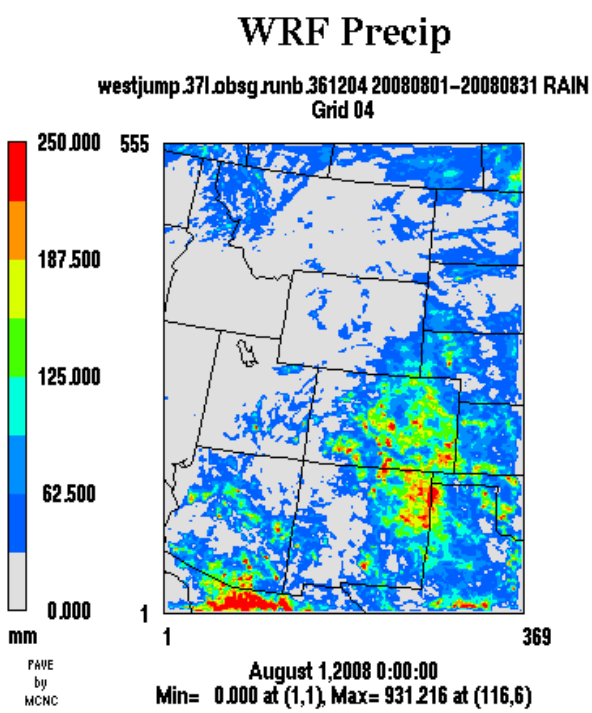


Figure 3-71. WRF Estimated Precipitation for August 2008 over the 4 km Domain.

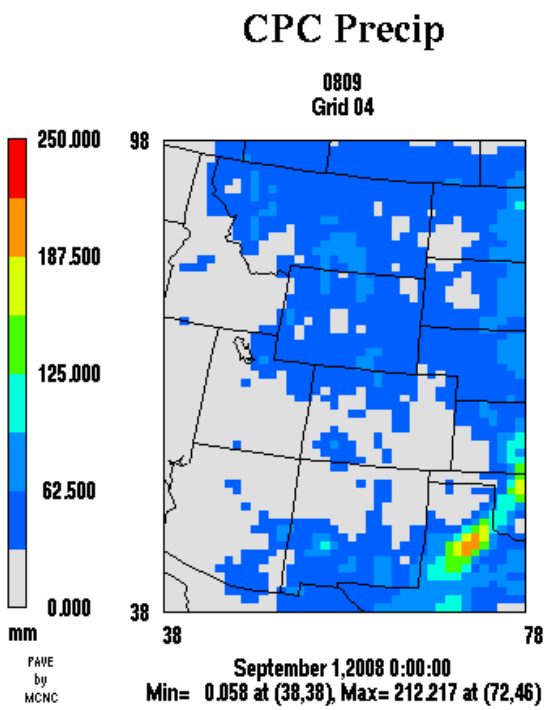


Figure 3-72. CPC Analyzed Precipitation for September 2008 over the 4 km Domain.

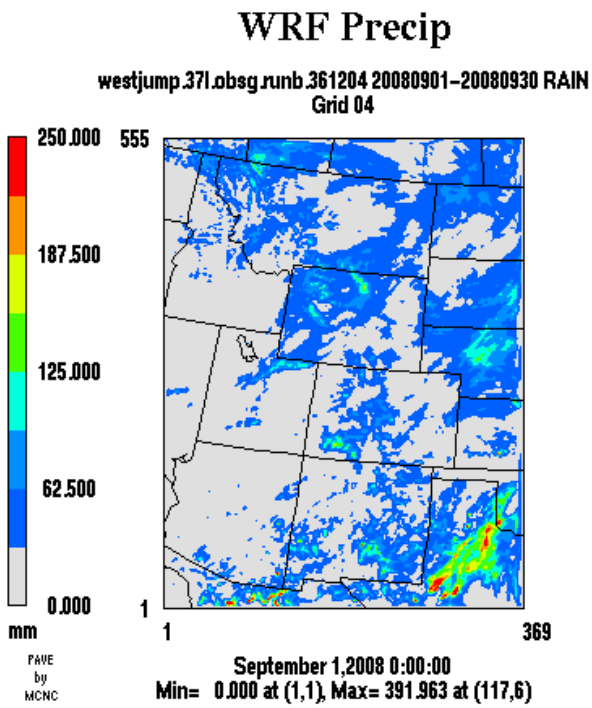


Figure 3-73. WRF Estimated Precipitation for September 2008 over the 4 km Domain.

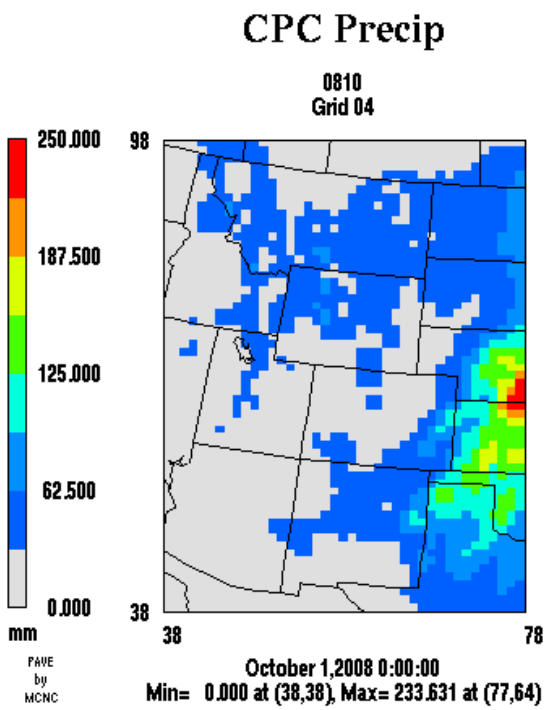


Figure 3-74. CPC Analyzed Precipitation for October 2008 over the 4 km Domain.

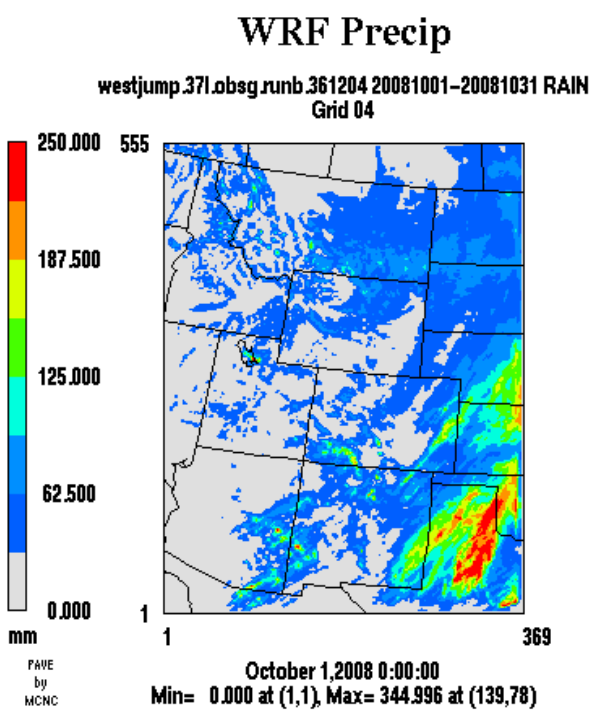


Figure 3-75. WRF Estimated Precipitation for October 2008 over the 4 km Domain.

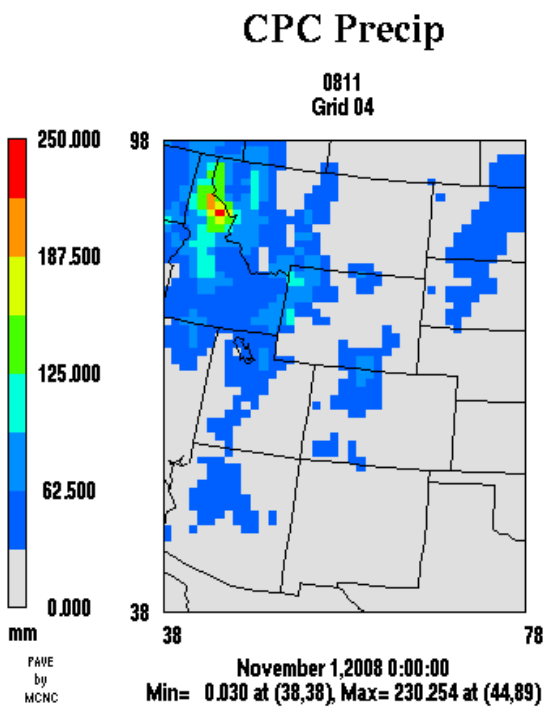


Figure 3-76. CPC Analyzed Precipitation for November 2008 over the 4 km Domain.

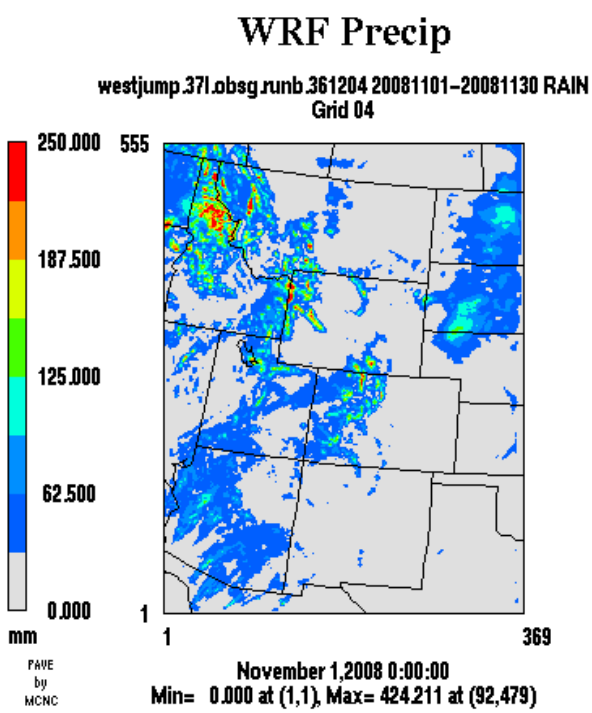


Figure 3-77. WRF Estimated Precipitation for November 2008 over the 4 km Domain.

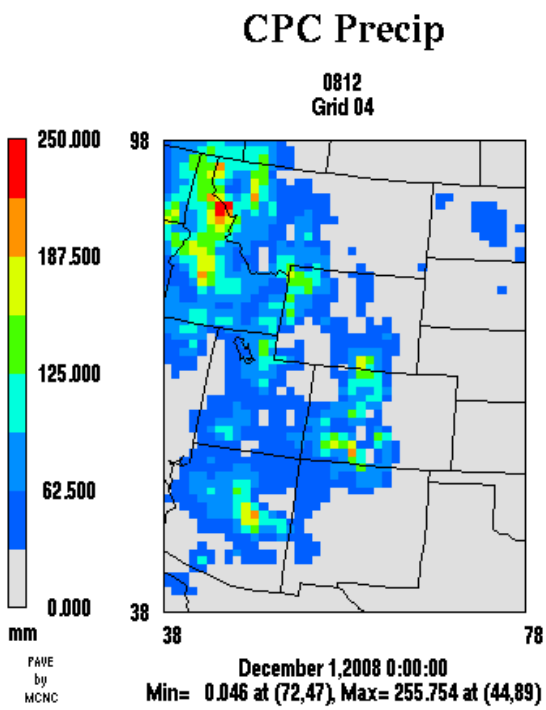


Figure 3-78. CPC Analyzed Precipitation for December 2008 over the 4 km Domain.

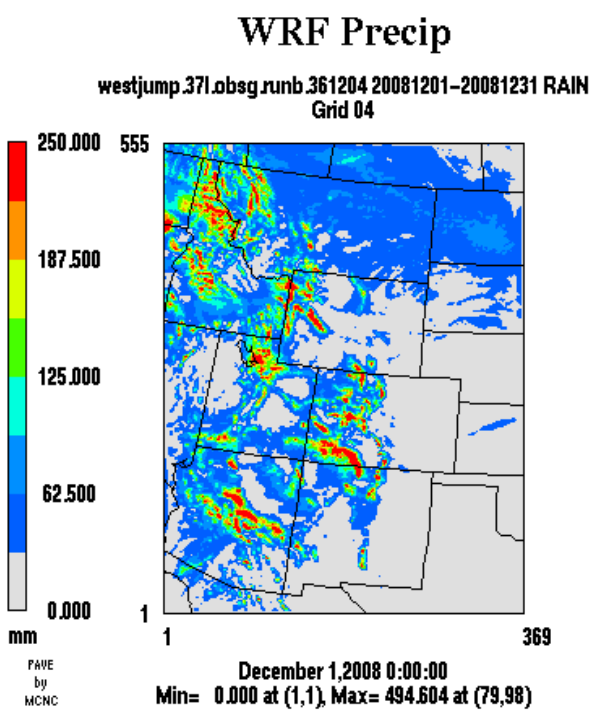


Figure 3-79. WRF Estimated Precipitation for December 2008 over the 4 km Domain.

4 COMPARISON WITH OTHER ANNUAL MM5 SIMULATIONS

This section presents a comparison of the model performance of the WestJumpAQMS 2008 WRF simulation with other annual meteorological simulations that have been completed during the past several years and used in air quality modeling studies. Comparisons were made for the current 36 km and 12 km WRF simulation to other 36 km and 12 km MM5 simulations. Comparisons for the 4 km domain are problematic since historically the MM5/WRF has not typically been applied to such a large 4 km domain that encompasses whole states which would facilitate intercomparison with the WestJumpAQMS 4 km WRF simulation.

While the MM4/MM5 model[19] served the air quality and meteorological modeling communities well the past two decades, it was recognized that certain limitations in the model formulation and implementation were hampering the development of advanced physical and dynamic treatments. As such, the next generation Weather, Research, and Forecasting (WRF) model was designed and the MM5 development ceased in 2004. Since that time the WRF model implementation has been ongoing and the modeling system is now mature enough to be used for air quality applications with the inclusion of FDDA in 2007 and an objective observation scheme in 2008. The WRF model now contains much more advanced physical treatments than MM5, and is fully supported with interface programs for use with contemporary air quality models, such as CALPUFF, CAMx and CMAQ. As the WRF model is relatively new, the number of simulations with which to intercompare studies is limited, thus comparisons to historical MM5 simulations are necessary.

Intercomparisons are performed for temperature and mixing ratio (humidity). Unfortunately not all of the previous model performance evaluations included wind direction bias and error and wind speed RMSE calculations, which were performed for this study, so it is not possible to perform a comparison for winds.

4.1 Comparison to Other Annual 36 km Simulations

Comparisons between the performance of the WestJumpAQMS WRF 36 km simulation for 2008 and the performance of other MM5 simulations were conducted. All MM5 simulations used in the comparison were performed using the same 36 km grid resolution and same CONUS horizontal domain and similar vertical grid definitions as the WestJump 36 km WRF simulation presented in this report. The simulations compared include the 2001 EPA[20], 2002 WRAP[21], 2002 VISTAS[22], the 2003 Midwest RPO[23],

19 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

20 McNally, D. E., and T W. Tesche, 2003. “Annual Application of MM5 to the Continental United States”, prepared for the U. S. Environmental Protection Agency, Office of Air Quality Planning and Standards, prepared by Alpine Geophysics, LLC, Arvada, CO.

21 Kemball-Cook S., Y. Jia, et al. 2005. “Annual 2002 MM5 Meteorological Modeling to Support Regional Haze Modeling of the Western United States”, Prepared for the Western Regional Air Partnership, prepared by ENVIRON International Corporation and University of California at Riverside.

22 Olerud Don, and A. Sims, 2004, “MM5 2002 Modeling in Support of VISTAS (Visibility Improvement – State and Tribal Association of the Southeast”, prepared for the VISTAS Technical Analysis Workgroup, prepared by Baron Advanced Meteorological Systems, LLC, Raleigh, NC.

23 Baker, Kirk, and M. Johnson, et al. 2005. “Meteorological Modeling Performance Summary for Application to PM2.5/Haze/Ozone Modeling Projects”, prepared by the Lake Michigan Air Directors Consortium, Des Plaines, IL.

the 2003-2005 NMED studies[24], the 2006 ENSR study[25], the 2005 and 2007 Midwest Ozone Group simulations[26], the Denver RAQC 2006 study[27] and the 2005 EPA study[28]. For purposes of model comparisons, the current study will be referred herein as the WestJump WRF 2008. The analysis of these simulations was subdivided by RPO region (CENRAP, MANE_VU, MRPO, VISTAS, and WRAP, see Figure 3-1).

The performance benchmarks for typical meteorological model performance that were used in this comparison were based on the same measures as in Section 3 of this report. As stated before, the purpose of these benchmarks was not to give a passing or failing grade to any one particular meteorological model application, but rather to put its results into the proper context of other derived meteorological data sets. As a reference, the performance benchmarks for temperature and mixing ratio are repeated below:

- Temperature Bias: ≤±0.5 °K simple and ≤±1.0 °K complex conditions.
- Temperature Error: ≤2.0 °K simple and ≤3.0 °K complex conditions.
- Mixing Ratio Bias: ≤±1.0 g/kg.
- Mixing Ratio Error: ≤2.0 g/kg.

Temperature bias model performance statistics for the entire domain and each RPO for the fifteen studies and for the current study (WestJump WRF 2008) simulation are presented in Table 4-1. The WestJump WRF 2008 application was well within the temperature bias benchmark range of ≤±1.0 °K with a 0.31 K average over the whole U.S. (ALL in Table 4-1). When comparing the WestJump WRF 2008 performance across the RPOs, the simulation was one of the best performing of all the meteorological simulations in the WRAP (-0.08 °K), MANE_VU (0.17 °K) and Midwest RPO (0.16 °K), and performed similarly to the other simulations in the other RPOs.

Temperature error is presented in Table 4-2. For the WestJump WRF 2008 application, the temperature error was the best of any simulations in the entire domain and the Midwest RPO, and nearly the best in the other RPOs (second in WRAP, MANE-VU and VISTAS; fourth in CENRAP).

Mixing ratio bias is presented in Table 4-3. The domain-wide bias for the WestJump WRF 2008 simulation was 0.04 g/kg, a very good score that was only bested by a single simulation and is well within the benchmark of ≤±1.0 g/kg. The WestJump WRF 2008 mixing ratio bias is comparable and in most regions, improved, to the overall performance of the other studies and other years across each RPO.

24 McNally, D. E., and G. J. Schewe, 2006. "Evaluation of 36/12/4 km MM5 for Calendar Year 2003", "Evaluation of 36/12/4 km MM5 for Calendar Year 2004", "Evaluation of 36/12/4 km MM5 for Calendar Year 2005", prepared for the New Mexico Environment Department, prepared by Alpine Geophysics, LLC, Arvada, CO.
25 McNally, D. E. and G. J. Schewe, 2007. "Evaluation of 36 km MM5 for Calendar Year 2006 Over the continental United States", prepared for the ENSR Corporation, prepared by Alpine Geophysics, LLC, Arvada, CO.
26 McNally, D.E. and G.M. Stella, 2009. "Evaluation of 36/12 km MM5 for Calendar Year 2007 over the Continental and Midwest/Eastern United States", prepared for the Midwest Ozone Group, prepared by Alpine Geophysics, LLC, Arvada, CO.
27 McNally, D.E., G. J. Schewe, 2008. "Evaluation of Preliminary MM5 Meteorological Model Simulation for the June-July 2006 Denver Ozone SIP Modeling Period Focused on Colorado", prepared for the Regional Air Quality Council, prepared by Alpine Geophysics, LLC, Arvada, CO.
28 McNally, D.E., and J.G. Wilkinson, 2008. "Evaluation of 36/12 km MM4 for Calendar Year 2005 over the Continental and Western United States", prepared for USEPA OAQPS, prepared by Alpine Geophysics, LLC, Arvada, CO.

Table 4-4 presents the mixing ratio error comparisons between the fifteen studies and the WestJump WRF 2008 simulation across the U.S. and the five RPO regions. The domain-wide mixing ratio error is 0.91 g/kg, which is the lowest (best) overall mixing ratio of any of the studies. All the simulations are well under the benchmark error of 2.0 g/kg. The WestJump WRF 2008 simulation resulted in mixing ratio errors that were the lowest for WRAP, MANE_VU, MW and VISTAS, and only 0.05 g/kg from the best performing for CENRAP.

4.2 Comparison to Other 12 km Annual Simulations

Over the past several years there have been a number of 12 km MM5 applications performed to support air quality modeling. These studies have simulated a variety of years using 12 km resolution grids varying in size and location to the 12 km WESTUS domain used in the WestJumpAQMS.

These studies evaluated the model on a state-by-state basis for states that were wholly, or very nearly wholly, contained in the modeling domains. Thus, a direct comparison between the current study and the previous studies can be performed for a number of states.

The other studies used the most recent versions of MM5 at the time of the study, starting with version 3.7.2. While changes to the MM5 model have been occurring, only minor model changes have occurred since versions 3.7.2 and 3.7.4. The largest differences between the previous studies and this study are the MM5 options. The previous studies were based on the Western Regional Air Partnership (WRAP) configuration (Kemball-Cook, et. al. 2005) and used the Reisner 1 moisture scheme and the Betts-Miller cumulus parameterizations with a western U.S. 12 km domain that was similar although slightly smaller than used in the WestJumpAQMS.

Table 4-5 through Table 4-8 present the meteorological model performance evaluation results for 12 km simulations from previous studies and the current study for temperature and mixing ratio. Simulation names are consistent with the modeling nomenclature for the 36 km studies noted above.

Temperature bias model performance evaluation results for the 12 km grid are presented in Table 4-5. Examination of this table reveals the current WestJump WRF 12 km simulation has temperature bias performance that is generally better than the majority of the other simulations. For instance, WestJump WRF is the only simulation where the benchmark is attained for all 12 months in Arizona, Colorado, and Idaho. Counting states which were included in more than two studies, in the annual average the WestJump WRF simulation has the lowest annual average temperature bias in Arizona, Idaho, and Nevada, but the highest annual average temperature bias in California, New Mexico, Utah and Wyoming.

Table 4-6 shows the temperature error model performance evaluation results for the 12 km WRF/MM5 simulations. Examination of this table reveals that the WestJump WRF simulation had by far the most skill replicating observed temperatures. On a monthly basis by state, WestJump WRF met the benchmark more than any other 12 km meteorological model simulation. On the annual average, WestJump WRF had the lowest temperature error in every state.

Mixing ratio bias model performance evaluation results for the 12 km simulations are presented in Table 4-7. Examination of this table reveals the WestJump WRF simulation has mixing ratio bias performance characteristics that are of mixed quality compared to previous simulations; the WestJump WRF simulation has both more and in some comparisons fewer months that do not fall with the +1.0 g/kg benchmark. One notable feature is the current simulation showed a stronger negative bias in California from June through September than the other simulations.

Table 4-8 shows the mixing ratio error model performance evaluation results for the 12 km simulations. Examination of this table reveals the WestJump WRF simulation has mixing ratio error performance characteristics that are quite similar to the other simulations for most states/months. On the annual average, WestJump WRF has the lowest annual average mixing ratio error in Arizona, Colorado, Idaho, Nevada, Utah, and Wyoming, but the highest mixing ratio error in California.

4.3 Summary of Intercomparison of Model Performance Evaluation Results

Temperature bias and error statistics and mixing ratio bias and error statistics were compared for meteorological model predictions using 36 km and 12km resolution modeling grids including those for the WestJump WRF current simulation. These values were compared with similar model performance evaluation statistics from previous MM5 simulations performed in previous studies upon the same or overlapping portions of the domain. As is often seen in meteorological model inter-comparisons, individual simulation often have strengths when looking at one variable or metric, and the same simulation may have weaknesses looking at another variable or metric.

In regards to the 36 km and 12 km domains, the current simulation has among the best performance characteristics for temperature and mixing ratio compared to prior studies.

The WestJump WRF simulation is performing at par or better than other meteorological simulations that have or are currently being used for air quality planning so the overall performance of the WestJump WRF simulation is judged to be adequate.

Table 4-1. Temperature Bias (°K) for 36 km Annual MM5 and WRF Simulations.

Simulation	ALL	CENRAP	MANE_VU	MW	VISTAS	WRAP
EPA 2001	-0.51	-0.26	-0.40	-0.31	-0.25	-1.10
WRAP 2002	-0.12	0.14	-0.15	-0.11	0.05	-0.49
VISTAS 2002	-0.05	0.14	0.00	0.05	0.24	-0.55
MRPO 2003	-0.15	0.11	-0.17	-0.10	0.18	-0.67
NMED 2005	0.52	0.86	0.15	0.58	0.75	0.13
NMED 2004	0.49	0.79	0.27	0.55	0.73	0.07
NMED 2003	0.27	0.54	0.21	0.28	0.65	-0.26
MOG 2005	0.38	0.75	0.05	0.49	0.61	-0.12
ENSR 2006	0.44	0.68	0.37	0.59	0.72	-0.10
RAQC 2006	0.51	0.72	0.40	0.63	0.75	0.04
EPA 2005	-0.33	-0.05	-0.82	-0.44	-0.09	-0.52
MOG 2007	-0.33	-0.14	-0.41	-0.41	-0.12	-0.63
MOG 2008	-0.31	-0.09	-0.33	-0.50	-0.05	-0.64
WY WRF 2008	0.31	0.95	0.12	0.13	0.49	0.03
ACHD WRF 2007	0.31	0.88	0.06	0.20	0.36	0.00
WestJump WRF 2008	0.33	0.93	0.17	0.16	0.40	-0.08

Table 4-2. Temperature Error (°K) for 36 km Annual MM5 Simulations.

Simulation	ALL	CENRAP	MANE_VU	MW	VISTAS	WRAP
EPA 2001	2.04	1.77	1.85	1.63	1.92	2.70
WRAP 2002	2.10	1.85	1.80	1.74	1.93	2.79
VISTAS 2002	2.02	1.76	1.80	1.72	1.84	2.67
MRPO 2003	2.17	1.94	1.86	1.92	1.98	2.82
NMED 2005	2.28	2.20	2.05	2.05	2.10	2.74
NMED 2004	2.26	2.13	1.99	2.01	2.11	2.75
NMED 2003	2.23	2.07	1.97	1.97	2.06	2.73
MOG 2005	2.26	2.16	2.05	2.03	2.07	2.74
ENSR 2006	2.24	2.15	1.95	1.90	2.13	2.75
RAQC 2006	2.25	2.16	1.96	1.92	2.15	2.76
EPA 2005	2.22	2.08	2.11	1.98	2.01	2.72
MOG 2007	2.15	1.95	1.95	1.88	2.03	2.72
MOG 2008	2.15	1.96	1.92	1.88	2.01	2.74
WY WRF 2008	2.02	1.99	1.77	1.71	1.75	2.41
ACHD WRF 2007	2.08	1.99	1.82	1.92	1.68	2.51
WestJump WRF 2008	1.94	1.87	1.78	1.57	1.69	2.48

Table 4-3. Mixing Ratio Bias (g/kg) for 36 km Annual MM5 Simulations.

Simulation	ALL	CENRAP	MANE_VU	MW	VISTAS	WRAP
EPA 2001	-0.11	-0.24	-0.06	-0.22	0.06	-0.08
WRAP 2002	-0.09	-0.34	0.08	-0.11	0.20	-0.09
VISTAS 2002	0.01	-0.07	0.19	0.13	0.02	-0.04
MRPO 2003	0.22	0.11	0.30	0.29	0.49	0.05
NMED 2005	0.17	-0.02	0.54	0.24	0.47	-0.08
NMED 2004	0.07	-0.09	0.36	0.19	0.38	-0.20
NMED 2003	0.05	-0.18	0.35	0.17	0.35	-0.13
MOG 2005	0.29	0.11	0.59	0.30	0.67	0.03
ENSR 2006	0.17	-0.04	0.57	0.27	0.46	-0.05
RAQC 2006	0.13	-0.07	0.53	0.23	0.42	-0.09
EPA 2005	0.33	0.13	0.54	0.31	0.75	0.15
MOG 2007	0.39	0.23	0.51	0.35	0.66	0.32
MOG 2008	0.29	0.09	0.48	0.26	0.52	0.25
WY WRF 2008	0.06	-0.09	0.32	0.20	0.31	-0.21
ACHD WRF 2007	0.13	0.04	0.29	0.27	0.34	-0.18
WestJump WRF 2008	0.04	-0.10	0.29	0.22	0.20	-0.22

Table 4-4. Mixing Ratio Error (g/kg) for 36 km Annual MM5 Simulations.

Simulation	ALL	CENRAP	MANE_VU	MW	VISTAS	WRAP
EPA 2001	1.02	1.09	0.80	0.85	1.13	1.04
WRAP 2002	1.03	1.17	0.82	0.93	1.16	0.94
VISTAS 2002	0.94	0.98	0.78	0.82	1.13	0.90
MRPO 2003	0.96	0.98	0.78	0.82	1.14	0.97
NMED 2005	1.12	1.20	0.96	0.97	1.32	1.03
NMED 2004	1.05	1.11	0.89	0.85	1.29	0.99
NMED 2003	1.03	1.09	0.86	0.85	1.22	1.00
MOG 2005	1.16	1.23	0.98	1.00	1.38	1.07
RAQC 2006	1.03	1.10	0.91	0.85	1.23	0.96
ENSR 2006	1.04	1.10	0.92	0.86	1.24	0.97
EPA 2005	1.04	1.10	0.86	0.89	1.31	0.93
MOG 2007	0.97	0.97	0.81	0.79	1.19	0.97
MOG 2008	0.93	0.95	0.76	0.76	1.12	0.92
WY WRF 2008	0.95	1.02	0.77	0.76	1.14	0.91
ACHD WRF 2007	0.92	0.92	0.80	0.76	1.10	0.91
WestJump WRF 2008	0.91	0.97	0.75	0.74	1.03	0.89

Table 4-5. Temperature Bias (°K) model performance evaluation (MPE) results by state for 12 km annual MM5 and WRF simulations. MPE results that are within the benchmark of ±1.0 °K are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008".

Simulation	Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NMED2003	AZ	0.65	-0.12	-0.25	-1.49	-1.20	-1.59	-1.66	-1.36	-0.36	0.29	0.15	0.96	-0.50
NMED2004	AZ	0.73	0.14	-0.03	-0.98	-1.63	-1.32	-0.87	-0.52	-0.78	-0.41	-0.07	0.61	-0.43
EPA2005	AZ	0.27	-0.38	-0.56	-1.22	-1.61	-1.91	-1.44	-0.27	-0.80	-0.77	0.32	1.09	-0.61
NMED2005	AZ	0.59	-0.30	-0.36	-0.97	-1.43	-1.70	-1.44	-0.48	-0.44	-0.52	0.77	-0.57	-0.57
ENSR2006	AZ	0.56	0.46	-0.55	-1.28	-1.71	-1.52	-0.62	-0.62	-0.36	-0.13	1.07	1.63	-0.26
WESTJ2008	AZ	0.40	-0.17	0.03	-0.23	-0.29	-0.47	0.93	0.79	0.08	0.06	0.14	0.43	0.14
NMED2003	CA	1.24	0.28	-0.18	-0.99	-0.80	-0.97	-0.81	-0.94	0.33	1.09	0.54	0.96	-0.02
NMED2004	CA	1.15	0.22	0.58	-0.48	-1.20	-1.05	-0.66	-0.26	0.19	0.15	1.00	1.57	0.10
EPA2005	CA	0.88	-0.14	-0.30	-0.79	-1.25	-1.54	-0.57	-0.11	-0.44	-0.18	0.81	0.64	-0.25
NMED2005	CA	1.36	0.16	0.20	-0.34	-0.83	-1.15	-0.03	0.40	0.15	0.44	1.38	0.16	0.16
ENSR2006	CA	0.76	1.24	-0.36	-0.79	-0.82	-0.62	-0.27	-0.22	0.45	0.49	0.89	1.92	0.22
WESTJ2008	CA	0.99	0.89	0.74	0.37	0.30	0.52	0.48	0.32	0.45	0.68	0.88	1.13	0.65
NMED2003	CO	0.55	-0.68	-2.11	-2.20	-0.75	-0.59	-0.75	-0.63	0.33	0.80	-0.14	0.99	-0.43
EAGLE2004	CO	1.42	-0.13	-1.20	-1.25	-0.33	-0.11	0.22	0.15	0.05	-0.21	0.20	0.56	-0.05
NMED2004	CO	1.47	-0.04	-1.04	-1.08	-0.17	0.00	0.25	0.22	0.07	-0.17	0.26	0.58	0.03
EAGLE2005	CO	0.69	0.08	-1.40	-0.97	-0.26	0.00	-0.07	0.53	0.41	0.40	0.44	0.43	0.02
EPA2005	CO	0.27	-0.31	-1.16	-0.99	-0.41	-0.16	-0.39	0.27	0.24	0.12	0.02	0.11	-0.20
NMED2005	CO	0.68	-0.06	-1.42	-0.94	-0.30	-0.01	-0.14	0.45	0.38	0.32	0.46	-0.05	-0.05
EAGLE2006	CO	0.26	0.24	-1.20	-1.38	-0.43	-0.26	0.52	0.53	0.44	0.00	0.13	1.19	0.00
ENSR2006	CO	-0.46	-0.24	-1.34	-1.39	-0.43	-0.33	0.47	0.56	0.32	-0.04	0.06	0.85	-0.16
WESTJ2008	CO	0.34	-0.86	0.07	0.19	0.57	0.40	0.78	1.00	0.90	0.85	1.04	0.79	0.51
NMED2003	ID	0.13	-1.12	-1.98	-1.50	-0.92	-1.34	-0.37	-0.17	0.59	0.98	-0.18	0.25	-0.47
NMED2004	ID	0.96	-0.07	-1.02	-0.31	-0.50	-0.32	0.45	0.40	0.78	0.40	1.41	0.24	0.20
EPA2005	ID	0.33	0.21	-0.46	-0.49	0.08	0.31	0.35	0.67	1.22	0.87	0.54	0.19	0.32
NMED2005	ID	1.37	0.32	-0.92	-1.14	-0.05	0.29	0.58	0.70	1.64	1.20	1.39	0.49	0.49
ENSR2006	ID	-0.43	-0.54	-1.78	-1.70	0.03	0.10	0.71	0.87	1.36	0.84	-0.41	1.28	0.03
WESTJ2008	ID	-0.11	-0.12	-0.44	-0.24	0.06	-0.33	-0.31	0.13	0.36	0.63	0.50	0.28	0.03
EPA2005	MT	0.98	0.67	0.00	-0.33	0.23	0.21	0.30	0.64	0.38	0.71	-0.08	0.56	0.36
WESTJ2008	MT	1.39	1.06	0.69	0.58	0.87	0.81	0.69	0.91	1.33	0.93	0.90	1.95	1.01
NMED2003	NM	0.32	-0.13	-0.53	-1.06	-0.81	-1.05	-1.32	-0.96	-0.45	0.52	0.11	1.08	-0.36
NMED2004	NM	0.70	0.48	0.17	-0.03	-0.24	-0.68	-0.11	0.19	-0.09	0.02	0.34	1.01	0.15
EPA2005	NM	0.49	0.11	-0.10	-0.20	-0.28	-0.59	-0.74	-0.03	-0.17	-0.04	0.45	0.24	-0.07
NMED2005	NM	0.64	0.08	-0.15	-0.06	-0.07	-0.40	-0.66	0.12	0.03	0.25	0.89	0.06	0.06

Table 4-5. Temperature Bias (°K) model performance evaluation (MPE) results by state for 12 km annual MM5 and WRF simulations. MPE results that are within the benchmark of ±1.0 °K are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008".

Simulation	Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
ENSR2006	NM	0.32	0.52	-0.63	-0.78	-0.79	-0.56	-0.06	-0.01	0.33	0.49	1.19	1.11	0.09
WESTJ2008	NM	0.90	0.18	0.67	0.79	0.72	0.72	1.88	1.77	1.40	0.94	1.13	1.09	1.02
NMED2003	NV	0.63	-0.87	-1.66	-2.34	-1.56	-2.33	-1.88	-1.54	-0.33	0.49	-0.35	0.18	-0.96
NMED2004	NV	0.39	-1.40	-1.03	-1.36	-1.73	-1.98	-1.72	-1.40	-0.75	-0.61	-0.05	0.25	-0.95
EPA2005	NV	0.31	-1.37	-1.67	-2.18	-1.99	-2.41	-1.79	-1.22	-1.01	-0.67	-0.13	-0.12	-1.19
NMED2005	NV	0.72	-1.09	-1.55	-2.01	-1.75	-2.20	-1.61	-1.19	-0.79	-0.39	0.27	-1.05	-1.05
ENSR2006	NV	-0.98	-0.79	-1.86	-2.14	-1.57	-1.99	-1.68	-2.02	-0.81	-0.51	0.72	1.73	-0.99
WESTJ2008	NV	0.11	-0.32	-0.84	-0.76	-0.44	-0.93	-0.57	-1.03	-0.63	-0.23	-0.03	0.25	-0.45
EPA2005	OR	0.35	1.07	0.47	-0.46	-0.56	-1.28	-1.12	-0.75	-0.09	0.40	0.78	0.46	-0.06
WESTJ2008	OR	0.20	1.04	0.48	-0.03	-0.05	-0.15	0.07	0.44	0.68	0.70	0.72	0.24	0.36
NMED2003	UT	0.91	-1.04	-1.78	-1.35	-0.61	-1.20	-1.27	-0.70	0.54	1.51	-0.02	0.93	-0.34
EAGLE2004	UT	2.22	0.48	-0.55	-0.52	-0.65	-0.50	-0.48	-0.18	0.07	0.27	1.09	1.27	0.21
NMED2004	UT	1.90	0.14	-0.72	-0.45	-0.53	-0.45	-0.44	-0.16	0.18	0.33	1.03	1.09	0.16
EAGLE2005	UT	0.97	0.56	-0.58	-0.92	-0.28	-0.37	0.06	0.46	0.78	1.02	1.44	1.29	0.37
EPA2005	UT	0.64	0.37	-0.57	-0.92	-0.36	-0.43	-0.32	0.28	0.56	0.74	1.06	0.89	0.16
NMED2005	UT	0.76	0.34	-0.63	-0.97	-0.25	-0.32	0.07	0.45	0.87	1.00	1.40	0.25	0.25
EAGLE2006	UT	0.89	0.06	-0.99	-1.32	-0.54	-0.42	-0.44	-0.18	0.85	0.94	1.68	2.28	0.23
ENSR2006	UT	0.59	-0.14	-1.03	-1.46	-0.37	-0.50	-0.31	-0.11	0.70	0.83	1.57	2.06	0.15
WESTJ2008	UT	0.92	0.85	-0.08	0.02	0.38	-0.01	0.35	0.22	0.83	1.37	1.43	1.49	0.65
EPA2005	WA	0.16	1.09	0.11	-0.20	-0.45	-1.13	-0.87	-0.44	-0.28	0.18	0.01	-0.13	-0.16
WESTJ2008	WA	1.27	0.15	0.09	-0.21	-0.33	-0.62	-0.72	0.18	-0.08	0.14	0.42	-0.19	0.01
NMED2003	WY	-0.01	-0.08	-1.38	-1.62	-0.64	-0.43	-0.51	-0.61	0.26	0.57	-0.08	0.95	-0.30
EAGLE2004	WY	1.97	1.07	-0.35	-0.17	-0.28	-0.19	0.25	0.06	0.25	0.76	1.33	-0.18	0.38
NMED2004	WY	1.43	0.56	-0.63	-0.26	-0.34	-0.25	0.20	-0.01	0.14	0.64	1.00	-0.68	0.15
EAGLE2005	WY	1.18	1.98	-0.58	-0.73	0.20	0.55	0.22	1.12	0.84	0.98	0.54	0.62	0.58
EPA2005	WY	0.50	1.42	-0.68	-0.86	-0.05	0.28	-0.12	0.83	0.62	0.54	-0.22	-0.14	0.18
NMED2005	WY	0.73	1.56	-0.80	-0.93	0.09	0.45	0.17	1.05	0.68	0.78	0.20	0.36	0.36
EAGLE2006	WY	0.07	-0.05	-1.01	-1.09	0.17	-0.07	0.18	0.42	0.84	0.30	0.05	1.76	0.13
ENSR2006	WY	-0.49	-0.40	-1.18	-1.35	0.12	-0.14	0.14	0.34	0.61	0.02	-0.22	1.28	-0.11
WESTJ2008	WY	0.72	-1.24	-0.33	-0.03	0.88	0.99	1.01	1.12	1.58	0.48	0.99	0.94	0.59

Table 4-6. Temperature Error (°K) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of 3.0 °K are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008".

Simulation	Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NMED2003	AZ	3.00	2.20	2.39	2.71	2.75	2.75	2.83	2.77	2.88	3.06	2.62	2.94	2.74
NMED2004	AZ	2.36	2.26	2.64	2.43	2.98	2.79	2.59	2.56	2.61	2.53	2.24	2.69	2.56
EPA2005	AZ	2.02	1.76	2.30	2.76	2.90	3.14	2.99	2.36	2.71	2.63	2.80	2.80	2.60
NMED2005	AZ	2.21	1.85	2.48	2.88	3.04	3.19	3.16	2.57	2.77	2.77	3.08	2.73	2.73
ENSR2006	AZ	3.03	3.03	2.40	2.83	3.20	2.98	2.43	2.35	2.58	2.85	3.46	3.20	2.86
WESTJ2008	AZ	1.79	2.09	1.49	1.86	1.36	1.81	1.28	2.54	1.63	1.41	1.46	2.20	1.74
NMED2003	CA	2.93	2.40	2.34	2.28	2.34	2.39	2.58	2.52	2.85	3.30	2.52	2.53	2.58
NMED2004	CA	2.69	2.24	2.82	2.57	2.62	2.41	2.36	2.45	2.88	2.44	2.72	3.08	2.61
EPA2005	CA	2.44	2.05	2.23	2.37	2.38	2.46	2.44	2.34	2.56	2.48	2.91	2.44	2.43
NMED2005	CA	2.73	2.20	2.38	2.43	2.33	2.35	2.56	2.56	2.73	2.72	3.25	2.57	2.57
ENSR2006	CA	2.60	3.15	2.13	2.23	2.50	2.48	2.71	2.44	2.72	2.86	2.83	3.46	2.68
WESTJ2008	CA	1.83	2.43	1.45	1.55	1.57	2.12	1.96	1.97	2.64	1.81	2.11	2.68	2.01
NMED2003	CO	3.69	2.79	3.50	3.64	2.82	2.73	3.23	2.62	2.86	3.50	2.94	3.53	3.15
EAGLE2004	CO	3.78	2.88	3.38	2.99	3.02	2.82	2.84	2.80	2.75	2.81	2.75	3.44	3.02
NMED2004	CO	3.71	2.92	3.33	2.91	3.04	2.88	2.85	2.78	2.75	2.82	2.73	3.48	3.02
EAGLE2005	CO	3.28	3.09	3.29	3.22	2.95	2.78	3.13	2.72	2.99	2.90	3.23	3.29	3.07
EPA2005	CO	2.98	3.00	3.09	3.06	2.79	2.70	3.00	2.56	2.76	2.67	3.09	3.08	2.90
NMED2005	CO	3.26	3.06	3.29	3.17	2.93	2.80	3.11	2.69	2.93	2.90	3.32	3.04	3.04
EAGLE2006	CO	3.49	3.47	3.04	3.60	3.04	2.94	2.67	2.56	2.75	2.79	3.44	3.44	3.10
ENSR2006	CO	3.19	3.49	3.11	3.56	3.02	2.97	2.66	2.61	2.75	2.77	3.33	3.30	3.06
WESTJ2008	CO	2.53	2.82	2.62	2.62	2.10	2.20	2.21	2.50	2.12	2.37	1.97	4.01	2.51
NMED2003	ID	2.36	2.73	3.00	2.90	2.90	3.15	3.60	3.37	3.54	3.57	2.51	2.21	2.99
NMED2004	ID	3.19	2.61	3.61	2.94	2.83	3.00	3.37	3.29	3.18	2.75	2.93	2.56	3.02
EPA2005	ID	2.66	2.75	2.68	2.63	2.37	2.47	2.94	3.06	2.89	2.59	2.60	2.76	2.70
NMED2005	ID	3.06	3.09	3.05	3.06	2.58	2.64	3.38	3.45	3.35	3.02	3.11	3.07	3.07
ENSR2006	ID	2.29	3.09	2.81	3.37	3.16	2.84	3.48	3.31	3.30	3.03	2.59	2.94	3.02
WESTJ2008	ID	1.91	2.51	2.38	1.95	1.81	2.55	2.37	2.32	2.65	3.52	1.84	2.71	2.38
EPA2005	MT	3.39	3.00	2.79	2.52	2.14	1.99	2.63	2.59	2.43	2.58	2.35	3.06	2.62
WESTJ2008	MT	2.55	1.66	2.19	2.09	1.76	2.49	2.22	2.43	2.56	3.37	1.91	3.40	2.39
NMED2003	NM	3.14	2.40	2.70	2.94	2.76	2.73	2.70	2.46	2.49	2.89	2.78	3.10	2.76
NMED2004	NM	2.74	2.51	2.52	2.24	2.79	2.78	2.62	2.38	2.46	2.51	2.36	3.12	2.59
EPA2005	NM	2.61	2.02	2.42	2.78	2.48	2.61	2.52	2.28	2.54	2.46	3.05	2.86	2.55
NMED2005	NM	2.75	2.11	2.58	2.86	2.54	2.66	2.55	2.37	2.65	2.55	3.30	2.63	2.63
ENSR2006	NM	3.04	3.02	2.57	2.74	2.76	2.51	2.23	2.02	2.41	2.71	3.44	3.20	2.72

Table 4-6. Temperature Error (°K) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of 3.0 °K are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008".

Simulation	Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
WESTJ2008	NM	1.72	2.35	1.77	2.32	1.74	2.20	2.32	2.33	1.62	2.08	2.14	2.70	2.11
NMED2003	NV	3.29	2.89	3.28	3.14	3.36	3.89	3.99	3.57	4.12	4.28	2.86	3.00	3.47
NMED2004	NV	3.41	2.97	3.63	3.10	3.58	3.78	3.85	3.71	3.98	3.34	2.87	3.26	3.46
EPA2005	NV	2.89	2.71	3.01	3.19	3.04	3.59	3.80	3.46	3.86	3.50	3.56	2.95	3.30
NMED2005	NV	3.10	2.73	3.14	3.23	3.06	3.58	3.89	3.61	4.00	3.63	3.67	3.42	3.42
ENSR2006	NV	3.04	3.60	3.12	3.30	3.54	3.69	3.68	4.12	3.94	3.72	3.86	4.16	3.65
WESTJ2008	NV	2.02	2.17	1.66	1.82	1.87	2.33	2.06	2.28	1.86	2.23	2.17	3.25	2.14
EPA2005	OR	2.35	2.69	2.54	2.00	2.04	2.53	2.85	2.76	2.69	2.40	2.40	2.24	2.46
WESTJ2008	OR	1.82	2.23	1.94	1.40	1.82	2.31	2.35	1.57	2.75	2.16	2.58	2.16	2.09
NMED2003	UT	2.93	2.46	2.87	2.85	2.81	3.06	3.52	2.85	3.31	3.62	2.17	2.79	2.94
EAGLE2004	UT	3.86	2.72	3.48	2.50	2.91	3.11	3.16	3.04	3.17	2.61	2.68	3.14	3.03
NMED2004	UT	3.67	2.58	3.42	2.42	2.78	3.02	3.05	2.95	3.04	2.55	2.53	3.04	2.92
EAGLE2005	UT	2.84	2.84	2.99	2.80	2.55	2.82	3.28	3.05	3.34	3.12	3.23	3.13	3.00
EPA2005	UT	2.55	2.58	2.63	2.54	2.30	2.61	2.94	2.80	2.96	2.73	2.92	2.81	2.70
NMED2005	UT	2.74	2.70	2.88	2.75	2.46	2.68	3.15	2.90	3.19	2.96	3.11	2.87	2.87
EAGLE2006	UT	2.72	3.22	2.56	3.08	3.01	3.25	3.02	3.10	3.14	2.76	3.22	3.39	3.04
ENSR2006	UT	2.59	3.21	2.59	3.16	3.03	3.13	2.96	2.95	2.96	2.66	3.15	3.29	2.97
WESTJ2008	UT	3.05	1.97	1.79	2.01	1.82	2.16	2.19	2.51	2.22	2.35	2.25	4.27	2.38
EPA2005	WA	2.07	2.55	2.00	1.76	1.81	1.92	2.18	2.31	2.15	1.75	1.77	1.94	2.02
WESTJ2008	WA	2.33	1.79	1.57	1.41	1.67	2.53	1.70	1.32	2.15	1.71	1.91	1.44	1.79
NMED2003	WY	3.37	2.87	2.92	3.00	2.50	2.38	3.09	2.74	2.65	3.33	3.07	3.26	2.93
EAGLE2004	WY	4.48	3.15	3.17	2.51	2.47	2.39	2.66	2.58	2.55	2.46	3.04	2.97	2.87
NMED2004	WY	4.36	3.00	3.22	2.53	2.54	2.45	2.70	2.61	2.60	2.46	2.95	3.02	2.87
EAGLE2005	WY	3.34	3.74	2.74	2.70	2.13	2.34	2.89	2.93	2.90	2.78	2.80	3.46	2.90
EPA2005	WY	3.04	3.41	2.66	2.58	2.05	2.22	2.71	2.75	2.74	2.56	2.64	3.16	2.71
NMED2005	WY	3.30	3.57	2.81	2.75	2.17	2.36	2.86	2.92	2.90	2.72	2.72	2.83	2.83
EAGLE2006	WY	3.02	3.14	2.69	2.88	2.77	2.68	2.92	2.75	2.62	2.42	2.91	3.82	2.89
ENSR2006	WY	2.90	3.14	2.73	2.99	2.90	2.78	3.03	2.87	2.66	2.49	2.94	3.65	2.92
WESTJ2008	WY	2.01	1.81	1.87	1.87	1.61	1.96	1.78	2.08	2.31	3.13	1.37	3.76	2.13

Table 4-7. Mixing ratio bias (g/kg) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of ±1.0 g/kg are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008".

Simulation	Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NMED2003	AZ	-0.12	-0.15	-0.26	0.26	0.53	0.57	0.54	0.26	0.18	0.48	-0.20	0.03	0.18
NMED2004	AZ	-0.29	-0.14	-0.06	0.08	0.86	1.04	0.77	0.39	0.13	0.20	-0.21	-0.37	0.20
EPA2005	AZ	-0.06	-0.04	0.08	0.73	1.34	1.98	2.17	0.81	1.92	1.10	0.94	0.55	0.96
NMED2005	AZ	-0.24	-0.16	-0.13	0.54	1.17	1.55	1.75	0.32	1.07	0.70	0.71	0.66	0.66
ENSR2006	AZ	0.43	0.47	0.49	1.05	1.92	1.56	0.08	0.41	-0.15	0.43	0.65	0.20	0.63
WESTJ2008	AZ	-0.13	-0.44	-0.12	0.15	0.01	-0.45	-1.25	-0.71	-0.33	0.17	-0.05	-0.38	-0.29
NMED2003	CA	-0.17	-0.27	-0.39	-0.17	-0.46	-0.69	-0.75	-0.44	-0.87	-0.80	-0.55	-0.23	-0.48
NMED2004	CA	-0.29	-0.35	-0.70	-0.54	-0.46	-0.88	-0.79	-0.89	-0.65	-0.32	-0.45	-0.30	-0.55
EPA2005	CA	0.20	-0.02	-0.12	-0.14	-0.08	-0.26	-0.15	0.13	-0.19	-0.28	-0.27	-0.14	-0.11
NMED2005	CA	0.02	-0.19	-0.29	-0.35	-0.20	-0.36	-0.03	0.23	-0.26	-0.36	-0.45	-0.20	-0.20
ENSR2006	CA	-0.20	-0.47	0.08	0.02	-0.11	-0.24	-0.47	-0.75	-0.63	-0.50	-0.21	-0.12	-0.30
WESTJ2008	CA	-0.26	-0.73	-0.54	-0.38	-0.78	-1.28	-1.47	-1.24	-1.61	-0.81	-0.58	-0.51	-0.85
NMED2003	CO	0.26	0.04	0.10	0.15	-0.09	-0.14	0.63	-0.05	-0.36	0.04	-0.15	0.01	0.04
EAGLE2004	CO	-0.10	-0.13	0.19	-0.07	-0.48	-0.17	-0.67	-0.88	-0.67	-0.25	-0.13	0.02	-0.28
NMED2004	CO	-0.09	-0.09	0.26	-0.05	-0.42	-0.13	-0.54	-0.76	-0.60	-0.20	-0.10	0.01	-0.23
EAGLE2005	CO	0.13	0.09	0.06	0.18	-0.21	-0.54	0.14	-0.68	-0.23	-0.41	-0.13	0.12	-0.12
EPA2005	CO	0.21	0.08	0.12	0.34	0.16	0.05	1.08	0.17	0.32	-0.14	0.01	0.15	0.21
NMED2005	CO	0.15	0.08	0.10	0.23	-0.12	-0.46	0.24	-0.57	-0.10	-0.37	-0.08	-0.08	-0.08
EAGLE2006	CO	0.13	0.18	0.09	0.18	-0.15	0.10	-0.84	-0.94	-0.65	-0.38	-0.09	0.14	-0.19
ENSR2006	CO	0.14	0.21	0.15	0.27	-0.01	0.22	-0.65	-0.82	-0.54	-0.36	-0.06	0.12	-0.11
WESTJ2008	CO	0.37	0.33	0.30	0.25	0.07	-0.20	-0.35	-0.83	-0.70	-0.31	-0.01	0.21	-0.07
NMED2003	ID	0.03	0.07	0.39	0.05	0.20	0.12	0.37	0.36	0.47	0.33	0.22	0.13	0.23
NMED2004	ID	0.14	0.11	0.82	0.44	-0.11	-0.04	0.00	0.10	0.08	0.19	0.07	0.19	0.17
EPA2005	ID	0.23	0.11	0.41	0.07	-0.27	0.02	0.16	0.51	-0.23	-0.01	0.10	0.15	0.10
NMED2005	ID	0.25	-0.01	0.49	0.20	-0.60	-0.47	-0.22	0.29	-0.32	-0.15	0.15	-0.04	-0.04
ENSR2006	ID	0.11	0.05	0.02	-0.07	-0.02	-0.06	0.06	-0.14	-0.34	-0.13	0.15	0.20	-0.01
WESTJ2008	ID	0.22	0.20	0.04	0.28	0.20	-0.16	-0.43	-0.63	-0.67	-0.34	-0.25	0.01	-0.13
EPA2005	MT	0.34	0.39	0.42	0.19	-0.21	-0.36	-0.23	0.24	0.10	0.14	0.22	0.29	0.13
WESTJ2008	MT	0.40	0.47	0.37	0.45	0.18	0.01	-0.01	-0.28	-0.58	-0.03	0.04	0.30	0.11
NMED2003	NM	0.48	0.29	0.26	0.41	0.57	0.85	0.96	0.34	0.12	0.39	0.10	0.25	0.42
NMED2004	NM	0.03	0.08	0.20	-0.03	0.52	0.93	0.22	-0.09	-0.13	-0.06	-0.04	-0.09	0.13
EPA2005	NM	0.19	-0.12	0.04	0.36	0.78	1.23	1.42	0.29	1.15	0.35	0.69	0.46	0.57
NMED2005	NM	0.10	-0.08	-0.07	0.22	0.22	0.60	0.60	-0.81	0.43	-0.08	0.47	0.15	0.15
ENSR2006	NM	0.26	0.23	0.50	0.72	0.74	0.58	-0.48	-0.56	-0.68	-0.47	0.00	-0.07	0.06

Table 4-7. Mixing ratio bias (g/kg) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of ±1.0 g/kg are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008".

Simulation	Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
WESTJ2008	NM	0.26	0.16	0.16	0.02	-0.32	-0.57	-1.44	-1.38	-0.76	-0.18	0.10	0.12	-0.32
NMED2003	NV	0.09	0.15	0.09	0.10	-0.13	-0.24	-0.11	-0.33	0.03	0.40	-0.10	-0.05	-0.01
NMED2004	NV	-0.04	0.07	0.54	-0.16	0.01	0.12	0.24	-0.16	0.23	0.31	-0.20	0.05	0.08
EPA2005	NV	0.16	-0.04	0.27	0.20	0.09	0.65	1.06	0.76	0.99	0.37	0.39	0.24	0.43
NMED2005	NV	0.07	-0.06	0.34	0.12	-0.09	0.45	0.87	0.69	0.96	0.23	0.28	0.35	0.35
ENSR2006	NV	0.09	0.04	0.04	0.19	0.27	0.62	-0.01	0.87	0.54	0.35	0.61	0.35	0.33
WESTJ2008	NV	0.17	-0.02	0.19	0.22	-0.17	0.01	-0.67	-0.36	-0.25	0.04	-0.21	-0.01	-0.09
EPA2005	OR	0.20	0.36	0.28	-0.02	-0.21	-0.20	0.30	0.35	0.17	0.10	0.22	0.22	0.15
WESTJ2008	OR	0.15	0.32	-0.02	0.14	-0.08	-0.17	-0.25	-0.59	-0.61	-0.25	-0.24	0.02	-0.13
NMED2003	UT	0.15	0.04	0.27	0.25	0.06	0.47	1.24	0.46	0.46	0.42	-0.06	0.13	0.32
EAGLE2004	UT	0.21	0.07	0.60	0.17	-0.14	0.33	0.58	0.27	0.39	0.20	-0.16	0.05	0.21
NMED2004	UT	0.24	0.10	0.77	0.27	-0.05	0.48	0.84	0.50	0.47	0.26	-0.13	0.08	0.32
EAGLE2005	UT	0.06	-0.04	0.28	0.05	-0.45	-0.21	0.44	-0.07	0.14	-0.11	-0.15	0.09	0.00
EPA2005	UT	0.27	0.13	0.41	0.27	-0.12	0.21	1.30	0.96	0.55	0.15	0.04	0.23	0.37
NMED2005	UT	0.10	0.04	0.37	0.11	-0.35	-0.13	0.68	0.25	0.22	-0.07	-0.14	0.10	0.10
EAGLE2006	UT	0.01	-0.03	-0.05	-0.02	0.07	0.29	-0.07	-0.42	-0.14	-0.27	0.02	0.17	-0.04
ENSR2006	UT	0.02	-0.03	-0.03	0.01	0.11	0.47	0.09	-0.13	0.03	-0.22	0.02	0.16	0.04
WESTJ2008	UT	0.38	0.24	0.26	0.23	-0.08	-0.40	-1.04	-0.57	-0.45	-0.27	-0.05	0.22	-0.13
EPA2005	WA	0.09	0.28	0.33	0.09	-0.13	-0.27	-0.07	0.06	0.08	-0.01	0.15	0.01	0.05
WESTJ2008	WA	0.33	0.13	-0.05	0.09	0.17	-0.08	-0.22	-0.53	-0.43	-0.45	-0.28	0.00	-0.11
NMED2003	WY	0.33	0.09	0.23	0.37	-0.01	-0.33	0.23	0.29	-0.31	0.29	0.11	0.17	0.12
EAGLE2004	WY	0.19	0.09	0.23	0.08	-0.37	-0.46	-0.54	-0.37	-0.39	-0.14	-0.03	0.07	-0.14
NMED2004	WY	0.22	0.12	0.40	0.16	-0.28	-0.35	-0.41	-0.25	-0.25	-0.08	0.04	0.13	-0.05
EAGLE2005	WY	0.19	0.16	0.10	0.04	-0.67	-1.04	-0.29	-0.15	-0.07	-0.29	-0.01	0.22	-0.15
EPA2005	WY	0.27	0.28	0.16	0.27	-0.34	-0.42	0.46	0.61	0.35	-0.02	0.09	0.22	0.16
NMED2005	WY	0.23	0.22	0.19	0.13	-0.59	-0.89	-0.10	0.00	0.11	-0.23	0.06	-0.08	-0.08
EAGLE2006	WY	0.19	0.16	-0.01	-0.16	-0.45	-0.12	0.15	-0.44	-0.17	0.00	0.11	0.31	-0.04
ENSR2006	WY	0.20	0.18	0.00	-0.11	-0.33	-0.06	0.31	-0.21	-0.10	0.05	0.13	0.31	0.03
WESTJ2008	WY	0.30	0.04	0.24	0.34	0.17	-0.12	-0.22	-0.35	-0.42	-0.03	0.13	0.26	0.03

Table 4-8. Mixing Ratio Error (g/kg) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of 2.0 g/kg are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008".

Simulation	Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
NMED2003	AZ	0.74	0.76	0.84	0.75	1.17	1.38	1.99	2.04	1.73	1.44	0.80	0.66	1.19
NMED2004	AZ	0.74	0.64	1.00	0.91	1.19	1.49	1.81	1.80	1.59	1.02	0.76	0.71	1.14
EPA2005	AZ	0.80	0.76	0.86	0.97	1.57	2.26	2.97	2.10	2.66	1.54	1.14	0.75	1.53
NMED2005	AZ	0.88	0.79	0.95	0.89	1.46	1.88	2.69	1.84	2.02	1.30	1.00	1.43	1.43
ENSR2006	AZ	0.67	0.74	1.03	1.25	2.04	2.01	1.58	1.73	1.46	1.33	0.91	0.64	1.28
WESTJ2008	AZ	0.69	0.78	0.51	0.47	0.68	0.94	1.66	1.66	1.12	0.72	0.64	0.78	0.89
NMED2003	CA	0.89	0.85	0.90	0.78	1.02	1.20	1.58	1.49	1.50	1.45	1.02	0.95	1.14
NMED2004	CA	0.88	0.84	1.21	1.05	1.06	1.32	1.49	1.42	1.47	1.03	0.97	0.88	1.14
EPA2005	CA	0.75	0.76	0.87	0.91	0.94	1.02	1.42	1.46	1.32	1.10	1.16	0.94	1.05
NMED2005	CA	0.79	0.83	0.97	1.01	0.98	1.06	1.48	1.49	1.35	1.14	1.22	1.12	1.12
ENSR2006	CA	0.87	1.08	0.75	0.78	0.99	1.27	1.61	1.53	1.36	1.13	1.02	0.85	1.10
WESTJ2008	CA	0.82	1.09	0.96	0.91	1.13	1.64	1.82	1.71	1.93	1.36	1.24	1.00	1.30
NMED2003	CO	0.55	0.47	0.61	0.85	1.14	1.23	1.73	1.46	1.05	0.79	0.56	0.46	0.91
EAGLE2004	CO	0.47	0.49	0.76	0.79	1.09	1.26	1.63	1.48	1.21	0.82	0.56	0.44	0.92
NMED2004	CO	0.46	0.48	0.77	0.78	1.05	1.27	1.64	1.47	1.15	0.79	0.56	0.45	0.91
EAGLE2005	CO	0.51	0.56	0.54	0.80	0.97	1.43	1.52	1.45	1.19	0.90	0.64	0.43	0.91
EPA2005	CO	0.55	0.60	0.59	0.82	1.01	1.47	2.02	1.56	1.27	0.79	0.61	0.43	0.98
NMED2005	CO	0.51	0.58	0.56	0.80	0.95	1.39	1.57	1.46	1.19	0.88	0.62	0.96	0.96
EAGLE2006	CO	0.46	0.43	0.62	0.73	0.96	1.17	1.46	1.49	1.08	0.82	0.55	0.47	0.85
ENSR2006	CO	0.47	0.45	0.64	0.77	0.99	1.29	1.48	1.46	1.05	0.81	0.55	0.46	0.87
WESTJ2008	CO	0.50	0.70	0.56	0.59	0.78	1.04	1.23	1.33	1.04	0.68	0.49	0.48	0.79
NMED2003	ID	0.48	0.44	0.65	0.64	0.99	1.23	1.71	1.59	1.13	0.86	0.50	0.44	0.89
NMED2004	ID	0.46	0.41	0.98	0.80	0.94	1.22	1.65	1.46	0.98	0.74	0.55	0.47	0.89
EPA2005	ID	0.55	0.54	0.81	0.74	0.97	1.18	1.34	1.66	1.05	0.77	0.61	0.50	0.89
NMED2005	ID	0.48	0.45	0.74	0.69	1.09	1.22	1.26	1.38	0.95	0.71	0.61	0.87	0.87
ENSR2006	ID	0.42	0.40	0.47	0.70	0.89	1.11	1.34	0.99	0.82	0.71	0.55	0.42	0.74
WESTJ2008	ID	0.44	0.61	0.46	0.55	0.75	0.90	1.23	1.21	0.98	0.71	0.56	0.42	0.74
EPA2005	MT	0.48	0.52	0.68	0.70	0.81	1.23	1.38	1.34	0.94	0.75	0.49	0.45	0.81
WESTJ2008	MT	0.48	0.55	0.54	0.64	0.67	0.86	1.08	0.92	0.80	0.57	0.43	0.41	0.66
NMED2003	NM	0.72	0.66	0.73	0.86	1.19	1.59	1.94	1.51	1.34	1.18	0.85	0.51	1.09
NMED2004	NM	0.53	0.61	0.86	0.95	1.30	1.75	1.79	1.53	1.34	1.10	0.66	0.60	1.09
EPA2005	NM	0.73	0.67	0.72	0.84	1.42	2.01	2.41	2.04	2.05	1.06	0.84	0.59	1.28
NMED2005	NM	0.74	0.70	0.75	0.79	1.12	1.59	1.91	1.89	1.67	1.01	0.68	1.17	1.17
ENSR2006	NM	0.56	0.58	0.86	1.09	1.26	1.51	1.45	1.50	1.34	1.13	0.60	0.52	1.03

Table 4-8. Mixing Ratio Error (g/kg) MPE results by state for 12 km annual MM5 and WRF simulations. MPE results that meet the benchmark of 2.0 g/kg are shaded yellow. Current study MPE results are identified as Simulation "WESTJ2008".

Simulation	Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
WESTJ2008	NM	0.51	0.45	0.49	0.49	0.85	1.13	1.76	1.71	1.18	0.78	0.48	0.50	0.86
NMED2003	NV	0.66	0.55	0.79	0.62	1.02	1.60	1.92	1.71	1.49	1.15	0.64	0.67	1.07
NMED2004	NV	0.57	0.55	1.05	0.83	0.92	1.46	1.92	1.68	1.30	0.90	0.66	0.58	1.04
EPA2005	NV	0.59	0.57	0.87	0.69	1.12	1.22	1.88	1.62	1.32	0.96	0.77	0.51	1.01
NMED2005	NV	0.60	0.57	0.95	0.68	1.12	1.22	1.77	1.56	1.29	0.95	0.77	1.04	1.04
ENSR2006	NV	0.54	0.47	0.61	0.86	1.13	1.13	1.33	1.31	0.98	0.85	0.82	0.57	0.88
WESTJ2008	NV	0.46	0.52	0.48	0.45	0.63	0.51	1.16	0.97	0.68	0.51	0.60	0.55	0.63
EPA2005	OR	0.54	0.61	0.73	0.62	0.77	0.75	1.04	1.07	0.82	0.82	0.55	0.53	0.74
WESTJ2008	OR	0.45	0.61	0.41	0.45	0.66	0.77	0.94	1.07	0.87	0.74	0.58	0.49	0.67
NMED2003	UT	0.57	0.51	0.62	0.66	0.99	1.25	2.13	1.64	1.16	0.93	0.61	0.50	0.96
EAGLE2004	UT	0.45	0.40	0.99	0.75	0.90	1.41	1.63	1.35	1.17	0.78	0.59	0.46	0.91
NMED2004	UT	0.45	0.40	1.11	0.78	0.92	1.44	1.74	1.42	1.20	0.77	0.59	0.46	0.94
EAGLE2005	UT	0.55	0.52	0.68	0.71	1.16	1.41	1.63	1.48	1.12	0.86	0.69	0.47	0.94
EPA2005	UT	0.60	0.58	0.75	0.78	1.11	1.44	2.12	1.87	1.27	0.86	0.65	0.53	1.05
NMED2005	UT	0.55	0.52	0.71	0.72	1.12	1.38	1.74	1.54	1.16	0.87	0.69	1.00	1.00
EAGLE2006	UT	0.45	0.43	0.60	0.74	1.04	1.26	1.41	1.33	0.88	0.92	0.57	0.42	0.84
ENSR2006	UT	0.43	0.43	0.60	0.74	1.02	1.29	1.43	1.25	0.91	0.94	0.58	0.43	0.84
WESTJ2008	UT	0.51	0.59	0.51	0.53	0.66	0.80	1.37	1.02	0.81	0.67	0.56	0.51	0.71
EPA2005	WA	0.49	0.58	0.67	0.65	0.75	0.74	0.95	0.99	0.81	0.73	0.48	0.45	0.69
WESTJ2008	WA	0.48	0.54	0.35	0.41	0.70	0.71	0.91	1.06	0.82	0.66	0.53	0.43	0.63
NMED2003	WY	0.52	0.37	0.50	0.76	0.90	1.20	1.61	1.41	1.01	0.77	0.43	0.43	0.83
EAGLE2004	WY	0.45	0.42	0.63	0.69	0.90	1.05	1.43	1.09	0.97	0.75	0.52	0.38	0.77
NMED2004	WY	0.47	0.43	0.72	0.71	0.90	1.06	1.46	1.08	0.97	0.75	0.53	0.40	0.79
EAGLE2005	WY	0.45	0.47	0.51	0.68	1.03	1.58	1.37	1.24	0.97	0.74	0.54	0.41	0.83
EPA2005	WY	0.47	0.53	0.54	0.74	0.86	1.44	1.60	1.57	1.14	0.68	0.51	0.42	0.88
NMED2005	WY	0.46	0.51	0.55	0.73	1.01	1.52	1.39	1.28	1.03	0.75	0.55	0.89	0.89
EAGLE2006	WY	0.42	0.36	0.44	0.69	0.98	1.07	1.19	1.07	0.83	0.65	0.47	0.47	0.72
ENSR2006	WY	0.43	0.38	0.44	0.69	0.98	1.11	1.25	1.07	0.85	0.67	0.48	0.48	0.74
WESTJ2008	WY	0.40	0.46	0.45	0.58	0.70	0.94	1.18	1.06	0.81	0.55	0.46	0.40	0.67

APPENDIX A

WRF 36, 12 and 4 km Model Performance For The Four Impact Assessment Domains (IADs)

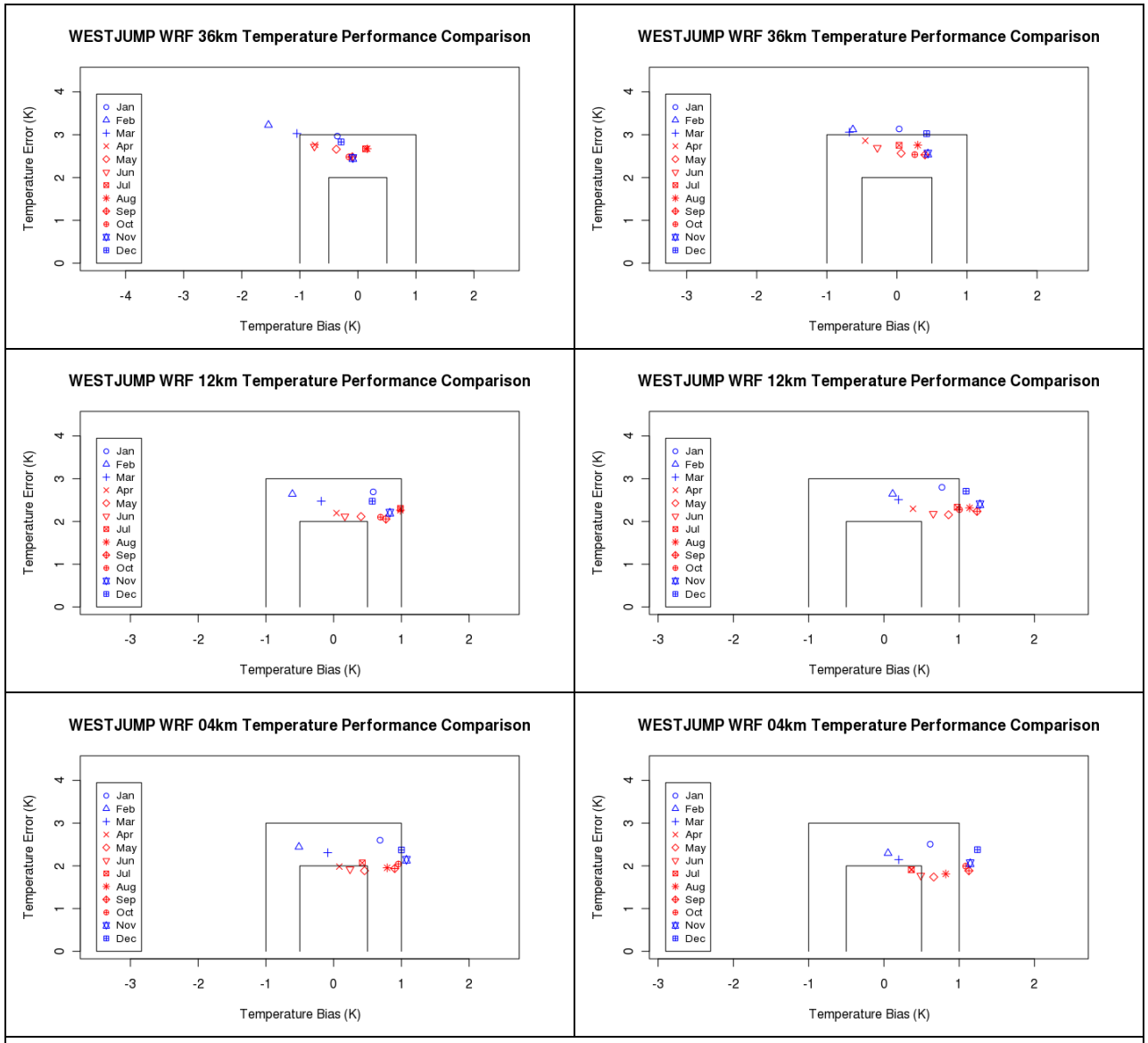


Figure A-1a. Monthly Temperature performance for all sites in the San Juan NM (left) and CO_UT (right) 4 km Impact Assessment Domains for the 36 km (top), 12 km (middle) and 4 km (bottom) WRF runs.

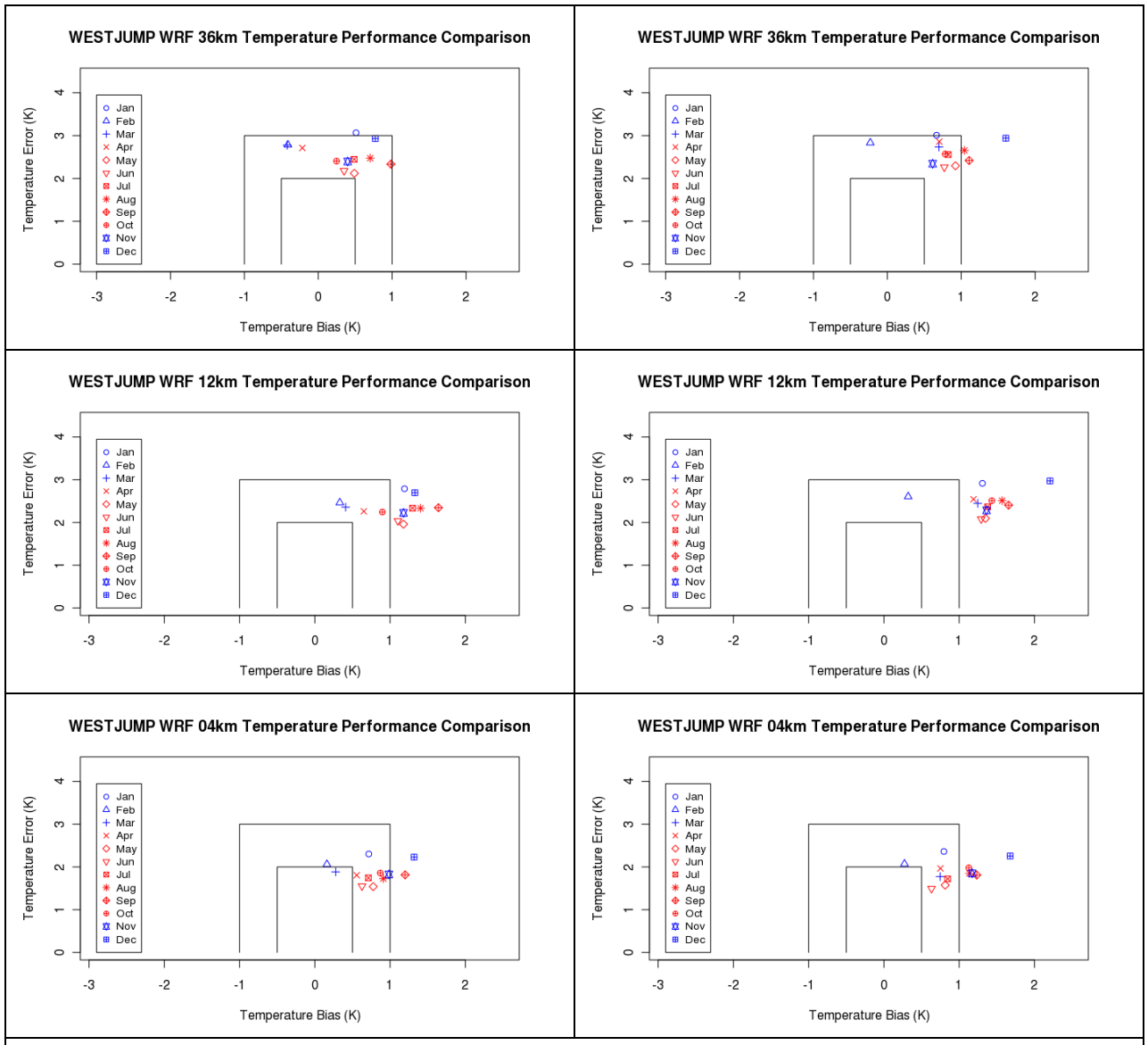


Figure A-1b. Monthly Temperature performance for all sites in the WY (left) and MT_ND (right) 4 km Impact Assessment Domains for the 36 km (top), 12 km (middle) and 4 km (bottom) WRF runs.

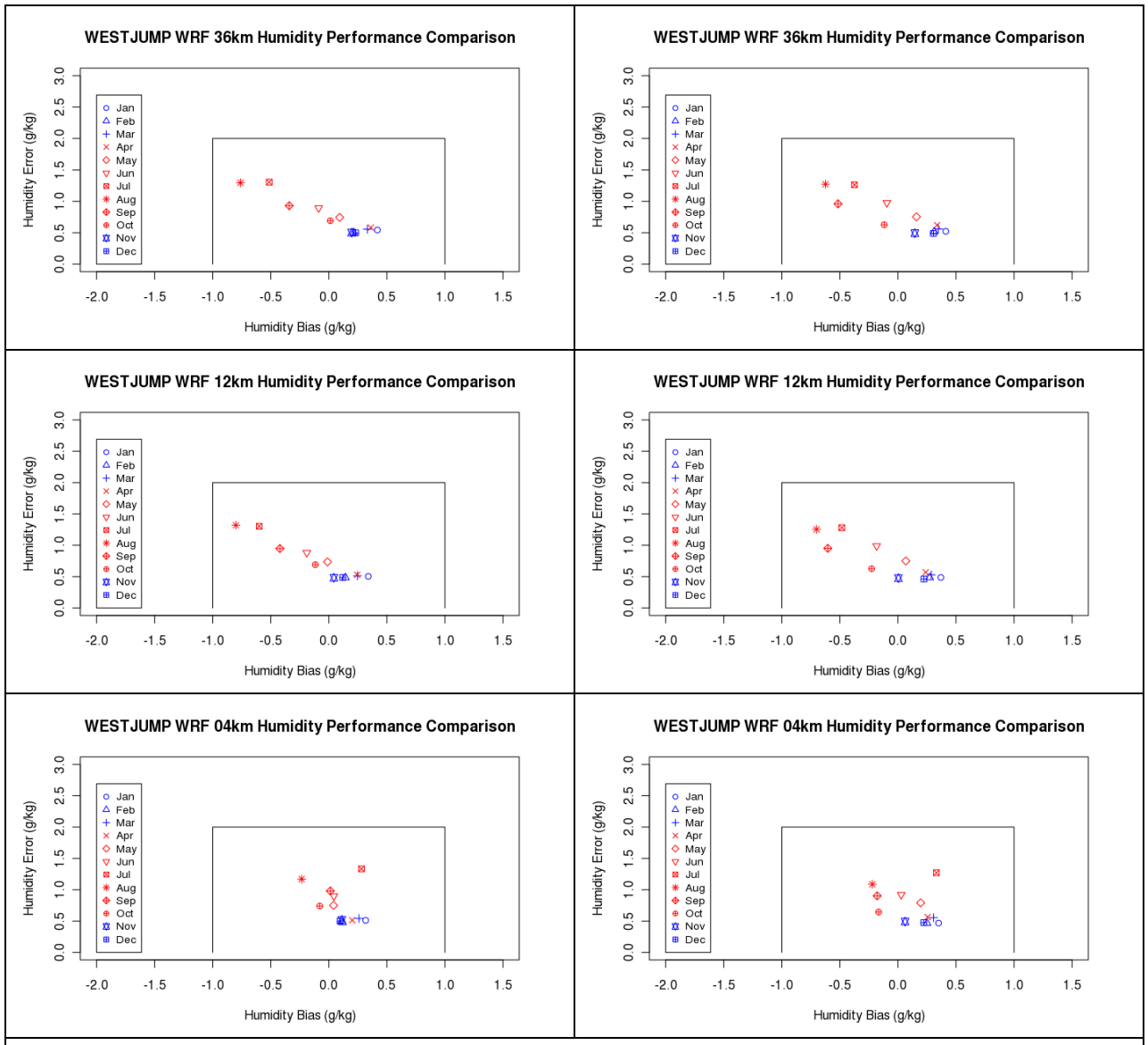


Figure A-2a. Monthly Humidity performance for all sites in the San Juan NM (left) and CO_UT (right) 4 km Impact Assessment Domains for the 36 km (top), 12 km (middle) and 4 km (bottom) WRF runs.

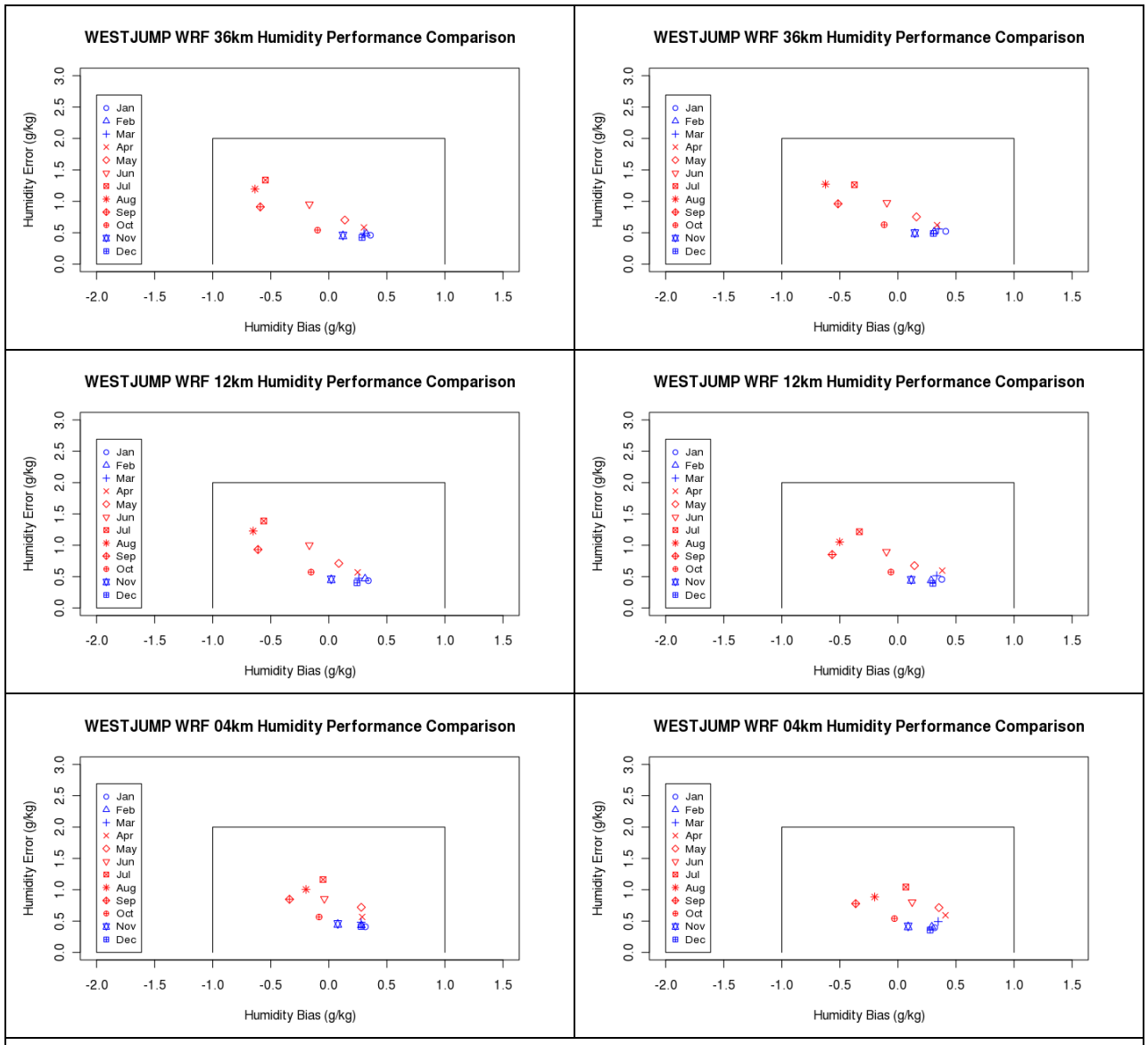


Figure A-2b. Monthly Humidity performance for all sites in the WY (left) and MT_ND (right) 4 km Impact Assessment Domains for the 36 km (top), 12 km (middle) and 4 km (bottom) WRF runs.

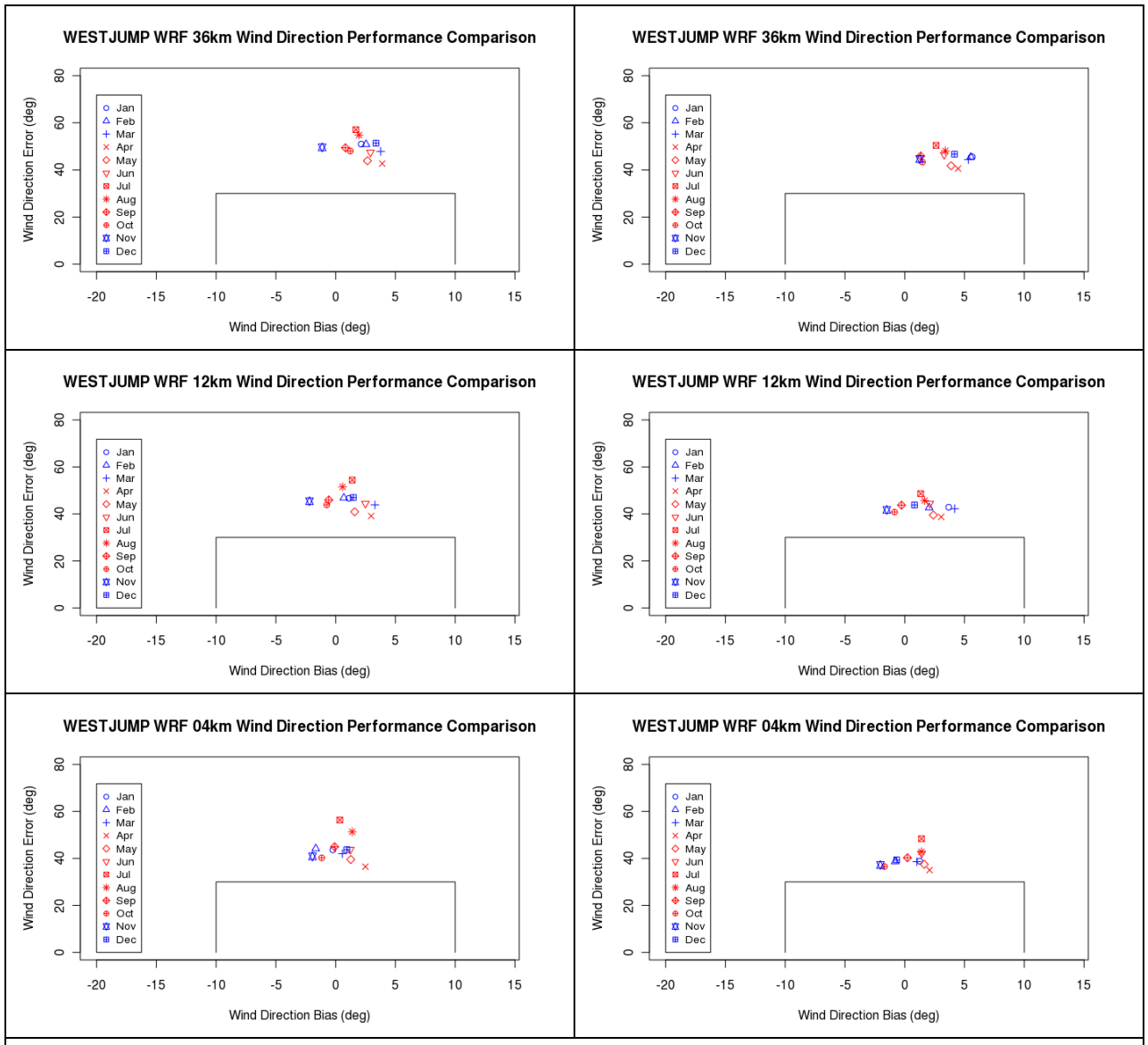


Figure A-3a. Monthly Wind Direction performance for all sites in the San Juan NM (left) and CO_UT (right) 4 km Impact Assessment Domains for the 36 km (top), 12 km (middle) and 4 km (bottom) WRF runs.

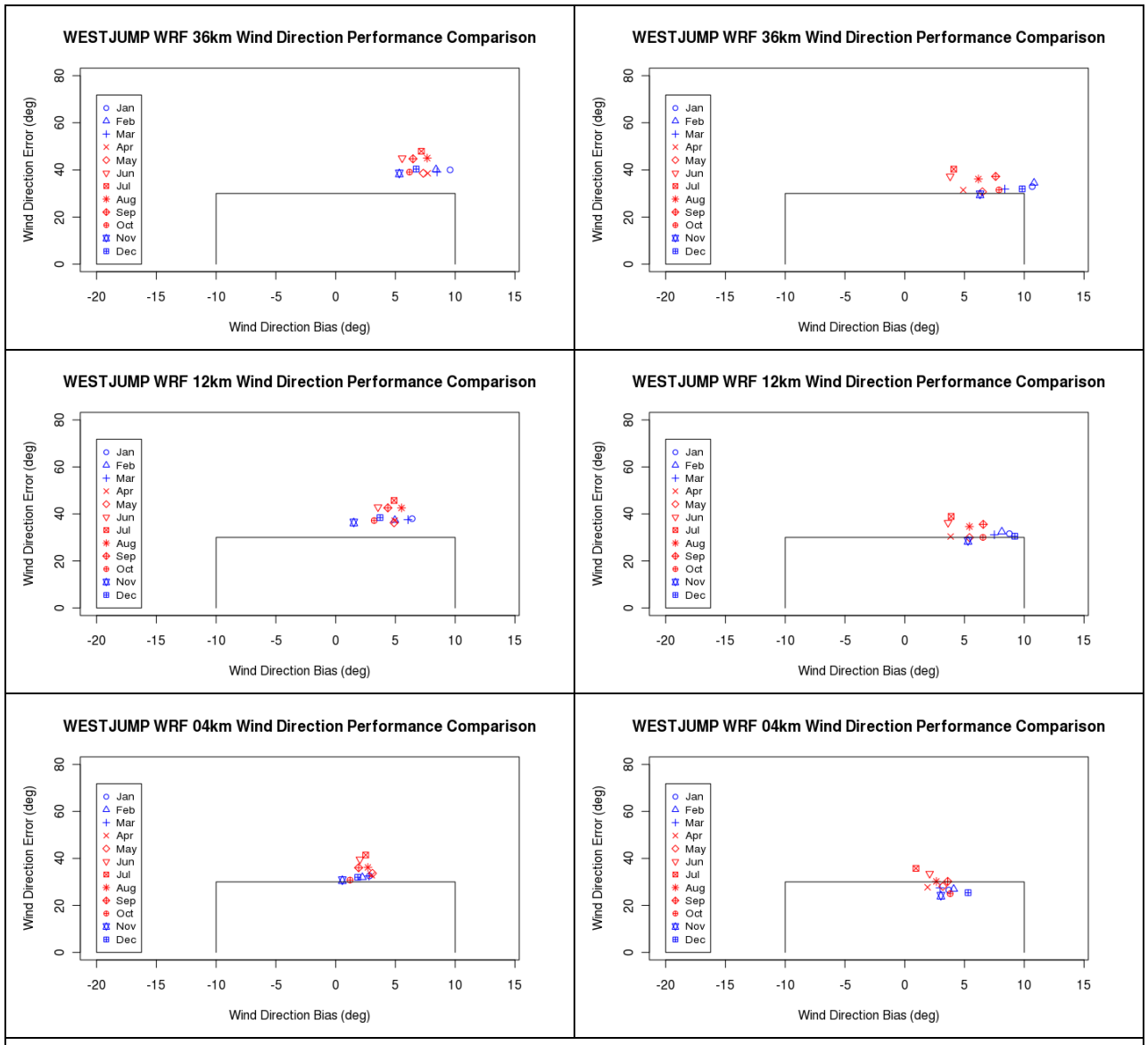


Figure A-3b. Monthly Wind Direction performance for all sites in the WY (left) and MT_ND (right) 4 km Impact Assessment Domains for the 36 km (top), 12 km (middle) and 4 km (bottom) WRF runs.

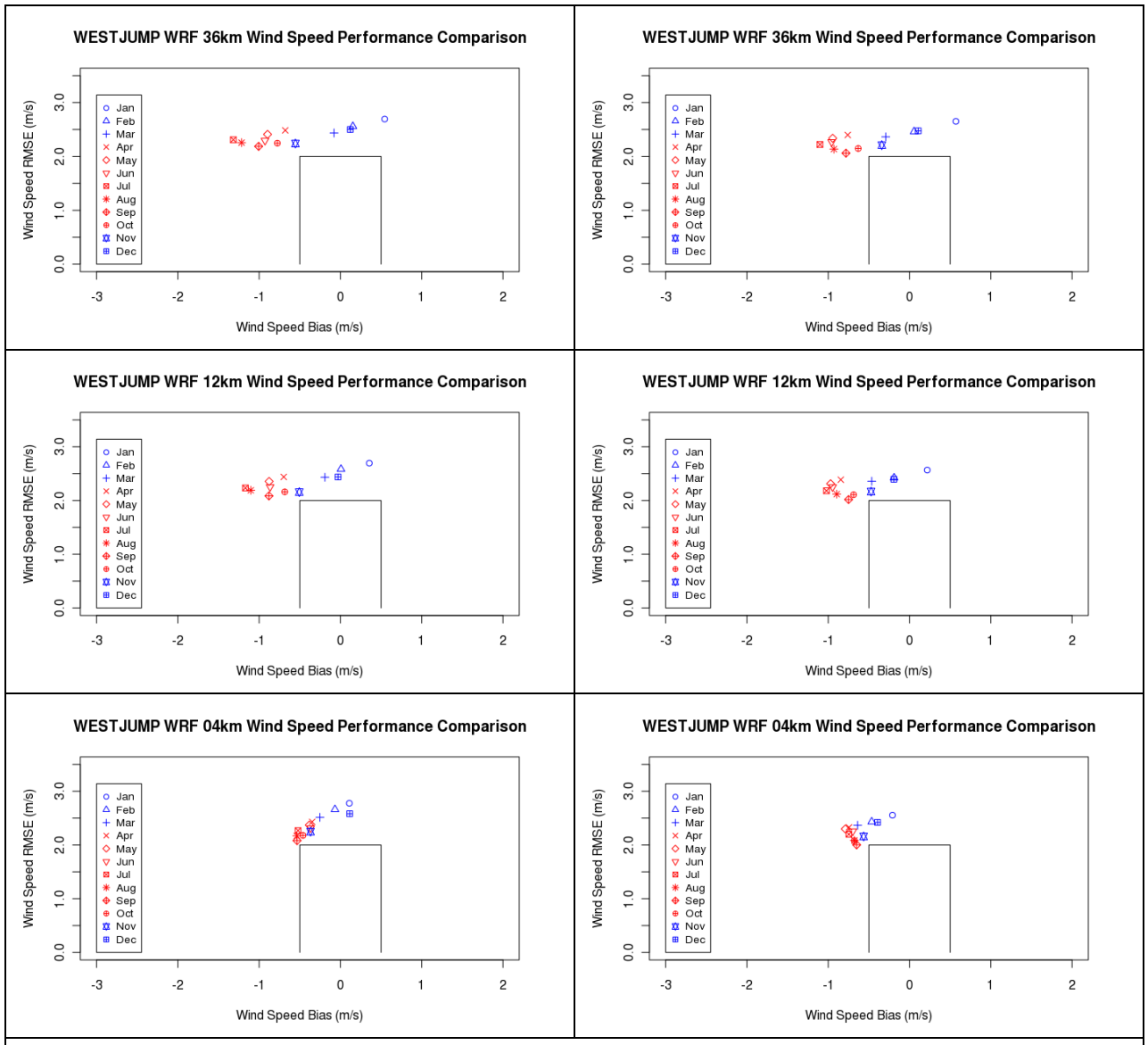


Figure A-4a. Monthly Wind Speed performance for all sites in the San Juan NM (left) and CO_UT (right) 4 km Impact Assessment Domains for the 36 km (top), 12 km (middle) and 4 km (bottom) WRF runs.

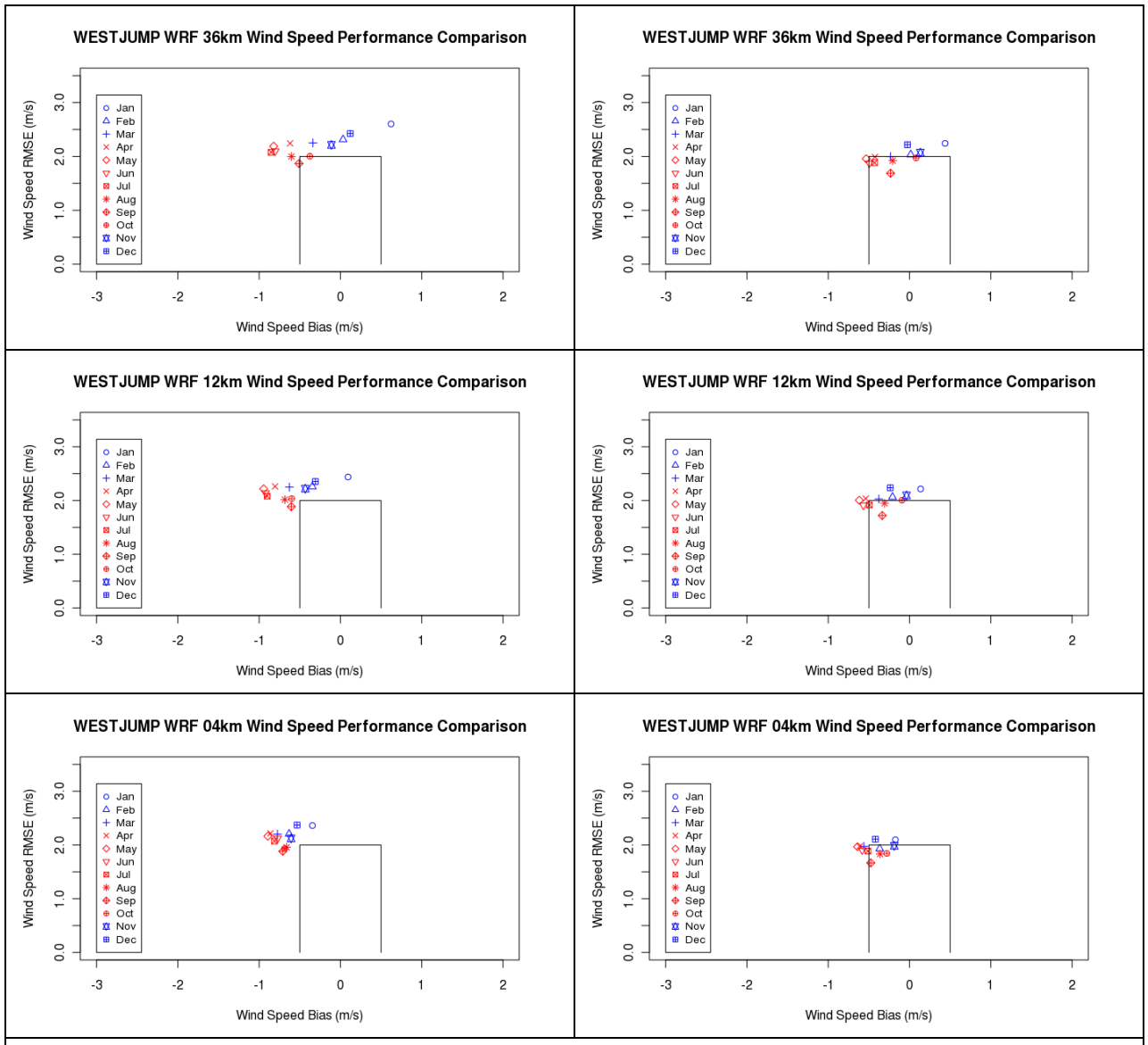


Figure A-4b. Monthly Wind Speed performance for all sites in the WY (left) and MT_ND (right) 4 km Impact Assessment Domains for the 36 km (top), 12 km (middle) and 4 km (bottom) WRF runs.