APPENDIX A

METEOROLOGICAL MODELING FOR THE TRANSPORT STATE IMPLEMENTATION PLAN REVISION FOR THE 2015 EIGHT-HOUR OZONE NATIONAL AMBIENT AIR QUALITY STANDARD

Project Number 2017-039-SIP-NR

Adoption
August 8, 2018
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1: WEATHER RESEARCH AND FORECASTING (WRF) MODELING OVERVIEW

The Texas Commission on Environmental Quality (TCEQ) used the WRF model version 3.8.1 to generate the meteorological inputs for the photochemical modeling supporting the Federal Clean Air Act, sections 110(a)(1) and (2) Transport State Implementation Plan revision for the 2015 Eight-hour Ozone National Ambient Air Quality Standard (2015 Ozone NAAQS Transport SIP revision). The WRF modeling system was developed by a broad user community including the Air Force Weather Agency, national laboratories, and academia. WRF modeling was conducted for the period beginning at 00:00 UTC on April 15, 2012 and ending at 00:00 UTC on October 2, 2012. This period covers the five-month modeling period of the TCEQ 2012 modeling platform (May through September 2012) including the ramp-up period.

A Lambert Conformal Conic (LCC) map projection with geographical coordinates defined in Table 1-2: Lambert Conformal Map Projections was used for the WRF modeling.

### Table 1-1: Lambert Conformal Map Projections

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>First True Latitude (Alpha)</td>
<td>33°N</td>
</tr>
<tr>
<td>Second True Latitude (Beta)</td>
<td>45°N</td>
</tr>
<tr>
<td>Central Longitude (Gamma)</td>
<td>97°W</td>
</tr>
<tr>
<td>Projection Origin</td>
<td>97°W, 40°N</td>
</tr>
<tr>
<td>Spheroid</td>
<td>Perfect Sphere, Radius = 6370 km</td>
</tr>
</tbody>
</table>

WRF was configured as a single 12 km grid as shown in Figure 1-1: WRF Good Neighbor Modeling Domain. This WRF grid embeds a corresponding CAMx grid of the same horizontal resolution. The easting and northing ranges for the 12 km grid in the LCC projection are defined in Table 1-3: WRF Modeling Domain Definitions in units of km. Table 1-4: Vertical Layer Structure provides details regarding the heights and thicknesses of the vertical layers in WRF.

---

1 UTC stands for Coordinated Universal Time, formerly Greenwich Mean Time.
Figure 1-1: WRF Good Neighbor Modeling Domain

Table 1-2: WRF Modeling Domain Definitions

<table>
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<tr>
<th>Domain Name</th>
<th>Easting Range (km)</th>
<th>Northing Range (km)</th>
<th>East/West Grid Points</th>
<th>North/South Grid Points</th>
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<td>na_12 km</td>
<td>(-2916,2916)</td>
<td>(-2304,2304)</td>
<td>489</td>
<td>387</td>
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Table 1-3: Vertical Layer Structure

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<td>9</td>
<td>0.930</td>
<td>611</td>
<td>566</td>
<td>89</td>
</tr>
<tr>
<td>8</td>
<td>0.940</td>
<td>522</td>
<td>477</td>
<td>89</td>
</tr>
<tr>
<td>7</td>
<td>0.950</td>
<td>433</td>
<td>389</td>
<td>88</td>
</tr>
<tr>
<td>6</td>
<td>0.960</td>
<td>345</td>
<td>301</td>
<td>87</td>
</tr>
<tr>
<td>5</td>
<td>0.970</td>
<td>258</td>
<td>214</td>
<td>87</td>
</tr>
<tr>
<td>4</td>
<td>0.980</td>
<td>171</td>
<td>128</td>
<td>86</td>
</tr>
<tr>
<td>3</td>
<td>0.990</td>
<td>85</td>
<td>60</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>0.996</td>
<td>34</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td>1</td>
<td>0.998</td>
<td>17</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>0</td>
<td>1.000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The WRF vertical layer structure provides high resolution in the lowest part of the atmosphere where pollutant mixing is critical, as shown in Figure 1-2: *WRF Vertical Layer Structure*.

2: WRF PREPARATION

2.1 WRF PREPROCESSING SYSTEM (WPS)

The preparation of WRF input files involves the execution of different modules within the WPS as described below.
GEOGRID

- GEOGRID defined the WRF grids on a Lambert-Conformal Projection (see Table 1-2) and allocated the Land Use/Land Cover (LULC) data.

UNGRIB/METGRID

- UNGRIB unpacked the GRIB (Gridded Binary) files with surface and upper level meteorological data to standard pressure levels native to the Global Energy and Water Experiment Continental-scale International Project (GCIP) National Centers for Environmental Prediction (NCEP) Eta data archive. This archive has the highest temporal resolution (three-hour as well as six-hour) of the archived data available for processing into initial conditions and boundary conditions. These data also extend to 50 millibars (mb), which is higher than other archived data. Both of these features have proven desirable for preparing WRF initial conditions and boundary conditions files.
- METGRID re-gridded the unpacked data onto the WRF grid defined in GEOGRID and reformatted the data into a NetCDF (Network Common Data Form) format.

MOD_LEVS

- Where data were missing from the GCIP NCEP Eta archive, data extracted from NCEP North American Mesoscale (NAM) model were used. This model is archived on a six-hour interval, compared to the 3-hour interval of the GCIP NCEP Eta. The NAM model extends to 50 mb but has additional pressure levels beyond what is needed to match the GCIP NCEP Eta data. The MOD_LEVS program was run to remove the extra data levels. METGRID was then re-run. Extracting data consistently across matching pressure levels facilitated scripting WRF preprocessing across multiple months.

OBSGRID

- This optional program was used to develop the WRF Surface Four Dimensional Data Assimilation (WRFSFDDA) for the 12 km grid. In addition to generating the surface nudging files, new gridded data files consistent with the surface analysis replace the gridded met data for the 12 km grid generated by the METGRID program. Furthermore, running the WRF model with the Pleim-Xiu (PX) land surface model with soil nudging requires the WRFSFDDA file.

REAL

- The REAL program defined the WRF sigma level vertical structure (Figure 1-2) and mapped the archived data retrieved on pressure levels to the sigma levels defined by the WRF user, consistent with surface land use data and definitions of the upper atmosphere. Base state variables were set to Texas summer values: 1013 hectopascal (hPa) sea-level pressure, a reference temperature lapse rate of 45 degrees Kelvin divided by the natural logarithm of pressure (K/ln p), and a 304 degrees K sea-level temperature. The REAL program produced the WRF initial conditions files, boundary condition files, and WRF FDDA (Four Dimensional Data
Assimilation) files, where the four dimensions are three spatial dimensions plus time.

In addition to the analysis nudging files (WRFSFDDA and WRFFDDA) produced during WPS preparation, archived Meteorological Assimilation Data Ingest System (MADIS) boundary layer radar profiler data were processed. The retrieved profiler data were filtered, reorganized, and reformatted with Python and SAS routines to generate an observational nudging file for the 12 km WRF grid. The profiler locations are shown in Figure 2-1: Radar Profilers throughout CONUS during the 2012 Season; National Profiler Network (NPN) in blue and Cooperative Agency Profilers (CAP) in red. The NCEP data gridded analyses used by WPS already include all available upper air and surface data, which taken with WRF model system improvements has lessened the dependence on the profiler data for acceptable model performance. However, sensitivity tests showed improved performance with observational radar profiler nudging, and so all available archived profiler data were used.

---

**Figure 2-1: Radar Profilers throughout CONUS during the 2012 Season; National Profiler Network (NPN) in blue and Cooperative Agency Profilers (CAP) in red**

Further details about WRF preprocessing can be found at the following URL: [http://www2.mmm.ucar.edu/wrf/users/docs/user_guide/users_guide_chap3.htm](http://www2.mmm.ucar.edu/wrf/users/docs/user_guide/users_guide_chap3.htm).

### 2.2 WPS QUALITY ASSURANCE

As described above, data from the GCIP NCEP Eta archive were processed with WPS to prepare WRF initial conditions, boundary conditions, and FDDA nudging files. This archive was preferred because surface data were usually available in three-hour intervals. WPS will interpolate to create one-hour WRF input files. In many cases, the WPS can interpolate across periods of missing data. Figure 2-2: Missing Upper Air Data during WPS Preprocessing and Figure 2-3: Missing Surface Data during WPS.
Preprocessing summarize missing data during the May through September 2012 episode. Each figure is color coded by number of three-hour data periods that were missing or had contaminated data during each day in the five-month modeling season. As seen in Figure 2-2, most upper data were complete with notable exceptions on May 3, August 21 through 25, and September 1 through 3. Figure 2-3 shows that in addition to the days with extensive missing upper air data, the entire season had at least two 3-hour periods with problematic surface analysis data. Many days during June had particular hours with a temperature of zero degrees Celsius or zero wind speeds across the entire 12 km domain. These days were successfully processed by WPS. Other days that had complete data that included some corrupted hours caused WPS to crash. Missing data on May 3, May 17, August 21 through 25, and September 1 through 3 were patched with data from the NCEP NAM 12 km model as described above. The “patched” days are shown in Figure 2-4: WPS Patch with NCEP NAM Data. The criterion for patching was missing data greater than or equal to 12 hours (four three-hour contiguous periods). All other days had problematic hours removed from the ungribbed GCIP NCEP Eta data, and WPS was re-run. The METGRID program internally interpolated across the removed hours. Exceptions to the above procedure are May 3 and September 23, 24, and 27. On May 3, the alternate dataset had missing data and METGRID was used to interpolate across the missing data in the original GCIP NCEP Eta archive. Fortunately, on September 23, 24, and 27, missing data were not contiguous, and therefore METGRID could interpolate across the missing hours.
Figure 2-2: Missing Upper Air Data during WPS Preprocessing
Figure 2-3: Missing Surface Data during WPS Preprocessing
2.3 WRF MODEL CONFIGURATION

The selection of the final meteorological modeling configuration for the May through September 2012 episode resulted from numerous sensitivity tests and model performance evaluation. The final WRF parameterization schemes and options selected are shown in Table 2-1: 2015 Ozone Transport SIP Revision WRF Configuration.
Table 2-1: 2015 Ozone Transport SIP Revision WRF Configuration

<table>
<thead>
<tr>
<th>Domain</th>
<th>Nudging Type</th>
<th>PBL</th>
<th>Cumulus</th>
<th>Radiation</th>
<th>Land-Surface</th>
<th>Microphysics</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 km</td>
<td>3-D, Surface Analysis, PX Soil Nudging, NPN and CAP Radar Profiler Observations</td>
<td>YSU</td>
<td>Multiscale Kain-Fritsch</td>
<td>RRTM / Dudhia</td>
<td>Pleim-Xiu</td>
<td>WSM5</td>
</tr>
</tbody>
</table>

Note: RRTM = Rapid Radiative Transfer Model; YSU = Yonsei University (South Korea)

Modeling a five-month episode, such as the 2015 Ozone Transport SIP Revision modeling platform, benefits from using a land surface model. For periods as short as a month when archived data reflect the default WRF seasonal averages, simple thermal diffusion may provide adequate performance. However, during longer and varied meteorological regimes, modeling soil moisture as well as temperature within a vegetative canopy will provide more realistic surface fluxes. The selected WRF configuration used the Pleim-Xiu (PX) land surface model (LSM) and the PX Soil Nudging option. The Multiscale Kain-Fritsch cumulus parameterization feature modifies the partitioning between parameterized convection and explicit moisture microphysics so that this scheme can be used at all grid resolutions (Bullock, 2015).

WRF output was post-processed using the WRFCAMX version 4.6 utility to convert the WRF meteorological fields to the Comprehensive Air Quality Model with Extensions (CAMx) grid and input format (Environ, 2016). The WRFCAMX utility generates several alternative vertical diffusivity (Kv) files based upon multiple methodologies for estimating mixing given the same WRF meteorological fields. The WRF Kv option based upon the CMAQ PBL profile was selected.

3: WRF MODEL PERFORMANCE EVALUATION (MPE) TOOLS

3.1 OBSERVATIONS
To evaluate the performance of WRF, surface data for wind speed, wind direction, temperature and specific humidity were collected from the NOAA ds472.0 dataset and the Meteorological Assimilation Data Ingest System (MADIS). Across the na_12km domain there were over 2800 stations as shown in Figure 3-1: DS472.0 Stations used for WRF model validation for the 2015 Ozone NAAQS Transport SIP Revision.
Figure 3-1: DS472.0 Stations used for WRF model validation for the 2015 Ozone NAAQS Transport SIP Revision

In Section 3.2 Daily Model Performance Bar Plots bar plot panels are displayed comparing modeled and observed data are averaged across all ds472 sites. Furthermore, in the bar plots presented below, the nation-wide averages were calculated on a daily basis for each of the five months in the episode. A variety of statistical metrics for the meteorological variables of wins speed, wind direction, temperature, specific humidity and short-wave radiation is discussed below.

Alternative ways of aggregating and averaging data provide other performance information. For that reason, in addition to evaluation of model performance across the entire domain, Chapter 4: WRF Regional Modeling Performance presents monthly statistical performance is calculated at individual ds472 sites through a series of spatial plots. These are complemented by daily-averaged bar plots created by sub-regions of the country.
Table 3-1: Simple and Complex Meteorological Modeling Performance Benchmarks for Meteorological Surface Variables provides a summary of meteorological benchmarks for simple and complex terrains. The simple benchmark are more stringent since expectations are higher when terrain is simple, and meteorology is restricted to a single met regime such as stable high pressure (Emery et al. 2001). As air quality modeling was used for longer study periods with more synoptic variability and in regions with mountains and land sea breezes, additional benchmarks for complex meteorology were proposed (Kemball-Cook et al., 2005). Since the modeling episode and domain for this episode involve complex terrains and meteorology, the complex benchmarks were used for performance evaluation. However, WRF performance met many of the more stringent simple benchmarks for several parameters.

Table 3-1: Simple and Complex Meteorological Modeling Performance Benchmarks for Meteorological Surface Variables

<table>
<thead>
<tr>
<th>Meteorological Variable</th>
<th>Simple Benchmark</th>
<th>Complex Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Bias</td>
<td>≤ ±0.5˚K</td>
<td>≤ ±2.0˚K</td>
</tr>
<tr>
<td>Temperature Error</td>
<td>≤ 2.0˚K</td>
<td>≤ 3.5˚K</td>
</tr>
<tr>
<td>Mixing Ratio Bias</td>
<td>≤ ±1.0 g/kg</td>
<td></td>
</tr>
<tr>
<td>Mixing Ratio Error</td>
<td>≤ 2.0 g/kg</td>
<td></td>
</tr>
<tr>
<td>Wind speed Bias</td>
<td>≤ ±0.5 m/s</td>
<td>≤ ±1.5 m/s</td>
</tr>
<tr>
<td>Wind Speed RMSE</td>
<td>≤ 2.0 m/s</td>
<td>≤ 2.5 m/s</td>
</tr>
<tr>
<td>Wind Direction Bias</td>
<td>≤ ±10 degrees</td>
<td></td>
</tr>
<tr>
<td>Wind Direction Error</td>
<td>≤ 30 degrees</td>
<td>≤ 55 degrees</td>
</tr>
</tbody>
</table>

There are no “bright lines” for model performance. Rather, these guidelines summarize a broad consensus of performance goals across different modeling exercises. It is also important to note that statistical measures are often developed for data forecast modeling. Almost all tools calculate Bias, root mean square error (RMSE) and Mean Absolute Error (MAE). For this SIP, MAE and Bias were the primary metrics for performance evaluation for wind speed and direction, temperature, and humidity. RMSE is reported in some of the solar radiation graphics later in Section 3.3, and as a metric highlights outliers in measurements.

It is also possible to evaluate the agreement of model-predicted downward shortwave radiation against observed surface solar radiation. The observations are collected from the Surface Radiation (SURFRAD) Budget Network and the site locations are shown in Figure 3-2: SURFRAD site locations. Additional site data are listed in Table 3-2: SURFRAD Location Data. Due to the limited number of observational sites and the high temporal variability of clouds, data from SURFRAD site were aggregated and averaged across the entire five-month modeling period. WRF model comparisons to these data is discussed in Section 3.3 SURFRAD Site Performance Plots.
Figure 3-2: SURFRAD site locations

Table 3-2: SURFRAD Location Data

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
<th>Time Zone</th>
<th>Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BND*</td>
<td>Bondville, Illinois</td>
<td>40.05192°N</td>
<td>88.37309°W</td>
<td>230 m</td>
<td>6 hours from UTC</td>
<td>April 1994</td>
</tr>
<tr>
<td>TBL</td>
<td>Table Mountain, Boulder, Colorado</td>
<td>40.12498°N</td>
<td>105.23680°W</td>
<td>1689 m</td>
<td>7 hours from UTC</td>
<td>July 1995</td>
</tr>
<tr>
<td>DRA</td>
<td>Desert Rock, Nevada</td>
<td>36.62373°N</td>
<td>116.01947°W</td>
<td>1007 m</td>
<td>8 hours from UTC</td>
<td>March 1998</td>
</tr>
<tr>
<td>FPK</td>
<td>Fort Peck, Montana</td>
<td>48.30783°N</td>
<td>105.10170°W</td>
<td>634 m</td>
<td>7 hours from UTC</td>
<td>November 1994</td>
</tr>
<tr>
<td>GCM</td>
<td>Goodwin Creek, Mississippi</td>
<td>34.2547°N</td>
<td>89.8729°W</td>
<td>98 m</td>
<td>6 hours from UTC</td>
<td>December 1994</td>
</tr>
<tr>
<td>PSU</td>
<td>Penn. State Univ., Pennsylvania</td>
<td>40.72012°N</td>
<td>77.93085°W</td>
<td>376 m</td>
<td>5 hours from UTC</td>
<td>June 1998</td>
</tr>
<tr>
<td>SXF</td>
<td>Sioux Falls, South Dakota</td>
<td>43.73403°N</td>
<td>96.62328°W</td>
<td>473 m</td>
<td>6 hours from UTC</td>
<td>June 2003</td>
</tr>
<tr>
<td>SGP</td>
<td>ARM Southern Great Plains Facility, Oklahoma</td>
<td>36.60406°N</td>
<td>97.48525°W</td>
<td>314 m</td>
<td>6 hours from UTC</td>
<td></td>
</tr>
</tbody>
</table>
3.2 DAILY MODEL PERFORMANCE BAR PLOTS

As discussed in Section 3.1 Observations, bar plots of observational and model data are daily averages of groups of monitors. In this section, all ds472 data are evaluated in daily averages, but smaller regions defined by the National Climatic Data Center (NCDC) are evaluated in Chapter 4. For each of the months May through September 2012, three figures present daily performance statistics for wind speed and direction, temperature, and humidity evaluating WRF performance against the entire ds472.0 dataset. At the end of each bar plot, a final pair of bars shows the monthly average of each daily averaged meteorological variable preceding it.

Figure 3-3: May 2012 Wind Performance Bar Plots (all ds472 data) shows daily magnitude of observed and modeled wind speed, wind speed bias and error, observed and modeled wind direction, and wind direction bias and error averaged over all ds472 data. Likewise Figure 3-6: June 2012 Wind Performance Bar Plots (all ds472 data), Figure 3-9: July 2012 Wind Performance Bar Plots (all ds472 data), Figure 3-12: August 2012 Wind Performance Bar Plots (all ds472 data), and Figure 3-15: September 2012 Wind Performance Bar Plots (all ds472 data) show daily magnitude of observed and modeled wind speed, wind speed bias and error, observed and modeled wind direction, and wind direction bias and error averaged over all ds472 data for each subsequent month. Daily average wind speed errors were less than 1.5 m/s for the entire modeling period. Daily average wind speed bias was well below the ± 0.5 m/s expected for simple terrain and also met complex terrain benchmarks. Wind direction errors were approximately 30 degrees and much less than the benchmark for complex meteorology. Thus, on a continental scale, daily average statistics for wind performance are satisfactory. In Chapter 4 although regional differences in performance are discussed, each region meets all performance benchmarks.

Figure 3-4: May 2012 Temperature Performance Bar Plots (all ds472 data) shows daily magnitude of observed and modeled temperature, and temperature bias and error. Likewise Figure 3-7: June 2012 Relative Temperature Performance Bar Plot (all ds472 data), Figure 3-10: July 2012 Temperature Performance Bar Plots (all ds472 data), Figure 3-13: August 2012 Temperature Performance Bar Plots (all ds472 data), Figure 3-16: September 2012 Temperature Performance Bar Plots (all ds472 data) show daily magnitude of observed and modeled temperature, and temperature bias and error performance for each subsequent month. Average daily temperature errors were below 1.5 degrees K, and temperature bias was well below ±0.5 degrees K. Thus, on a continental scale, daily average temperature performance is satisfactory. The generally positive temperature bias seen for each month (except a few days in May and early July) shows more variability on a regional scale where negative biases appear. This is discussed again in Chapter 4.

Figure 3-5: May 2012 Humidity Performance Bar Plots (all ds472 data) shows the daily magnitude of observed and modeled humidity and humidity bias and error. Likewise Figure 3-8: June 2012 Relative Humidity Performance Bar Plot (all ds472 data), Figure 3-11: July 2012 Humidity Performance Bar Plots (all ds472 data), Figure 3-14: August 2012 Humidity Performance Bar Plots (all ds472 data), and Figure 3-17: September 2012 Humidity Performance Bar Plots (all ds472 data) show humidity performance for each subsequent month. Average daily humidity errors remained below 2.0 g/kg for all months, and were often closer to 1.0 gm/km. Humidity biases were less than ±1.0
gm/kg for each month. As with temperatures, humidity biases were generally positive for each month; however it does tend to vary by region as discussed in Chapter 4.

Figure 3-3: May 2012 Wind Performance Bar Plots (all ds472 data)
Figure 3-4: May 2012 Temperature Performance Bar Plots (all ds472 data)

Figure 3-5: May 2012 Humidity Performance Bar Plots (all ds472 data)
Figure 3-6: June 2012 Wind Performance Bar Plots (all ds472 data)
Figure 3-7: June 2012 Relative Temperature Performance Bar Plot (all ds472 data)

Figure 3-8: June 2012 Relative Humidity Performance Bar Plot (all ds472 data)
Figure 3-9: July 2012 Wind Performance Bar Plots (all ds472 data)
Figure 3-10: July 2012 Temperature Performance Bar Plots (all ds472 data)

Figure 3-11: July 2012 Humidity Performance Bar Plots (all ds472 data)
Figure 3-12: August 2012 Wind Performance Bar Plots (all ds472 data)
Figure 3-13: August 2012 Temperature Performance Bar Plots (all ds472 data)

Figure 3-14: August 2012 Humidity Performance Bar Plots (all ds472 data)
Figure 3-15: September 2012 Wind Performance Bar Plots (all ds472 data)
Figure 3-16: September 2012 Temperature Performance Bar Plots (all ds472 data)

Figure 3-17: September 2012 Humidity Performance Bar Plots (all ds472 data)
3.3 SURFRAD SITE PERFORMANCE PLOTS

Surface radiation budget data can be helpful for validating model performance. However, given that data are only available at a limited number of sites nationally as shown in Figure 3-2, these data need to be examined cautiously. Furthermore, modeling of clouds on a 12 km grid requires sub-grid scale parameterizations, and this poses challenges for capturing natural behavior, which may be on a short time scale. Two sets of SURFRAD plots follow below. The first series shows plots of monthly averages across three-hour intervals during the day. This helps mitigate the short time scale variability of clouds. The second set of plots shows longer averages across all five months. Each plot references the global Coordinated Universal Time (UTC), a time standard to coordinate data around the world and referenced to Greenwich Mean Time (GMT), which is five hours ahead of Eastern Standard Time (EST).

Each plot that follows has four panels with Mean Shortwave Radiation Bias in the upper left-hand corner, Mean Shortwave Radiation MAE in the upper right-hand corner, Mean Shortwave Radiation RMSE in the lower left corner and Mean Shortwave Radiation SDEV (Standard Deviation) Difference in the lower right. As discussed in Chapter 3 Observations, although Bias is generally well understood, the differences between MAE and RMSE are subtle. For this reason, a plot of standard deviation differences helps interpret the other statistical values. Color scales are consistent on all plots varying between ±400 Watt/m², 0-400 Watt/m², 0-400 Watt/m², and ±400 Watt/m² respectively. Figure 3-18: Color Scale for SURFAD Site Performance Plots shows the color scale and corresponding parameter value ranges for the plots.

There is no commonly used performance benchmark to evaluate shortwave radiation in the meteorological modeling used to for CAMx. The first step is to characterize the data itself. Shortwave radiation grows from close to 0 Watt/m² at night up to approximately 1000 Watt/m². Measurement accuracies are 15 W/m² or 5%, whichever is the largest. Thus, data uncertainties can range up to 50 Watt/m² during the middle of the day and down to 15 Watt/m² in morning or late afternoon. Attempts to identify patterns for shortwave bias and/or error also need to account for the variable local times associated with each three-hour UTC interval. Since 12-14 UTC plots reflect three hours earlier local time at western sites, bias and errors may reflect physical properties that change rapidly at that time. For example, some sites may be more or less prone to early morning clouds which is very site specific. In general, a careful reading of the biases shows values that are mostly small, sometimes small and negative, and probably close to the uncertainty of the observations during the day/night transition.

A quick survey of the figures that follow shows shortwave radiation MAE and RMSE values, while geographically variable, are not widely different. RMSE values are more accentuated from MAE for August and September and during mid-afternoon times. As discussed with Figure 3-38 and Figure 3-39 below, since the RMSE is not only a measure of mean error but also reflects the distribution of magnitude of errors is more likely to grow and exceed MAE during mid-afternoon times.
3.3.1 May 2012 Averaged Performance Metrics at SURFRAD Sites

Figure 3-18: Color Scale for SURFAD Site Performance Plots

Figure 3-19: May Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 12-14 UTC.
Figure 3-20: May Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 15-17 UTC.
Figure 3-21: May Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 18-20 UTC.
Figure 3-22: May Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 21-23 UTC.
3.3.2 June 2012 Averaged Performance Metrics at SURFRAD Sites

Figure 3-23: June Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 12-14 UTC.
Figure 3-24: June Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 15-17 UTC.
Figure 3-25: June Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 18-20 UTC.
Figure 3-26: June Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 21-23 UTC.
3.3.3 July 2012 Averaged Performance Metrics at SURFRAD Sites

Figure 3-27: July Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 12-14 UTC.

Figure 3-28: July Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 15-17 UTC.
Figure 3-29: July Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 18-20 UTC.

Figure 3-30: July Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 21-23 UTC.
3.3.4 August 2012 Averaged Performance Metrics at SURFRAD Sites

Figure 3-31: August Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 12-14 UTC.
Figure 3-32: August Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 15-17 UTC.
Figure 3-33: August Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 18-20 UTC.
Figure 3-34: August Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 21-23 UTC.
3.3.5 September 2012 Averaged Performance Metrics at SURFRAD Sites

Figure 3-35: September Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 12-14 UTC.
Figure 3-36: September Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 15-17 UTC.
Figure 3-37: September Monthly Averaged Shortwave Radiation Bias, MAE, RMSE and SDEV at SURFRAD sites between 18-20 UTC.
3.3.6 May through September Surface Radiation Performance Analysis

In addition to the monthly averages for three-hour intervals shown above, the five-month episodic average was also evaluated. Figure 3-38: May-September Averaged Shortwave Radiation Bias all four UTC time periods shows the average of spatial radiation for all four three-hour time periods over the entire ozone season. Each panel in Figure 3-38 retains the global Coordinated Universal Time (UTC).

The dominant features are a negative bias early in the day (except in Pennsylvania), and positive biases by the end of the day (except in Nevada). From a performance point of view, all these biases are less than ±75 Watt/m² and thus seem reasonable. Without further investigation, it is not clear why the bias, albeit not very large, changes sign with time of day.
Figure 3-39: May-September Averaged Shortwave Radiation Bias all four UTC time periods

One final way to assess broad shortwave radiation performance is to look at diurnal shortwave radiation variability averaged across all five months in Figure 3-39: May-September 2012 Averaged Diurnal plots for Bondville, Penn State, Sioux Falls, and Goodwin Creek Monitors. As with previous figures, these four sites have shortwave radiation statistics plotted in UTC coordinates. Thus, shortwave radiation in the observational and modeling data rises from 0 Watt/m² at 10 UTC or 5 A.M. local time for sites in the Central Time Zone and 9 UTC is also 5 A.M. local time for the EST.

In keeping with observations made with the first series of shortwave radiation plots, MAE is roughly 200 Watt/m² at all sites in mid-afternoon. As is always the case, RMSE is larger than MAE, and the variance of error magnitudes is enough to push RMSE to about 300 Watt/m² across a five-month period. Taking Figure 3-38 and Figure 3-39 together, the WRF model appears to have a generally weak daytime positive bias in shortwave radiation with errors, given some observational uncertainty, of approximately 15-20 %. This value suggests a need for further investigation. However, one possible explanation is suggested by the low biases. If there is a temporal mismatch of modeled and observational data due to passing clouds, which is a likely outcome of matching a gridded model value to a point measurement, then an over-
prediction followed by under-prediction of shortwave radiation would produce canceling biases but result in two positive errors calculated for the period of temporal mismatch. This suggests a need for further investigation of cloud performance, not only spatially but temporally.

Figure 3-40: May-September 2012 Averaged Diurnal plots for Bondville, Penn State, Sioux Falls, and Goodwin Creek Monitors

4: WRF REGIONAL MODELING PERFORMANCE

The previous chapter summarized performance for the entire United States by month using daily averaged statistical bar charts for wind speed, wind direction, temperature and humidity, Chapter 4 presents regional statistics calculated over smaller regions than the entire continental U.S. The five sections of Chapter 4 presents regional WRF performance for wind, temperature, and specific humidity (also called mixing ratio) for the months of May through September.

Each monthly evaluation section begins with a sub-section presenting six maps of the continental U.S. showing the spatial location of each ds472 site color coded for wind speed error, wind speed bias, temperature error, temperature bias, humidity error and humidity bias. The spatial plots are monthly averages of each meteorological variable at each site.

In Figure 4-2: May 2012 Mean Wind Speed Error at Each ds472.0 Monitor Location, the monthly averaged MAE for each ds472.0 site shows that the lowest errors were found throughout the east and along the west coast and remained below about 1.5 m/s. Slightly higher errors were found through the intermountain west. The same characteristic distribution for wind speed errors is reflected in Figure 4-32, Figure 4-65,
Figure 4-98, and Figure 4-131, for the months of June, July, August, and September, respectively. By September errors increase along the west coast.

In Figure 4-3: May 2012 Mean Bias of Wind Speed at Each ds472.0 Monitor Location, the spatial plots for wind speed bias indicate predominantly positive biases across eastern Texas and Oklahoma and throughout the central Mississippi and Ohio Valleys and the Upper Midwest. A mixture of positive and negative biases extends across the rest of the country, but tends more to negative values.

In Figure 4-4: May 2012 Mean Temperature Error at Each ds472.0 Monitor Location, temperature errors tend to be lower in the east than in the west; however, with few exceptions, all errors remain within the benchmark guidelines. Figure 4-5: May 2012 Mean Bias of Temperature at Each ds472.0 Monitor Location shows that negative temperature biases occur more frequently in the eastern U.S. This feature continues until later in the summer. By September, however, a warm temperature bias extends across much of the country as shown in Figure 4-134: September 2012 Mean Bias of Temperature at Each ds472.0 Monitor Location. The most notable outliers of temperature bias were low values at spots in the Colorado Rocky Mountains, bordering the Great Lakes, and along the California coast. The California coast is particularly prone to fog, and both the California and Great Lakes coast lines may have warm air over-riding cooler waters in a stable marine environment. In general, coastal features are not well captured by the 12 km model grid. California poses special challenges with a cold Pacific current and nearby coastal ranges, and those biases are pronounced during each month.

Spatial plots of MAE and bias for the May mixing ratio, or specific humidity, are shown in Figure 4-6: May 2012 Mean Mixing Ratio Error at Each ds472.0 Monitor Location and Figure 4-7: May 2012 Mean Bias of Mixing Ratio at Each ds472.0 Monitor Location. The plots show somewhat different behavior than later in the episode, for example, in Figure 4-135: September 2012 Mean Mixing Ratio Error at Each ds472.0 Monitor Location and Figure 4-136: September 2012 Mean Bias of Mixing Ratio at Each ds472.0 Monitor Location. During May, the lowest errors are in the northern part of the country. Mixing ratio errors are somewhat larger along the Gulf Coast. Mixing ratio biases tend to be uniformly positive throughout the eastern U.S. and the Intermountain West, and regionally, the most noticeable negative biases for mixing ratio are located in the central Great Plains and the central valley of California. During June, July, and August, humidity errors extend from the Gulf Coast northward and especially into the Southwest. The humidity biases for these months are almost entirely positive throughout the country. By September, the negative humidity biases seen in the Great Plains have returned, but are even more pronounced in the southern Great Plains near eastern Oklahoma and throughout the Midwest.

The spatial plots of May ds472 data are followed by daily averaged bar charts similar to those in Section 3.2, but in this Chapter 4 are calculated according to U.S. Climate Regions defined by the National Climatic Data Center (NCDC) as shown in Figure 4-1: U.S. Climate Regions (NCDC).
The ds472 data set described above was sorted by region, and statistics calculated for each NCDC region and month. Each month in Chapter 4 comprises a sub-section with the spatial plots of ds472 data followed by sub-sections of daily averaged ds470 data averaged across an NCDC sub-region. As noted in Section 3.2, averaging over smaller regions frequently increases the size of errors. However, the NCDC regional wind speed errors remain within acceptable bounds.

For example, the graphical spatial distribution of wind speed error and bias, temperature errors and bias, and humidity errors and bias averaged for all of May 2012 shown above in Figure 4-2: May 2012 Mean Wind Speed Error at Each ds472.0 Monitor Location through Figure 4-7: May 2012 Mean Bias of Mixing Ratio at Each ds472.0 Monitor Location is shown in greater detail in Figure 4-8: May Wind Performance Bar Plots (NCDC Northeast Region), through Figure 4-10: May Humidity Performance Bar Plots (NCDC Northeast Region) This series of May daily averaged bar plots for the NCDC region is repeated for each of the remaining NCDC regions through Figure 4-31: May Humidity Bar Plots (NCDC West Region). In the following subsequent subsections of Chapter 4, each month will have a series of graphical spatial plots followed by bar plots for each of the nine NCDC regions shown in Figure 4-1: U.S. Climate Regions (NCDC).

Each series of bar charts for a given NCDC region can be compared to the graphical spatial plots that begin each monthly section. Each type of figure is useful in a
complementary way: the bar charts of daily averages by a sub-section of the United States can be compared to the spatial distribution of performance at all the individual ds472 sites averaged across the month. The bar charts provide a higher resolution of temporal averaging across a sub-region while the graphical spatial plots of individual ds472 sites provides site-specific spatial performance averaged across the entire month.

4.1 MAY 2012 REGIONAL PERFORMANCE EVALUATION

4.1.1 May 2012 Averaged Performance Metrics by ds472.0 Site

Figure 4-2: May 2012 Mean Wind Speed Error at Each ds472.0 Monitor Location
Figure 4-3: May 2012 Mean Bias of Wind Speed at Each ds472.0 Monitor Location

Figure 4-4: May 2012 Mean Temperature Error at Each ds472.0 Monitor Location
Figure 4-5: May 2012 Mean Bias of Temperature at Each ds472.0 Monitor Location

Figure 4-6: May 2012 Mean Mixing Ratio Error at Each ds472.0 Monitor Location
Figure 4-7: May 2012 Mean Bias of Mixing Ratio at Each ds472.0 Monitor Location
4.1.2 May 2012 Northeast Region Performance

Figure 4-8: May Wind Performance Bar Plots (NCDC Northeast Region)
Figure 4-9: May Temperature Performance Bar Plots (NCDC Northeast Region)

Figure 4-10: May Humidity Performance Bar Plots (NCDC Northeast Region)
4.1.3 May 2012 Upper Midwest Performance

Figure 4-11: May Wind Bar Plots (NCDC Midwest Region)
Figure 4-12: May Temperature Bar Plots (NCDC Midwest Region)

Figure 4-13: May Humidity Bar Plots (NCDC Midwest Region)
4.1.4 May 2012 Ohio Valley Performance

Figure 4-14 May Wind Bar Plots (NCDC Ohio Valley Region)
Figure 4-15: May Temperature Bar Plots (NCDC Ohio Valley Region)

Figure 4-16: May Humidity Bar Plots (NCDC Ohio Valley Region)
4.1.5 May 2012 Southeast Performance

Figure 4-17: May Wind Bar Plots (NCDC Southeast Region)
Figure 4-18: May Temperature Bar Plots (NCDC Southeast Region)

Figure 4-19: May Humidity Bar Plots (NCDC Southeast Region)
4.1.6 May 2012 South Performance

Observed/Predicted Windspeed

Bias/Gross Error Windspeed

Observed/Predicted Wind Direction

Bias/Gross Error Wind Direction

Figure 4-20: May Wind Bar Plots (NCDC South Region)
Figure 4-21: May Temperature Bar Plots (NCDC South Region)

Figure 4-22: May Humidity Bar Plots (NCDC South Region)
4.1.7 May 2012 Southwest Performance

Figure 4-23: May Wind Bar Plots (NCDC Southwest Region)
Figure 4-24: May Temperature Bar Plots (NCDC Southwest Region)

Figure 4-25: May Humidity Bar Plots (NCDC Southwest Region)
4.1.8 May 2012 Northern Rockies and Plains Performance

Figure 4-26: May Wind Bar Plots (NCDC Northern Rockies and Plains Region)
Figure 4-27: May Temperature Bar Plots (NCDC Northern Rockies and Plains Region)

Figure 4-28: May Humidity Bar Plots (NCDC Northern Rockies and Plains Region)
Figure 4-29: May Wind Bar Plots (NCDC West Region)
Figure 4-30: May Temperature Bar Plots (NCDC West Region)

Figure 4-31: May Humidity Bar Plots (NCDC West Region)
4.2 JUNE 2012 REGIONAL PERFORMANCE EVALUATION

4.2.1 June 2012 Averaged Performance Metrics by ds472.0 Site

Figure 4-32: June 2012 Mean Wind Speed Error at Each ds472.0 Monitor Location

Figure 4-33: June 2012 Mean Bias of Wind Speed at Each ds472.0 Monitor Location
Figure 4-34: June 2012 Mean Temperature Error at Each ds472.0 Monitor Location

Figure 4-35: June 2012 Mean Bias of Temperature at Each ds472.0 Monitor Location
Figure 4-36: June 2012 Mean Mixing Ratio Error at Each ds472.0 Monitor Location

Figure 4-37: June 2012 Mean Bias of Mixing Ratio at Each ds472.0 Monitor Location
4.2.2 June 2012 Northeast Region Performance

Figure 4-38: June Wind Bar Plots (NCDC Northeast Region)
Figure 4-39: June Temperature Plots (NCDC Northeast Region)

Figure 4-40: June Wind Humidity Plots (NCDC Northeast Region)
4.2.3  June 2012 Upper Midwest Region Performance

Figure 4-41: June Wind Plots (NCDC Upper Midwest Region)
Figure 4-42: June Temperature Plots (NCDC Upper Midwest Region)

Figure 4-43: June Humidity Plots (NCDC Upper Midwest Region)
4.2.4  June 2012 Ohio Valley Region Performance

Figure 4-44: June Wind Plots (NCDC Ohio Valley Region)
Figure 4-45: June Temperature Plots (NCDC Ohio Valley Region)

Figure 4-46: June Humidity Plots (NCDC Ohio Valley Region)
4.2.5 June 2012 Southeast Region Performance

Figure 4-47: June Wind Plots (NCDC Southeast Region)
Figure 4-48: June Temperature Plots (NCDC Southeast Region)

Figure 4-49: June Humidity Plots (NCDC Southeast Region)
4.2.6 June 2012 South Region Performance

Figure 4-50: June Wind Plots (NCDC South Region)
Figure 4-51: June Temperature Plots (NCDC South Region)

Figure 4-52: June Humidity Plots (NCDC South Region)
4.2.7 June 2012 Southwest Region Performance

Figure 4-53: June Wind Plots (NCDC Southwest Region)
Figure 4-54: June Temperature Plots (NCDC Southwest Region)

Figure 4-55: June Humidity Plots (NCDC Southwest Region)
4.2.8  June 2012 Northern Rockies and Plains Region Performance

Figure 4-56: June Wind Plots (NCDC Northern Rockies and Plains Region)
Figure 4-57: June Temperature Plots (NCDC Northern Rockies and Plains Region)

Figure 4-58: June Humidity Plots (NCDC Northern Rockies and Plains Region)
4.2.9 June 2012 Northwest Region Performance

Figure 4-59: June Wind Plots (NCDC Northwest Region)
Figure 4-60: June Temperature Plots (NCDC Northwest Region)

Figure 4-61: June Humidity Plots (NCDC Northwest Region)
4.2.10 June 2012 West Region Performance

Figure 4-62: June Wind Plots (NCDC West Region)
Figure 4-63: June Temperature Plots (NCDC West Region)

Figure 4-64: June Humidity Plots (NCDC West Region)
4.3 JULY 2012 REGIONAL PERFORMANCE EVALUATION

4.3.1 July 2012 Averaged Performance Metrics by ds472.0 Site

Figure 4-65: July 2012 Mean Wind Speed Error at Each ds472.0 Monitor Location

Figure 4-66: July 2012 Mean Bias of Wind Speed at Each ds472.0 Monitor Location
Figure 4-67: July 2012 Mean Temperature Error at Each ds472.0 Monitor Location

Figure 4-68: July 2012 Mean Bias of Temperature at Each ds472.0 Monitor Location
Figure 4-69: July 2012 Mean Mixing Ratio Error at Each ds472.0 Monitor Location

Figure 4-70: July 2012 Mean Bias of Mixing Ratio at Each ds472.0 Monitor Location
4.3.2 July 2012 Northeast Region Performance

Figure 4-71: July Wind Plots (NCDC Northeast Region)
Figure 4-72: July Temperature Plots (NCDC Northeast Region)

Figure 4-73: July Humidity Plots (NCDC Northeast Region)
4.3.3 July 2012 Upper Midwest Region Performance

Figure 4-74: July Wind Plots (NCDC Upper Midwest Region)
Figure 4-75: July Temperature Plots (NCDC Upper Midwest Region)

Figure 4-76: July Humidity Plots (NCDC Upper Midwest Region)
4.3.4 July 2012 Ohio Valley Region Performance

![Graphs showing observed/predicted windspeed and wind direction for July 2012 in the Ohio Valley Region](image)

Figure 4-77: July Wind Plots (NCDC Ohio Valley Region)
Figure 4-78: July Temperature Plots (NCDC Ohio Valley Region)

Figure 4-79: July Humidity Plots (NCDC Ohio Valley Region)
4.3.5 July 2012 Southeast Region Performance

**Observed/Predicted Windspeed**

- **Wind Spd Mean OBS**
- **Wind Spd Mean PRD**

**Bias/Gross Error Windspeed**

- **Wind Spd**
- **Bias**
- **Wind Spd Gross Error**

**Observed/Predicted Wind Direction**

- **Wind Dir Mean OBS**
- **Wind Dir Mean PRD**

**Bias/Gross Error Wind Direction**

- **Wind Dir**
- **Bias**
- **Wind Dir Gross Error**

Figure 4-80: July Wind Plots (NCDC Southeast Region)
Figure 4-81: July Temperature Plots (NCDC Southeast Region)

Figure 4-82: July Humidity Plots (NCDC Southeast Region)
4.3.6 July 2012 South Region Performance

Figure 4-83: July Wind Plots (NCDC South Region)
Figure 4-84: July Temperature Plots (NCDC South Region)

Figure 4-85: July Humidity Plots (NCDC South Region)
4.3.7 July 2012 Southwest Region Performance

Figure 4-86: July Wind Plots (NCDC Southwest Region)
Figure 4-87: July Temperature Plots (NCDC Southwest Region)

Figure 4-88: July Humidity Plots (NCDC Southwest Region)
4.3.8 July 2012 Northern Rockies and Plains Region Performance

Figure 4-89: July Wind Plots (NCDC Northern Rockies and Plains Region)
Figure 4-90: July Temperature Plots (NCDC Northern Rockies and Plains Region)

Figure 4-91: July Humidity Plots (NCDC Northern Rockies and Plains Region)
4.3.9 July 2012 Northwest Region Performance

**Figure 4-92: July Wind Plots (NCDC Northwest Region)**
Figure 4-93: July Temperature Plots (NCDC Northwest Region)

Figure 4-94: July Humidity Plots (NCDC Northwest Region)
4.3.10 July 2012 West Region Performance

Figure 4-95: July Wind Plots (NCDC West Region)
Figure 4-96: July Temperature Plots (NCDC West Region)

Figure 4-97: July Humidity Plots (NCDC West Region)
4.4 AUGUST 2012 REGIONAL PERFORMANCE EVALUATION

4.4.1 August 2012 Averaged Performance Metrics by ds472.0 Site

Figure 4-98: August 2012 Mean Wind Speed Error at Each ds472.0 Monitor Location

Figure 4-99: August 2012 Mean Bias of Wind Speed at Each ds472.0 Monitor Location
Figure 4-100: August 2012 Mean Temperature Error at Each ds472.0 Monitor Location

Figure 4-101: August 2012 Mean Bias of Temperature at Each ds472.0 Monitor Location
Figure 4-102: August 2012 Mean Mixing Ratio Error at Each ds472.0 Monitor Location

Figure 4-103: August 2012 Mean Bias of Mixing Ratio at Each ds472.0 Monitor Location
4.4.2 August 2012 Northeast Region Performance

Figure 4-104: August Wind Plots (NCDC Northeast Region)
4.4.3 August 2012 Upper Midwest Region Performance

Figure 4-107: August Wind Plots (NCDC Upper Midwest Region)
Figure 4-108: August Temperature Plots (NCDC Upper Midwest Region)

Figure 4-109: August Humidity Plots (NCDC Upper Midwest Region)
Figure 4-110: August Wind Plots (NCDC Ohio Valley Region)
Figure 4-111: August Temperature Plots (NCDC Ohio Valley Region)

Figure 4-112: August Humidity Plots (NCDC Ohio Valley Region)
4.4.5 August 2012 Southeast Region Performance

Figure 4-113: August Wind Plots (NCDC Southeast Region)
Figure 4-114: August Temperature Plots (NCDC Southeast Region)

Figure 4-115: August Humidity Plots (NCDC Southeast Region)
4.4.6 August 2012 South Region Performance

Figure 4-116: August Wind Plots (NCDC South Region)
Figure 4-117: August Temperature Plots (NCDC South Region)

Figure 4-118: August Humidity Plots (NCDC South Region)
4.4.7 August 2012 Southwest Region Performance

Figure 4-119: August Wind Plots (NCDC Southwest Region)
Figure 4-120: August Temperature Plots (NCDC Southwest Region)

Figure 4-121: August Humidity Plots (NCDC Southwest Region)
4.4.8 August 2012 Northern Rockies and Plains Region Performance

Figure 4-122: August Wind Plots (NCDC Northern Rockies and Plains Region)
Figure 4-123: August Temperature Plots (NCDC Northern Rockies and Plains Region)

Figure 4-124: August Humidity Plots (NCDC Northern Rockies and Plains Region)
4.4.9 August 2012 Northwest Region Performance

Figure 4-125: August Wind Plots (NCDC Northwest Region)
Figure 4-126: August Temperature Plots (NCDC Northwest Region)

Figure 4-127: August Humidity Plots (NCDC Northwest Region)
4.4.10 August 2012 West Region Performance

Figure 4-128: August Wind Plots (NCDC West Region)
Figure 4-129: August Temperature Plots (NCDC West Region)

Figure 4-130: August Humidity Plots (NCDC West Region)
4.5 SEPTEMBER 2012 REGIONAL PERFORMANCE EVALUATION

4.5.1 September 2012 Averaged Performance Metrics by ds472.0 Site

Figure 4-131: September 2012 Mean Wind Speed Error at Each ds472.0 Monitor Location

Figure 4-132: September 2012 Mean Bias of Wind Speed at Each ds472.0 Monitor Location
Figure 4-133: September 2012 Mean Temperature Error at Each ds472.0 Monitor Location

Figure 4-134: September 2012 Mean Bias of Temperature at Each ds472.0 Monitor Location
Figure 4-135: September 2012 Mean Mixing Ratio Error at Each ds472.0 Monitor Location

Figure 4-136: September 2012 Mean Bias of Mixing Ratio at Each ds472.0 Monitor Location
4.5.2  September 2012 Northeast Region Performance

Figure 4-137: September Wind Plots (NCDC Northeast Region)
Figure 4-138: September Temperature Plots (NCDC Northeast Region)

Figure 4-139: September Humidity Plots (NCDC Northeast Region)
4.5.3 September 2012 Upper Midwest Region Performance

Figure 4-140: September Wind Plots (NCDC Upper Midwest Region)
Figure 4-141: September Temperature Plots (NCDC Upper Midwest Region)

Figure 4-142: September Humidity Plots (NCDC Upper Midwest Region)
4.5.4 September 2012 Ohio Valley Region Performance

Figure 4-143: September Wind Plots (NCDC Ohio Valley Region)
Figure 4-144: September Temperature Plots (NCDC Ohio Valley Region)

Figure 4-145: September Humidity Plots (NCDC Ohio Valley Region)
4.5.5 September 2012 Southeast Region Performance

Figure 4-146: September Wind Plots (NCDC Southeast Region)
Figure 4-147: September Temperature Plots (NCDC Southeast Region)

Figure 4-148: September Humidity Plots (NCDC Southeast Region)
4.5.6 September 2012 South Region Performance

Figure 4-149: September Wind Plots (NCDC South Region)
Figure 4-150: September Temperature Plots (NCDC South Region)

Figure 4-151: September Humidity Plots (NCDC South Region)
4.5.7 September 2012 Southwest Region Performance

Figure 4-152: September Wind Plots (NCDC Southwest Region)
Figure 4-153: September Temperature Plots (NCDC Southwest Region)

Figure 4-154: September Humidity Plots (NCDC Southwest Region)
4.5.8 September 2012 Northern Rockies and Plains Region Performance

Figure 4-155: September Wind Plots (NCDC Northern Rockies and Plains Region)
Figure 4-156: September Temperature Plots (NCDC Northern Rockies and Plains Region)

Figure 4-157: September Humidity Plots (NCDC Northern Rockies and Plains Region)
4.5.9 September 2012 Northwest Region Performance

Figure 4-158: September Wind Plots (NCDC Northwest Region)
Figure 4-159: September Temperature Plots (NCDC Northwest Region)

Figure 4-160: September Humidity Plots (NCDC Northwest Region)
4.5.10 September 2012 West Region Performance

Figure 4-161: September Wind Plots (NCDC West Region)
Figure 4-162: September Temperature Plots (NCDC West Region)

Figure 4-163: September Humidity Plots (NCDC West Region)
4.6 CONCLUSIONS

WRF modeling of the Good Neighbor 2012 season provided consistently good regional performance across several metrics. The spatial plots of monthly averaged shortwave radiation provided additional information about regional performance in addition to traditional metrics of daily averaged wind speed, wind direction, temperature and humidity. Regional and daily differences across such a large domain long modeling episode (five months) are expected, but performance stayed within or near expected guidance. In total, this meteorology was considered suitable for input to photochemical modeling.

5: REFERENCES


