

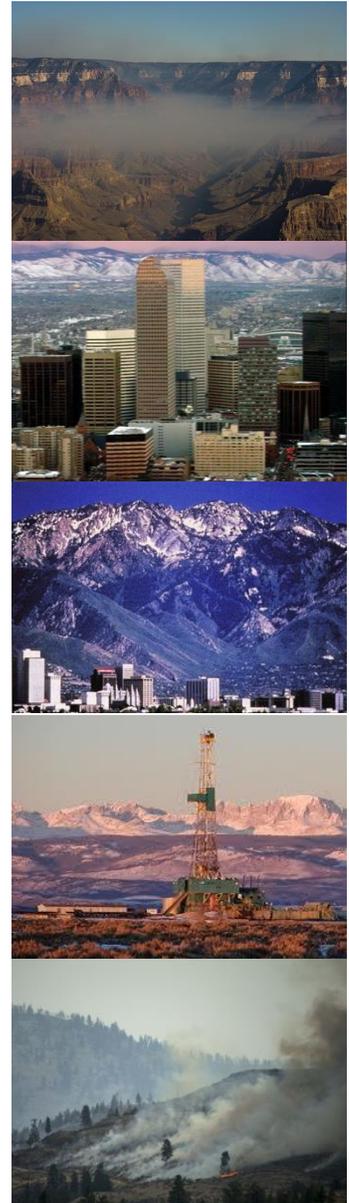
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**Western Air Quality Study (WAQS)  
Weather Research Forecast (WRF)  
Meteorological Model  
Final Modeling Protocol  
2014 Modeling Year**

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September 4, 2015

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## 1 Introduction

The Western Air Quality Study (WAQS) includes cooperators from U.S. Environmental Protection Agency (EPA) Region 8, United States Forest Service (USFS), Bureau of Land Management (BLM), National Park Service (NPS), Fish and Wildlife Service (FWS) and state air quality management agencies (including Colorado, Utah, Wyoming and New Mexico). The WAQS is intended to facilitate air resource analyses for federal and state agencies in the intermountain western U.S. toward improved information for the public and stakeholders as a part of air quality planning including those undertaken under the National Environmental Policy Act (NEPA) as well as other studies. Funded by the EPA, BLM, and the USFS, and with in-kind support from state air agencies, by working closely with cooperators and overseeing the various agreements, the main focus of the study is on assessing the environmental impacts of sources related to oil and gas development and production. In particular, the cooperators will use photochemical grid models (PGMs) to quantify the impacts of proposed oil and gas development projects within the WAQS region on current and future air quality, including ozone and visibility levels in National Parks and Wilderness Areas.

Meteorological inputs are a key component for WAQS PGM modeling. Meteorological inputs for PGMs are generated using prognostic meteorological models. The WAQS meteorology modeling team consists of the University of North Carolina (UNC) at Chapel Hill and Ramboll Environ US Corporation. The team will build off of previous, recent modeling studies of meteorology in the Western U.S. to produce 2014 meteorology input data for input to regional air quality modeling studies.

Under the Three-State Air Quality Study (3SAQS), which was a predecessor of the WAQS, we simulated the years 2008 and 2011 for assessing the impacts of oil and gas development on local and regional air quality. The year 2008 was selected for the 3SAQS to leverage work completed during the West-wide Jumpstart Air Quality Modeling Study ([WestJumpAQMS](#)). With the release of the year 2011 EPA National Emission Inventory (NEI), the availability of new ozone monitoring data in oil and gas basins in the three-state region, and updates to the oil and gas emission inventories, the 3SAQS created a 2011 base year modeling platform. In anticipation of the next triennial NEI cycle, we are starting the development of a 2014 base year modeling platform by simulating the 2014 meteorology.

While the 2011 simulations performed reasonably well, a deficiency in wintertime ozone was noted in the oil and gas basins of the intermountain west. An effort was put forth to formulate a wintertime WRF configuration to improve the representation of the cold air pool (CAP) events in the WRF meteorological simulations used to drive the AQ models.<sup>1</sup> Snow cover is a key meteorological parameter for simulating CAPs. Snow cover favors a persistent stable boundary

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<sup>1</sup> Bowden, J., Talgo, K., Adelman, Z. (2015, August) WAQS WRF Model Winter Modeling Application/Evaluation, Chapel Hill, NC: University of North Carolina.

layer and other synoptic and mesoscale atmospheric circulations, in particular warming in the free atmosphere associated with warm air advection and subsidence.<sup>2</sup> Snow cover also increases the surface albedo and near-surface actinic flux, leading to enhanced wintertime photolysis rates that may produce high near-surface ozone concentrations.<sup>3</sup> By integrating high-resolution snow cover/snow depth input data into the 2011 WRF simulations we showed an incremental improvement in the representation of CAPs in WRF. Improving the representation of the temperature inversions associated with CAPs enhanced the ability of the regional air quality model to simulate elevated ozone events observed during some CAP periods. The winter WRF configuration developed during the 2011 modeling will be implemented in the 2014 WRF simulation.

This document is a modeling protocol for the 2014 WAQS meteorological modeling. This protocol details the modeling inputs/outputs, modeling procedures, and evaluation procedures that will be used by the WAQS modeling team for the 2014 WRF modeling.

## 1.1 Organization of the WRF Modeling Protocol

This document presents the WAQS protocol for simulating and evaluating year 2014 meteorology with WRF. Although the WAQS modeling analysis is not currently being performed to fill any particular regulatory requirement, such as a State Implementation Plan (SIP) attainment demonstration, EIA, or Resource Management Plan (RMP) as part of the National Environmental Policy Act (NEPA), it is being conducted with the same level of technical rigor as a SIP-type analysis and may ultimately be used as a basis for regulatory air quality modeling.

This WAQS 2014 WRF Modeling Protocol has the following sections:

1. Introduction: Presents a summary of the background, purpose and objectives of the study.
2. Modeling Domain Specifications: Presents the modeling domains selected for the study
3. Modeling Specifications: Presents the modeling software selected for this study and how these models will be applied to simulate 2014 air quality. This section describes how the meteorological modeling and the WRF model evaluation will be conducted. It presents the emissions input data and how the emissions modeling will be conducted. This section also describes the procedures for conducting the photochemical grid modeling.
4. Model Performance Evaluation: Provides the procedures for conducting the model performance evaluation of the photochemical grid models.

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<sup>2</sup> Laraeu, N. P., E. Crosman, C. D. Whiteman, J.D. Horel, S. W. Hoch, W. O. J. Brown, and T. W. Horst, 2010: The Persistent Cold-Air Pool Study, *Bull. Am. Meteorol. Soc.*, 94 (1), 51-63 doi:10.1174/Bams-D-11-00255.1.

<sup>3</sup> Schnell, R.C. Oltmans, S.J., Neely, R.R., Endres, M.S., Molenaar, J.V., & White, A.B. (2009). Rapid photochemical production of ozone at high concentrations in a rural site during winter, *Nature Geoscience*, 2, 120-122. doi: 10.1038/NGEO415.

## 1.2 Project Participants

Cooperators on the WAQS include Federal agencies, state Divisions of Air Quality, and contractors. Contributions from Federal agencies include (NPS, USFS, FWS, BLM and EPA Region 8). Several Western states, including Colorado, Utah, Wyoming and New Mexico as well as several contractors are involved in the study. The WAQS is facilitated and managed by the Western States Air Resources Council (WESTAR). UNC and Ramboll Environ are conducting the meteorology, emissions, and air quality modeling and analysis. The Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University is developing and hosting the Western Data Warehouse (WDW) for delivering modeling data, results, and analysis. Key contacts and their roles in the WAQS are listed in Table 1-1.

**Table 1-1. Key contacts for the WAQS 2014 modeling platform.**

Name	Role	Organization/Contact
Tom Moore	Manager WAQS and WDW	WESTAR c/o CSU/CIRA 1375 Campus Delivery Fort Collins, CO 80523 (970) 491-8837 <a href="mailto:tmoore@westar.org">tmoore@westar.org</a>
Zac Adelman	UNC Lead	University of North Carolina Institute for the Environment 100 Europa Dr., Suite 490, CB 1105 Chapel Hill, NC 27517 (919) 962-8510 <a href="mailto:zac@unc.edu">zac@unc.edu</a>
Ralph Morris	Ramboll Environ Lead	Ramboll-Environ 773 San Marin Drive, Suite 2115 Novato, CA 94998 (415) 899-0708 <a href="mailto:rmorris@environcorp.com">rmorris@environcorp.com</a>
Shawn McClure	CIRA and Data Warehouse Technical Lead	CSU/CIRA 1375 Campus Delivery Fort Collins, CO 80523 (970) 491-8598 <a href="mailto:shawn.mcclure@colostate.edu">shawn.mcclure@colostate.edu</a>

## 1.3 Related Studies

There are numerous meteorological modeling and data analysis studies related to the WAQS modeling with results and approaches that are being used to guide the 2014 WRF modeling. A few of the more recent and relevant studies are listed below.

### **1.3.1 WestJumpAQMS**

The West-wide Jump-start Air Quality Modeling Study (WestJumpAQMS) conducted meteorological, emissions and photochemical grid modeling of the western U.S. for the 2008 calendar year to investigate source-receptor relationships for ozone, particulate matter, visibility and deposition. WRF meteorological and SMOKE emissions modeling was conducted for a 36-km continental U.S., 12-km western U.S., and 4-km intermountain west domain. Ozone and PM source apportionment modeling was also conducted with CAMx to examine state-specific and source category-specific air quality impacts. The WestJumpAQMS 2008 36/12-km modeling platform was adapted by 3SAQS for their preliminary modeling using the 2008 year. Details on the WestJumpAQMS can be found at:

<http://www.wrapair2.org/WestJumpAQMS.aspx>

### **1.3.2 2008 3SAQS Modeling**

Year 2008 emissions and PGM modeling was conducted for the 3SAQS to provide initial results to use in near-term NEPA modeling analyses. The WRF meteorological input data for the PGM simulations were taken directly from the WestJumpAQMS. The majority of the SMOKE emissions input data were also taken from the WestJumpAQMS with the exception of the on-road mobile sector where 3SAQS used SMOKE-MOVES as compared to running MOVES in the inventory mode in WestJumpAQMS. The 3SAQS 2008 emissions also included targeted ancillary data improvements for some inventory sectors, including livestock ammonia, non-point, and residential wood combustion. PGM modeling for the 3SAQS 2008 modeling platform was conducted for a 36-km continental U.S. and a 12-km western U.S. domain. These data are being distributed to cooperators in the 3SAQS via the Three-State Data Warehouse (3SDW). Details on the 3SAQS and 3SDW can be found at:

<http://vista.cira.colostate.edu/tsdw>

### **1.3.3 2011 3SAQS Modeling**

The pilot (October 2012 through September 2014) Three State Air Quality Study (3SAQS) performed meteorological modeling for the year 2011 using the Weather Research and Forecasting (WRF) model. The meteorological simulations used a 36-km continental U.S. (CONUS), 12-km western U.S. (WESTUS), and 4-km three-state domain (3SD) covering the states of Colorado, Wyoming, and Utah and neighboring areas. The 2011 meteorological fields were subsequently used in photochemical grid model (PGM) application and model performance evaluation (MPE). The MPE for 2011 identified areas of poor model performance within the three-state study region. Of particular concern was the wintertime model performance in two locations in the intermountain west. High winter ozone events have occurred in the Jonah-Pinedale Anticline Development (JPAD) area in the Upper Green River area of southwest Wyoming and the Uinta Basin, Utah, both sites for rural oil and gas development. The 3SAQS identified that WRF did reproduce the low wind speeds, temperature inversions, and dry conditions associated with elevated winter ozone events. Subsequent efforts were put forth in the Winter Modeling Application/Evaluation task to improve the representation of meteorological processes important in the buildup of wintertime ozone

precursors. WRF configuration improvements will be implemented in an improved 2014 modeling platform.

#### **1.4 Overview of 3SAQS 2014 WRF Modeling Approach**

The WRF meteorological model will be applied for the 2014 calendar year using the 36/12/4-km domain structure used for the WAQS 2011 modeling. The WRF modeling results for the 2014 annual period will be evaluated against surface meteorological observations of wind speed, wind direction, temperature and humidity and the WRF model performance will be compared against meteorological modeling benchmarks and with past regional meteorological model performance evaluations (UNC and ENVIRON, 2012). The WRF precipitation fields will also be compared against analysis fields that were based on observations using the Parameter-elevation Relationships on Independent Slopes Model ([PRISM](#)). Snow cover will be evaluated against the Snow Data Assimilation System ([SNODAS](#)) data.

## **2 Model Selection**

This section discusses the meteorology modeling software used for the WAQS. The modeling software selection methodology follows EPA's guidance for regulatory modeling in support of ozone and PM<sub>2.5</sub> attainment demonstration modeling and showing reasonable progress with visibility goals.<sup>4</sup> EPA recommends that models be selected for regulatory ozone, PM and visibility studies on a "case-by-case" basis with appropriate consideration given to the candidate models':

- Technical formulation, capabilities and features;
- Pertinent peer-review and performance evaluation history;
- Public availability; and
- Demonstrated success in similar regulatory applications.

All of these considerations should be examined for each class of models to be used (e.g., emissions, meteorological, and photochemical) in part because EPA no longer recommends a specific model or suite of photochemical models for regulatory application as it did twenty years ago in the first ozone SIP modeling guidance.<sup>5</sup> Below we identify the most appropriate candidate models for the WAQS requirements, discuss the candidate model attributes and then justify the model selected using the four criteria above. The science configurations recommended for each model in this study are introduced in Chapter 3.

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<sup>4</sup> EPA. (2014) Guidance on the Use of Models and Other Analyses for Demonstrating Attainment of Air Quality Goals for Ozone, PM<sub>2.5</sub> and Regional Haze. U.S. Environmental Protection Agency, Research Triangle Park, NC.

<sup>5</sup> EPA (1991) Guideline on the Regulatory Application of the Urban Airshed Model. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, technical Support Division, Source Receptor Analysis Branch, Research Triangle Park, NC.

## 2.1 Justification and Overview of Selected Models

There are two prognostic meteorological models that are routinely used in the U.S. in photochemical grid modeling studies:

- The fifth generation Mesoscale Model (MM5); and
- The Weather Research Forecasting (WRF) model.

Both MM5 and WRF were developed by the community, with the National Center for Atmospheric Research (NCAR) providing coordination and support. For many years the MM5 model was widely used by both the meteorological research as well as the air quality modeling community. Starting around the year 2000, the WRF model started to be developed as a technical improvement and replacement to MM5 and today NCAR no longer supports MM5.

Based on the following four selection criteria, we selected WRF for simulating the WAQS 2014 meteorology:

- **Technical:** WRF is based on more recent physics and computing techniques and represents a technical improvement over MM5. WRF has numerous new capabilities and features not available in MM5 and, unlike MM5, it is supported by NCAR.
- **Performance:** WRF is being used by thousands of users and has been subjected to a community peer-reviewed development process using the latest algorithms and physics. In general, it appears that WRF is better able to reproduce the observed meteorological variables so it performs better than MM5. WRF is amassing a rich publication and application history.
- **Public Availability:** WRF is publicly available and can be downloaded from the WRF website with no costs or restrictions. MM5 is also publicly available.
- **Demonstrated Success:** The recent Denver ozone modeling of the 2008 episode using WRF has produced better meteorological and ozone model performance than achieved in past Denver ozone modeling efforts of 2002 and 2006 that used MM5 (Morris et al., 2012a,b).

More details on the selected WRF meteorological model are provided below.

The non-hydrostatic version of the Advanced Research version of the Weather Research Forecast (WRF-ARW<sup>6</sup>) model (Skamarock et al. 2004; 2005; 2006; Michalakes et al. 1998; 2001; 2004) is a three-dimensional, limited-area, primitive equation, prognostic model that has been used widely in regional air quality model applications. The basic model has been under continuous development, improvement, testing and open peer-review for more than 10 years and has been used world-wide by hundreds of scientists for a variety of mesoscale studies, including cyclogenesis, polar lows, cold-air damming, coastal fronts, severe thunderstorms, tropical storms, subtropical easterly jets, mesoscale convective complexes, desert mixed layers, urban-scale modeling, air quality studies, frontal weather, lake-effect snows, sea-breezes, orographically induced flows, and operational mesoscale forecasting. WRF is a next-generation mesoscale prognostic meteorological model routinely used for urban- and regional-scale photochemical, fine particulate and regional haze

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<sup>6</sup> All references to WRF in this document refer to the WRF-ARW

regulatory modeling studies. Developed jointly by the National Center for Atmospheric Research and the National Centers for Environmental Prediction, WRF is maintained and supported as a community model by researchers and practitioners around the globe. The code supports two modes: the Advanced Research WRF (ARW) version and the Non-hydrostatic Mesoscale Model (NMM) version. WRF-ARW has become the new standard model used in place of the older Mesoscale Meteorological Model (MM5) for regulatory air quality applications in the U.S. It is suitable for use in a broad spectrum of applications across scales ranging from hundreds of meters to thousands of kilometers.

### 3 Domain Selection

This section presents the model domain definitions for the WAQS 2014 WRF simulation, including the domain coverage, resolution, map projection, and nesting schemes for the high resolution sub-domains. The modeling domains for the WRF meteorological modeling are defined slightly larger than the PGM domains.

#### 3.1 Horizontal Modeling Domain

We selected the WAQS modeling domains as a trade-off between the need to have high resolution modeling for sources in the Inter-Mountain West versus ability to perform regional ozone and particulate matter source apportionment modeling among all of the western states. The WAQS 2014 modeling will use the same 36, 12 and 4-km domains as were used in the 3SAQS 2011 modeling. The WAQS 2014pre modeling will use 36, 12 and 4-km domains on the standard Lambert Conformal Projection (LCP) used for continental U.S. modeling domains. Table 3-1 includes the specifications for the following domains:

- A 36-km continental U.S. (CONUS) domain that is the same as used by the RPOs (e.g., WRAP) and most other recent modeling studies (e.g., Denver Ozone SIP). It is defined large enough so that the outer boundaries are far away from our primary areas of interest (i.e., western states).
- A 12-km western U.S. (WESTUS) domain is larger than used in WRAP and contains all of the WRAP and adjacent states as well as extending into Canada and Mexico.
- A 4-km three-state (3SAQS) domain focuses on the states of Colorado, Utah, Wyoming, and northern New Mexico.

The WRF computational grid was designed so that it can generate PGM meteorological inputs for the nested 36/12/4-km domains depicted in Figure 3-1. The WRF modeling domain was defined to be slightly larger than the PGM modeling domains to eliminate the occurrence of boundary artifacts in the meteorological fields used as input to the PGM. Such boundary artifacts can occur as the boundary conditions (BCs) for the meteorological variables come into dynamic balance with WRF's atmospheric equations and numerical methods. Figure 3-1 depicts the horizontal modeling domain that will be used for the WAQS 2014 WRF modeling. The outer 36-km domain (D01) has 165 x 129 grid cells, selected to be consistent with existing Regional Planning Organization (RPO) and EPA modeling CONUS domain. The projection is Lambert Conformal with the "national RPO" grid

projection pole of 40°, -97° with true latitudes of 33° and 45°. The 12-km domain has 256 x 253 grid cells with offsets from the 36-km grid of 15 columns and 26 rows. The 4-km domain has 301 x 361 grid cells with offsets from the 12 km grid of 75 columns and 55 rows.

The emissions and PGM modeling will be conducted on the 36/12/4-km domain grid structure shown in Figure 3-2.

## WPS Domain Configuration

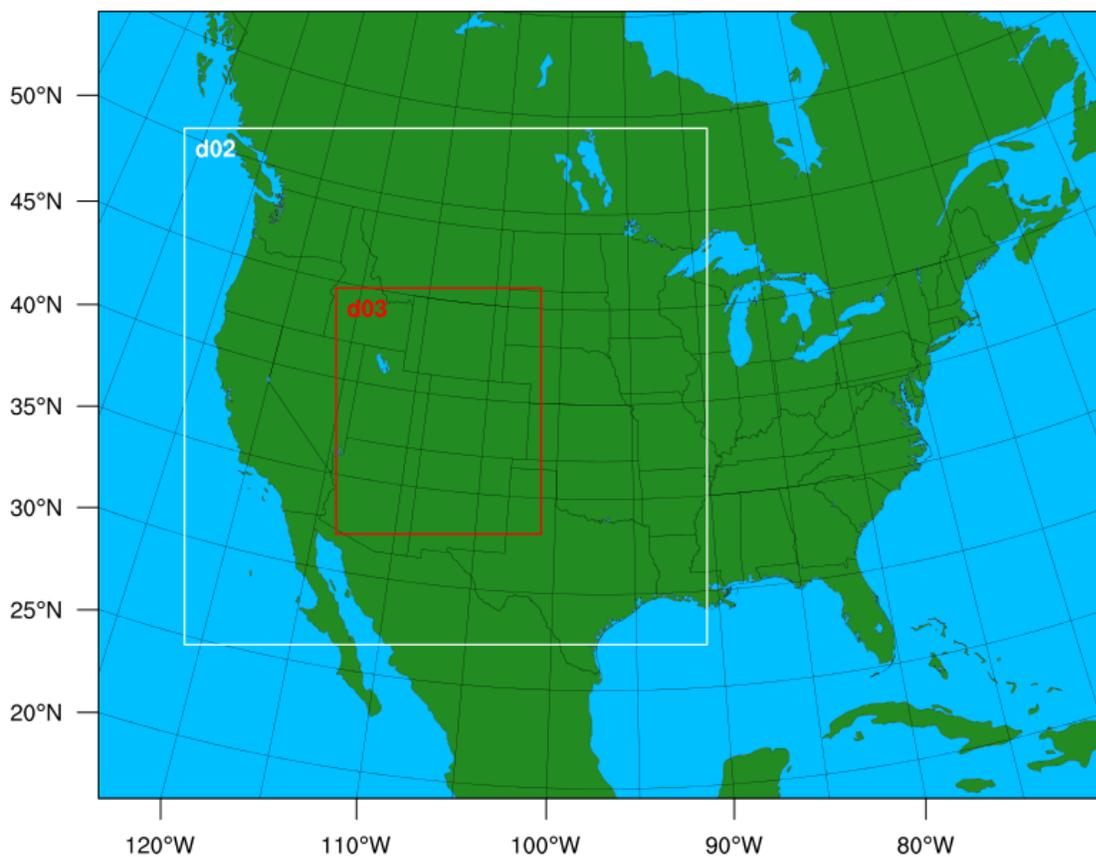


Figure 3-1. WRF 36/12/4-km grid structure for the WAQS meteorological modeling.

## 3SAQS 36/12/04km CAMx Domains

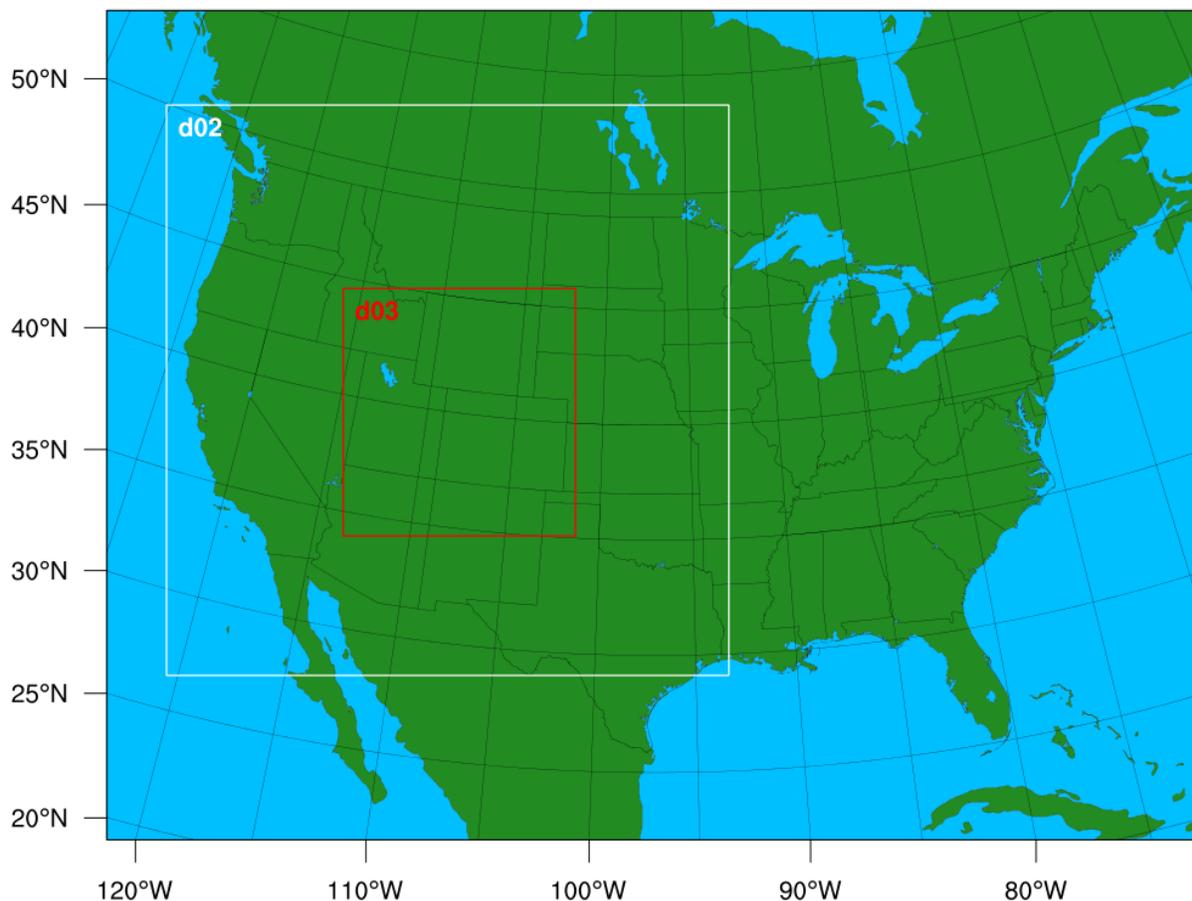


Figure 3-2. 36-km CONUS, 12-km WESTUS, and 4-km WAQS processing domain used for developing PGM inputs.

Table 3-1. Projection parameters for the 3SAQS modeling domains.

Parameter	Value
Projection	Lambert-Conformal
1st True Latitude	33 degrees N
2nd True Latitude	45 degrees N
Central Longitude	-97 degrees W
Central Latitude	40 degrees N
CONUS 36 km X,Y origin	-2736 km, -2088 km
WESTUS 12 km X,Y origin	-2388 km, -1236 km
3SAQS 4 km X,Y origin	-1516 km, -544 km

## 3.2 Vertical Domain Structure

The PGM vertical domain structure will depend on the definition of the WRF vertical layer structure. We will run WRF with 37 vertical layer interfaces (36 vertical layers) from the surface up to 50 mb (~19-km above ground level).<sup>7</sup> The WRF model employs a terrain-following coordinate system defined by pressure, using multiple layers that extend from the surface to 50 mb (approximately 19 km above mean sea level). A layer averaging scheme is adopted for the PGM simulations whereby multiple WRF layers are combined into one PGM layer to reduce computational time. Table 3-3 displays the approach for collapsing the WRF 36 vertical layers to 25 vertical PGM layers.

The WRF layer scheme in Table 3-3 illustrates a collapsing of two WRF layers into one PGM layer for the lowest four model layers. In the past, the lowest layers of WRF were mapped directly into the PGM with no layer collapsing. In those applications the WRF layer 1 was deeper (20-40 m) than used in this WRF application (12 m). We will collapse the surface layers for this application because of the impacts that shallow surface layers will have on emissions. The 12 m lowest layer will trap emissions in a shallow surface layer resulting in overstated emissions fluxes. For example, as NO<sub>x</sub> is primarily emitted from combustion sources, NO<sub>x</sub> emissions plumes are buoyant and would likely convect out of the first layer if it is defined too shallow. Despite concerns that meteorological layer collapsing may introduce uncertainties or errors in key variables, such as the horizontal wind fields, we chose to use a 12 m WRF surface layer to help WRF resolve the fine-resolution dynamical features associated with winter CAP events.

The Denver ozone SIP planning modeling of the May-August 2008 period, WestJumpAQMS 2008 modeling, and 3SAQS 2011 modeling used the same vertical layer structure and layer collapsing strategy as we will use for the WAQS 2014 modeling. The Denver study conducted a no layer collapsing CAMx sensitivity test (36 vertical layers) and found it had essentially no effect on the afternoon and daily maximum 8-hour ozone concentration estimates (Morris et al., 2012a). The 36 layer CAMx sensitivity tests produced lower nighttime ozone at many sites, but it tended to degrade rather than improve ozone model performance. The 36 layer sensitivity tests also took 22% more time to run and required 15% more disk space than the 25 vertical layer configuration. Additional layer sensitivity tests found negligible differences in model results between the collapse and no-layer-collapse configurations (Morris, Koo, Jung, Loomis and McNally, 2012; BLM, 2012).

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<sup>7</sup> UNC-IE and ENVIRON. 2014. Three State Air Quality Study Weather Research Forecast Model Year 2011 Modeling Application/Evaluation. April 2014.

**Table 3-2. 37 Vertical layer interface definition for WRF simulations (left most columns), and approach for reducing to 25 vertical layers for CAMx/CMAQ by collapsing multiple WRF layers (right columns).**

WRF Meteorological Model					Air Quality Model		
WRF Layer	Sigma	Pressure (mb)	Height (m)	Thickness (m)	CAMx Layer	Height (m)	Thickness (m)
37	0.0000	50.00	19260	2055	25	19260.0	3904.9
36	0.0270	75.65	17205	1850			
35	0.0600	107.00	15355	1725	24	15355.1	3425.4
34	0.1000	145.00	13630	1701			
33	0.1500	192.50	11930	1389	23	11929.7	2569.6
32	0.2000	240.00	10541	1181			
31	0.2500	287.50	9360	1032	22	9360.1	1952.2
30	0.3000	335.00	8328	920			
29	0.3500	382.50	7408	832	21	7407.9	1591.8
28	0.4000	430.00	6576	760			
27	0.4500	477.50	5816	701	20	5816.1	1352.9
26	0.5000	525.00	5115	652			
25	0.5500	572.50	4463	609	19	4463.3	609.2
24	0.6000	620.00	3854	461	18	3854.1	460.7
23	0.6400	658.00	3393	440	17	3393.4	439.6
22	0.6800	696.00	2954	421	16	2953.7	420.6
21	0.7200	734.00	2533	403	15	2533.1	403.3
20	0.7600	772.00	2130	388	14	2129.7	387.6
19	0.8000	810.00	1742	373	13	1742.2	373.1
18	0.8400	848.00	1369	271	12	1369.1	271.1
17	0.8700	876.50	1098	177	11	1098.0	176.8
16	0.8900	895.50	921	174	10	921.2	173.8
15	0.9100	914.50	747	171	9	747.5	170.9
14	0.9300	933.50	577	84	8	576.6	168.1
13	0.9400	943.00	492	84			
12	0.9500	952.50	409	83	7	408.6	83.0
11	0.9600	962.00	326	82	6	325.6	82.4
10	0.9700	971.50	243	82	5	243.2	81.7
9	0.9800	981.00	162	41	4	161.5	64.9
8	0.9850	985.75	121	24			
7	0.9880	988.60	97	24	3	96.6	40.4
6	0.9910	991.45	72	16			
5	0.9930	993.35	56	16	2	56.2	32.2
4	0.9950	995.25	40	16			
3	0.9970	997.15	24	12	1	24.1	24.1
2	0.9985	998.58	12	12			
1	1.0000	1000	0			0	

## 4 Meteorological Modeling

This section describes the modeling software and approach that will be used for the WAQS 2014 WRF simulation. The WRF meteorological model will be applied for the 2014 calendar year using the 36/12/4-km domain structure described in Section 3. We will evaluate the WRF modeling results for the 2014 annual period against surface meteorological observations of wind speed, wind direction, temperature and humidity. We will compare the 2014 WRF model performance against meteorological modeling benchmarks and with past regional meteorological model performance evaluations (UNC-IE and ENVIRON, 2012; UNC and ENVIRON, 2014). We will compare the WRF precipitation fields against analysis fields that are based on observations using the Parameter-elevation Relationships on Independent Slopes Model ([PRISM](#)). Snow cover will be evaluated against the Snow Data Assimilation System ([SNODAS](#)) data.

### 4.1 Model Selection and Application

The WAQS 2014 WRF modeling will use WRF version 3.6.1. The WRF preprocessor programs GEOGRID, UNGRID, and METGRID will be used to develop model inputs. We will use a program that we developed for the 3SAQS 2011 Winter WRF modeling to assimilate SNODAS data into WRF.<sup>8</sup>

### 4.2 Topographic Inputs

Topographic information for the WRF will be developed using the standard WRF terrain databases available from the National Center for Atmospheric Research ([NCAR](#)). The 36-km CONUS domain will be based on the 10 min. (~18 km) global data. The 12-km WESTUS domain will be based on the 2 min. (~4 km) data and the 4-km WAQS domain will be based on the 30 sec (~900 m) data.

### 4.3 Vegetation Type and Land Use Inputs

We developed the vegetation type and land use input data to WRF using the most recently released databases provided with the WRF distribution. The 24-category USGS dataset, included in the WRF distribution, was employed to develop the vegetation type and land use input data into WRF. Standard WRF surface characteristics corresponding to each land use category were used.

### 4.4 Atmospheric Data Inputs

The WRF simulation will be initialized with the the 12-km (Grid #218) North American Model (NAM) archives available from the National Climatic Data Center (NCDC) National Operational Model Archive and Distribution System (NOMADS) server.

### 4.5 Water Temperature Inputs

The water temperature data will be taken from the NCEP RTG global one-twelfth degree analysis.

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<sup>8</sup> Bowden, J., Talgo, K., Adelman, Z. (2015, August) WAQS WRF Model Winter Modeling Application/Evaluation, Chapel Hill, NC: University of North Carolina.

## 4.6 Time Integration

Third-order Runge-Kutta integration will be used (`rk_ord = 3`). The maximum time step, defined for the outer-most domain (36 km) only, should be set by evaluating the following equation:

$$dt = \frac{6dx}{F_{map}}$$

Where  $dx$  is the grid cell size in km,  $F_{map}$  is the maximum map factor (which can be found in the output from the WRF program REAL.EXE), and  $dt$  is the resulting time-step in seconds. For the case of the 36-km domain,  $dx = 36$  and  $F_{map} = 1.08$ , so  $dt$  should be taken to be less than 200 seconds. Longer time steps risk Courant-Friedrichs-Lewy (CFL) condition errors, associated with large vertical velocity values, which tend to occur in areas of steep terrain (especially during very stable conditions typical of winter).

For the WAQS 2014 modeling we will use a fixed time step of 90 seconds. Any initializations that fail due to CFL errors should be restarted with a timestep of 45 seconds.

## 4.7 Diffusion Options

Horizontal Smagorinsky first-order closure (`km_opt = 4`) with sixth-order numerical diffusion and suppressed up-gradient diffusion (`diff_6th_opt = 2`) will be used.

## 4.8 Lateral Boundary Conditions

Lateral boundary conditions will be specified from the initialization dataset on the 36-km domain with continuous updates nested from the 36-km domain to the 12-km domain and from the 12-km domain to the 4-km domain, using one-way nesting (`feedback = 0`).

## 4.9 Top and Bottom Boundary Conditions

The top boundary condition will be selected as an implicit Rayleigh dampening for the vertical velocity. Consistent with the model application for non-idealized cases, the bottom boundary condition will be selected as physical, not free-slip.

## 4.10 Sea Surface Temperature Inputs

The sea surface temperature data will be taken from the National Centers for Environmental Prediction (NCEP) Real Time Global (RTG) global one-twelfth degree analysis<sup>9</sup>.

## 4.11 Snow Cover/Depth Inputs

The snow cover and depth are initialized from the Snow Data Assimilation System (SNODAS)<sup>10</sup> archives. SNODAS integrates a physically based, spatially distributed energy and mass balance model with observed snow data from satellite and airborne platforms and ground stations.

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<sup>9</sup> Real-time, global, sea surface temperature (RTG-SST) analysis. <http://polar.ncep.noaa.gov/sst/oper/Welcome.html>

<sup>10</sup> Snow Data Assimilation System. <http://nsidc.org/data>

SNODAS output has high spatial resolution (~1 km) and temporal resolution (24 hours) over the United States.

#### 4.12 FDDA Data Assimilation

We will use analysis nudging for the 36 and 12-km domains and observation nudging for the 4-km domain. For winds and temperature, analysis nudging coefficients of  $5 \times 10^{-4}$  and  $3.0 \times 10^{-4}$  will be used on the 36 and 12-km grids, respectively. For mixing ratio, analysis nudging coefficients of  $1.0 \times 10^{-5}$  will be used for both the 36 and 12-km grids. We will use both surface and aloft nudging for temperature and mixing ratios; nudging will not be used within the boundary layer. Observation nudging will be performed on the 4-km grid domain using the Meteorological Assimilation Data Ingest System ([MADIS](#)) observation archive. The MADIS archive includes the National Climatic Data Center ([NCDC](#)) observations and the National Data Buoy Center ([NDBC](#)) Coastal-Marine Automated Network C-MAN stations. The observational nudging coefficients for winds, temperatures and mixing ratios will be  $1.2 \times 10^{-3}$ ,  $6.0 \times 10^{-4}$ , and  $1.0 \times 10^{-5}$ , respectively and the radius of influence will be set to 60 km.

#### 4.13 WRF Physics Options

WRF physics options for the 2014 calendar year 36/12/4-km WRF simulation will be based on the 2011 3SAQS WRF configuration. The 3SAQS 2011 Modeling Protocol (UNC and ENVIRON, 2014) describes the process that we used for developing this configuration, including sensitivity testing for different physics options. The 2011 WRF sensitivity modeling found that the following physics options optimized the mean model performance across sites in the western U.S. We will use the same physics options for the 2014 WRF simulation. Additional details of these options are provided in Table 4-1.

- Thompson ice, snow, and graupel scheme (mp\_physics=8)
- RRTMG long wave radiation (ra\_lw\_physics=4)
- RRTMG short wave radiation (rw\_sw\_physics=4)
- Monin-Obukhov surface layer (sf\_sfclay\_physics=1)
- Unified NOAH land-surface model (sf\_surface\_physics=2)
- Kain-Fritsch cumulus parameterization in the 36/12-km domains (cu\_physics=1) and no cumulus parameterization (cu\_physics=0) in the 4-km domain
- YSU planetary boundary layer (bl\_pbl\_physics=1)

**Table 4-1. Physics options proposed for the WAQS 2014 WRF modeling**

WRF Treatment	Option Selected	Notes
Microphysics	Thompson	A scheme with ice, snow, and graupel processes suitable for high-resolution simulations.
Longwave Radiation	RRTMG	Rapid Radiative Transfer Model (RRTM) for GCMs includes

WRF Treatment	Option Selected	Notes
		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 (Republic of 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 3SD.	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 and temperature only in the 4-km domain	moisture observation nudging produces excessive rainfall
Initialization Dataset	12 km North American Model (NAM)	

#### 4.14 WRF Output Variables

The WRF model will be configured to output additional variables to support air quality modeling with the Community Multiscale Air Quality Model (CMAQ). The following fields will be activated in the WRF output history files: fractional land use (LANDUSEF), aerodynamic resistance (RA), stomatal resistance (RS), vegetation fraction in the Pleim-Xiu LSM (VEGF\_PX), roughness length (ZNT), inverse Monin-Obukhov length (RMOL).

#### 4.15 WRF Application Methodology

The WRF model will be executed in 5-day blocks initialized at 12Z every 5 days with a 90-second integration time step. Model results will be output every 60 minutes and output files split at 12-hour intervals. Twelve hours of spin-up will be included in each 5-day block before the data are used in the subsequent evaluation. The model will be run at the 36-km, 12-km and 4-km grid resolution from December 16, 2013 through January 1, 2015 using two-way grid nesting with no feedback (i.e., the meteorological conditions are allowed to propagate from the coarser grid to the finer grid but not vice versa).

#### **4.16 Evaluation Approach**

The model evaluation approach will be based on a combination of qualitative and quantitative analyses. The quantitative analysis will be divided into monthly summaries of 2-m temperature, 2-m mixing ratio, and 10-m wind speed using the boreal seasons to help generalize the model bias and error relative to a standard benchmark. The evaluation will focus on the 4-km domain and the states of Colorado, Wyoming, and Utah and supplemented with select diurnal and time series analyses. Additional analysis will include a qualitative evaluation of the WRF daily and monthly precipitation fields against PRISM fields using PRISM data mapped to the WRF domains. WRF snow cover estimates will be evaluated against SNODAS data. The National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) Meteorological Assimilation Data Ingest System (MADIS) will be used to evaluate the winds, temperatures, and water mixing ratios in this simulation.

Calculating bulk statistics over a continental or regional scale domain is problematic because compensating errors and biases get averaged out when evaluating model performance across a broad spectrum of physical and dynamical conditions. Evaluation across large spatial and temporal scales masks important sub-regional, local, and episodic features in the meteorology. Despite these issues, cursory statistics of domain wide, annual and seasonal model performance provide a high-level overview of WRF's ability to simulate meteorology conditions in the region. We will augment the 36-km CONUS, 12-km WESTUS and 4-km 3SAQS domain-wide analysis with statistics by state. Particular attention will be paid to the model performance in the states of Colorado, Utah, Wyoming, and New Mexico.

Additional details of how we will conduct the model performance evaluation for this simulation are provided in Section 5.

#### **4.17 Reporting**

The WAQS 2014 WRF application and evaluation will be documented in a final report and through site-specific performance plots on Intermountain West Data Warehouse (IWDW).

## 5 Meteorological Model Performance Evaluation

The WRF model evaluation approach will be based on a combination of qualitative and quantitative analyses. The qualitative approach compares the spatial distribution of the model-estimated monthly total precipitation with the monthly Center for Prediction of Climate (CPC) or PRISM<sup>11</sup> precipitation analysis fields based on observations using graphical outputs and a comparison of the WRF estimated cloud cover with satellite observations. The quantitative approach calculates model performance statistics using predicted and observed surface meteorological variables. We will compare the performance statistics for the 2014 WRF simulation to the 2008 WestJumpAQMS and 2011 3SAQS WRF modeling; and with published performance benchmarks.

### 5.1 QUANTITATIVE EVALUATION USING SURFACE METEOROLOGICAL OBSERVATIONS

The statistical evaluation approach will examine tabular and graphical displays of the model bias and error for surface wind speed, wind direction, temperature, and mixing ratio (humidity). We will compare the 2014 WRF performance statistics to benchmarks developed based on a history of meteorological modeling as well as past meteorological model performance.<sup>12</sup> For this analysis the statistics will be performed on a state-by-state basis, a Regional Planning Organization (RPO) basis, and on a domain-wide basis for the 36-km CONUS, 12-km WESTUS, and 4-km modeling domains. In addition, separate evaluation will also be conducted at each meteorological modeling station in the 4-km domain. The WRF evaluation procedures used by 3SAQS 2011 WRF modeling will be used for the WAQS 2014 simulation (UNC and ENVIRON, 2014).

The observed database for winds, temperature, and water mixing ratio to be used in this analysis are 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 4-km WAQS WRF modeling domain are shown in Figure 5-1.

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<sup>11</sup> <http://www.prism.oregonstate.edu/>

<sup>12</sup> 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>).

### MADIS Observation Locations: 4km Domain

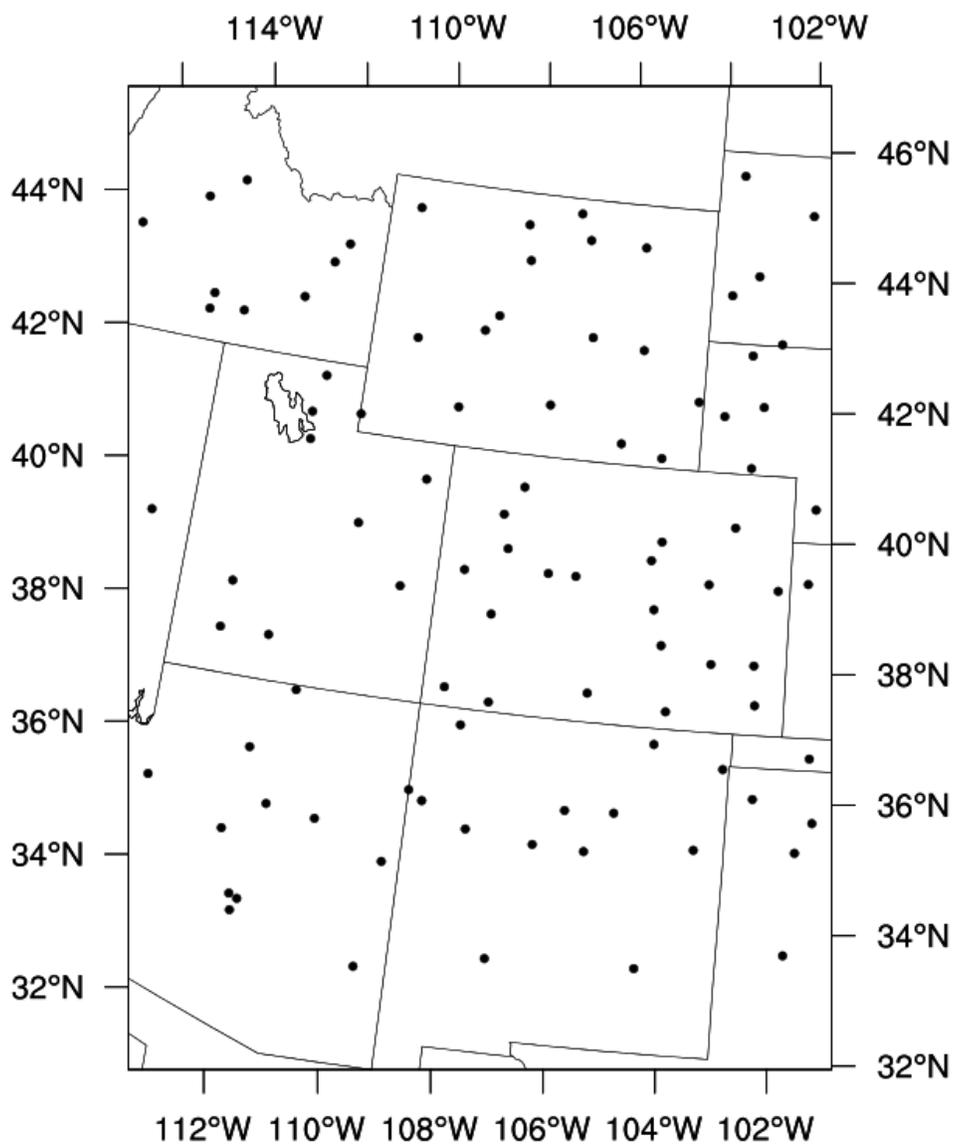


Figure 5-1. Locations of MADIS surface meteorological modeling sites with the WRF 4-km WSAQS modeling domain.

The quantitative model performance evaluation of WRF using surface meteorological measurements will be performed using the publicly available METSTAT<sup>13</sup> and Atmospheric Model Evaluation Tool (AMET)<sup>14</sup> evaluation tools. Both tools calculate 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, the WRF model evaluation will present results for several sub-regions, even at the individual site level within the 4-km domain, leaving potential data users to independently judge the adequacy of the model simulation. Overall comparisons are offered to judge the model efficacy, but this review does not necessarily cover all potential user needs and applications.

Statistical metrics will be presented for each state, for each RPO, and for the U.S. portion of the 12-km and 4-km modeling domains. To evaluate the performance of the WRF 2014 simulation for the U.S., a number of performance benchmarks for comparison will be used. Emery et al. derived and proposed a set of daily performance “benchmarks” for typical meteorological model performance.<sup>15</sup> 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. The simulations were 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 in context with other model applications and meteorological data sets.

Recognizing that these simple conditions benchmarks may not be appropriate for more complex conditions, McNally analyzed multiple annual runs that included complex terrain conditions and suggested an alternative set of benchmarks for temperature under more complex conditions.<sup>16</sup> As part of the WRAP meteorological modeling of the western U.S., including the Rocky Mountain Region, as well as the complex conditions up in Alaska, Kemball-Cook (2005b<sup>17</sup>) also came up with

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<sup>13</sup> <http://www.camx.com/down/support.php>

<sup>14</sup> <http://www.cmascenter.org>

<sup>15</sup> 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>

<sup>16</sup> McNally, D. E., 2009. “12km MM5 Performance Goals.” Presentation to the Ad-Hoc Meteorology Group. 25-June. <http://www.epa.gov/scram001/adhoc/mcnally2009.pdf>

<sup>17</sup> Kemball-Cook, S., Y. Jia, C. Emery and R. Morris. 2005. “Alaska MM5 Modeling for the 2002 Annual Period to Support Visibility Modeling” Prepared for Western Regional Air Partnership (WRAP). Prepared by Environ International Corporation. September.  
[http://pah.cert.ucr.edu/aqm/308/docs/alaska/Alaska\\_MM5\\_DraftReport\\_Sept05.pdf](http://pah.cert.ucr.edu/aqm/308/docs/alaska/Alaska_MM5_DraftReport_Sept05.pdf)

meteorological model performance benchmarks for complex conditions. Table 5-1 lists these benchmarks for simple and complex conditions, where we have adopted the complex benchmarks from Kemball-Cook et al., since they covered more of the meteorological parameters.<sup>18,19</sup>

The objective of comparing the 2014 WRF model performance to the benchmarks is to understand how well the model performs relative to other retrospective WRF applications for the U.S. These benchmarks include bias and error benchmarks for 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 benchmarks for each of the above meteorological variables are shown in Table 5-1.

**Table 5-1. Meteorological model performance benchmarks for simple and complex conditions.**

Parameter	Simple	Complex
Temperature Bias	≤ ±0.5 K	≤ ±2.0 K
Temperature Error	≤ 2.0 K	≤ 3.5 K
Mixing Ratio Bias	≤ ±1.0 g/kg	NA
Mixing Ratio Error	≤ 2.0 g/kg	NA
Wind Speed Bias	≤ ±0.5 m/s	≤ ±1.5 m/s
Wind Speed RMSE	≤ 2.0 m/s	≤ 2.5 m/s
Wind Direction Bias	≤ ±10 degrees	NA
Wind Direction Error	≤ 30 degrees	≤ 55 degrees

The equations for bias, error, and root mean square error (RMSE) are given below.

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

$$\text{Mean Absolute Gross Error (Error)} = \frac{1}{N} \sum_{i=1}^N |P_i - O_i|$$

$$\text{Root Mean Square Error (RMSE)} = \left[ \frac{1}{N} \sum_{i=1}^N (P_i - O_i)^2 \right]^{1/2}$$

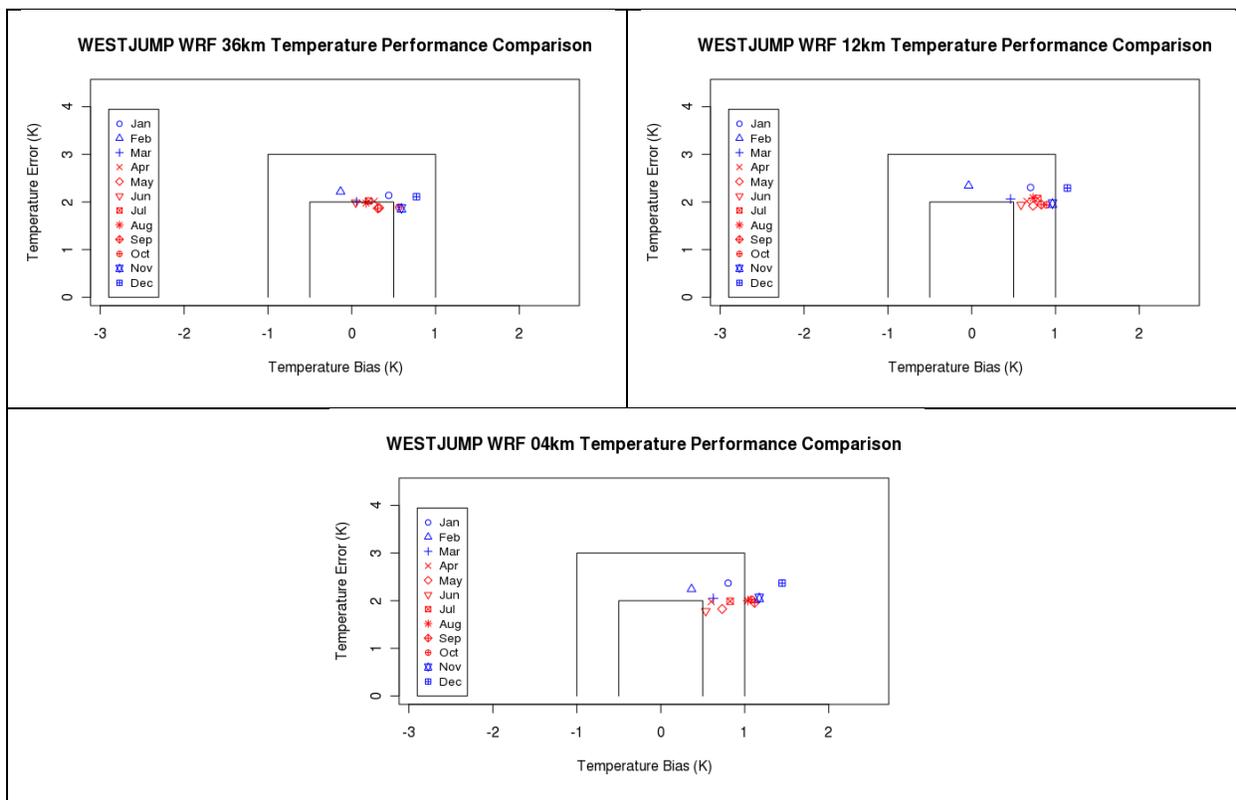
Figure 5-4 displays an example model performance soccer plot graphic from the WestJumpAQMS 2008 WRF run for monthly temperature performance within the three nested (36/12/4-km) modeling domains. The soccer plots shows the monthly temperature bias (x-axis) versus error (y-axis) as colored symbols with the simple and complex performance benchmarks<sup>20</sup> represented by the rectangles. When the WRF monthly performance achieves the benchmark, it falls within the rectangle (i.e., scores a goal). In this example we see the 2008 WRF simulation always achieves the

<sup>18</sup> Emery, C., et al., 2001.

<sup>19</sup> Kemball-Cook, S., et al., 2005b

<sup>20</sup> Note that Figure 5-4 is using the McNally (2009) versions of the complex benchmark for temperature whereas we have adopted the Emory et. al (2001) versions for the temperature and wind benchmarks.

complex benchmark in the 36-km domain and achieves the complex benchmark in 11 of 12 months over the 12-km domain, with just December falling just outside of the benchmark due to too warm temperatures. Across the 4-km domain, 7 of the 12 months achieve the complex benchmarks with 5 months failing due to overestimated temperatures.



**Figure 5-1. Figure 5-4. Example quantitative model performance evaluation display using soccer plots that compare monthly temperature performance (colored symbols) across the 36-km CONUS (top left), 12-km WESTUS (top right) and 4 km IMWD (bottom) domains with the simple and complex model performance benchmarks (rectangles).**

## 5.2 QUANTITATIVE EVALUATION USING ALOFT METEOROLOGICAL OBSERVATIONS

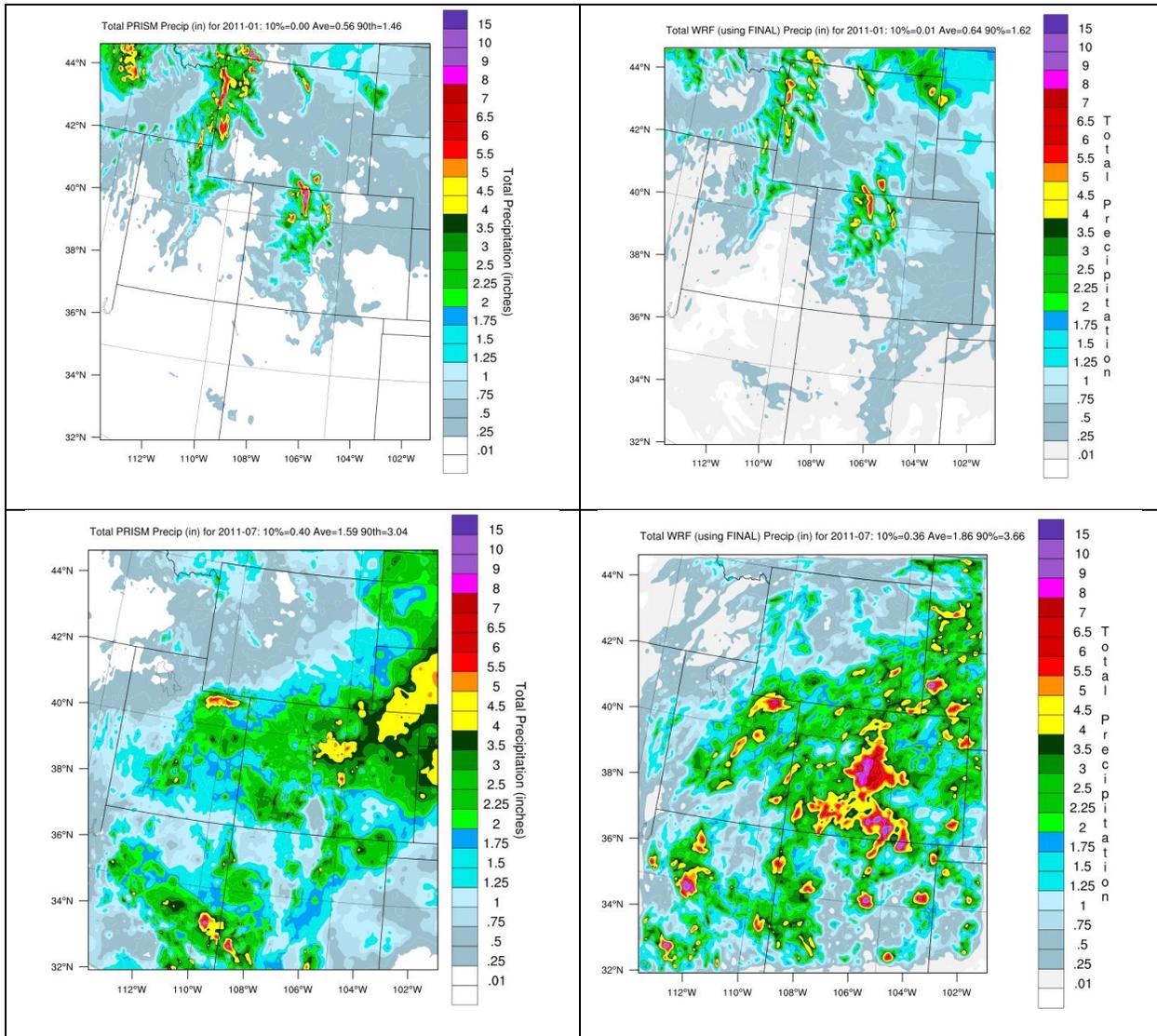
AMET will be used to compare WRF predictions to aloft observations of winds, temperature, and humidity. Data from the NOAA Wind profiler network will be used to evaluate the u and v wind components from the surface to the tropopause.<sup>21</sup> Upper air profile data from the RAOB network, which includes approximately 100 measurement sites in North America, will be used to evaluate potential temperature, relative humidity, and the wind components from the surface to the model top.

<sup>21</sup> <http://www.profiler.noaa.gov/npn/aboutNpnProfilers.jsp>

### 5.3 QUALITATIVE MODEL PERFORMANCE EVALUATION

The qualitative model performance evaluation of the WAQS 2014 WRF simulation will compare spatial maps of WRF estimated precipitation with precipitation maps based on observations from PRISM. One caveat of this analysis is that the PRISM analysis covers only the Continental U.S. and does not extend offshore or into Canada or Mexico.

Figure 5-5 displays example precipitation comparisons of WRF and PRISM fields from the 3SAQS 2011 WRF simulations for the months of January and July and the continental U.S. For the 3SAQS 2014 WRF modeling all months would be compared, for each of the 36, 12 and 4-km domains.



**Figure 5-5. Example comparison of PRISM analysis (left) and WRF modeling (right) monthly total precipitation amounts across the 3SAQS 4km WRF domain for the months of January (top) and July (bottom) from the 3SAQS 2011 WRF simulation.**