ANNUAL WRF SIMULATIONS FOR THE UTAH BUREAU OF LAND MANAGEMENT'S AIR RESOURCE MANAGEMENT STRATEGY (ARMS) AIR QUALITY MODELING

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1. INTRODUCTION AND BACKGROUND

The Uinta Basin is a region of northeast Utah that is projected to have extensive development of oil and gas reserves in the foreseeable future (Fig. 1). Several episodes of elevated fine particulate matter ($PM_{2.5}$) and ozone concentrations have been measured in the Uinta Basin since monitoring began in 2009. For example, the maximum 8-hour average ozone concentration exceeded 130 ppb in winter 2011. These poor air quality episodes typically occur during wintertime cold pool stagnation events, which are associated with light winds, strong and shallow inversions, and weak vertical mixing. Snow cover is also important both for cold pool formation and photochemistry enhancement. Cold pool stagnation events are common in the Uinta Basin during the winter months, but can be a challenge for meteorological models to reproduce.

Fig. 1. Drill rigs in winter.

To further understand and analyze the chemical and meteorological conditions that lead to poor air quality episodes in Utah's Uinta Basin, the Air Resource Management Strategy (ARMS) Modeling Project is being conducted under the direction of the Bureau of Land Management (BLM) Utah State Office (Utah BLM). The primary focus of the ARMS Modeling Project is the Uinta Basin study area, which encompasses land administered by BLM, National Parks Service, and the USDA Forest Service, as well as state, private, and tribal lands (Fig. 2). The ARMS Modeling Project is a cumulative assessment of potential future air quality impacts associated with projected oil and gas activity in the Uinta Basin, and will provide a reusable modeling platform suitable for air quality management decisions affecting the Uinta Basin.

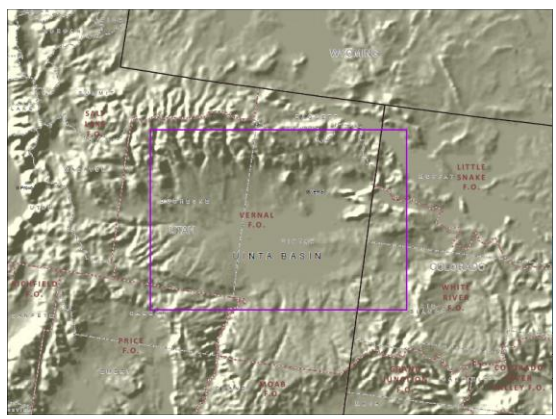

Fig. 2. Uinta Basin study area for the ARMS Modeling Project.

The ARMS Modeling project includes both meteorological and air quality modeling components. To support ongoing photochemical grid modeling efforts, AECOM and Sonoma Technology, Inc. conducted annual meteorological model simulations with the Weather Research and Forecast (WRF) model for 2010 for three nested modeling domains at 36-, 12-, and 4-km grid resolutions (Fig. 3). The Uinta Basin study area is contained within the WRF 4-km domain, which covers all of Utah.

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Because this air quality management tool will be used by stakeholders during all seasons, adequate meteorological and air quality model performance must be demonstrated throughout the year under a variety of conditions. We conducted several WRF sensitivity experiments for February and July of 2010 to determine the preferred configuration for the annual WRF simulation. The sensitivity experiments focused on numerous aspects of the WRF modeling system, including domain size, vertical grid structure, land surface models (LSM), planetary boundary layer (PBL) schemes, and the data assimilation strategy. This abstract presents key findings from a subset of these sensitivity experiments, including the LSM, PBL, and data assimilation tests, which led to important conclusions about the WRF configurations that we selected for the annual modeling. Important issues discovered during these sensitivity analyses are also presented, along with a brief summary of model performance results from the annual WRF simulation. Additional information about all the sensitivity experiments can be found in the ARMS Modeling Project final report on meteorological modeling (AECOM, 2013).

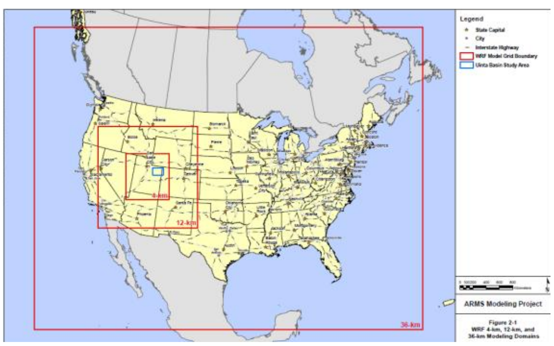

Fig. 3. WRF domains for the ARMS modeling project.

2. METHODS

The Utah Department of Environmental Quality, Division of Air Quality (UDAQ) conducted WRF modeling for the state of Utah in support of the ARMS Modeling Project. The work presented here leverages many aspects of this modeling effort, including the modeling domains, vertical grid structure, and pre-processing data and methods. Unlike the modeling performed by UDAQ, this modeling effort uses WRF version 3.4, but initial and boundary conditions for the 36-km domain were identical to those used by UDAQ, which were extracted from the 12-km North American Model archives. Analysis nudging was used on all domains above the boundary layer. Observational nudging was performed on the 4-km domain using Meteorological Assimilation Data Ingest System (MADIS) datasets provided by UDAQ, as well as data from two observation sites in the Uinta Basin, Ouray and Redwash, provided by Utah BLM. Additional details on modeling configurations common to all of the sensitivity experiments can be found in AECOM (2013).

Sensitivity tests were performed for February and July of 2010 to cover a spectrum of meteorological conditions. In the Uinta Basin, cold-pool stagnation conditions are prevalent during February, while diurnal patterns of mountain-valley flows with afternoon thunderstorms are dominant in July. The results of the sensitivity tests were evaluated by comparing model-predicted values to measured meteorological conditions, using methods described in AECOM (2013). Results and discussion presented here is focused exclusively on the 4-km domain and the Uinta Basin study area.

3. SENSITIVITY EXPERIMENTS

a. LSM Sensitivity

Three LSMs were considered for the ARMS Modeling Project.

1. Pleim-Xiu LSM model coupled with the Asymmetric Convective Model version 2 (ACM2).

2. Noah-MP (multi-physics) LSM with default settings, coupled with the Mellor-Yamada-Janjic (MYJ) PBL scheme.

3. Unified Noah LSM coupled with the MYJ PBL scheme.

The Noah-MP LSM was included in this test because it contains more advanced snow physics than the Unified Noah LSM. Note that in WRF, the Pleim-Xiu LSM has only been tested with the ACM2 PBL scheme, so no attempt was made to test the Pleim-Xiu LSM coupled with a different PBL scheme.

Daily temperature and humidity performance for the 4-km domain from the LSM sensitivity experiment is shown in Fig. 4. The Noah-MP LSM performed poorly for temperature and moisture in both seasons. Noah-MP contains numerous settings, and additional testing with Noah-MP would be required to improve its performance for cold pool stagnation events. Therefore, the Noah-MP LSM was excluded from further consideration for the ARMS Modeling project. Because the other two LSMs must be coupled to different PBL schemes, a final decision on which LSM to use for annual modeling was made after analyzing results from the PBL sensitivity experiment.

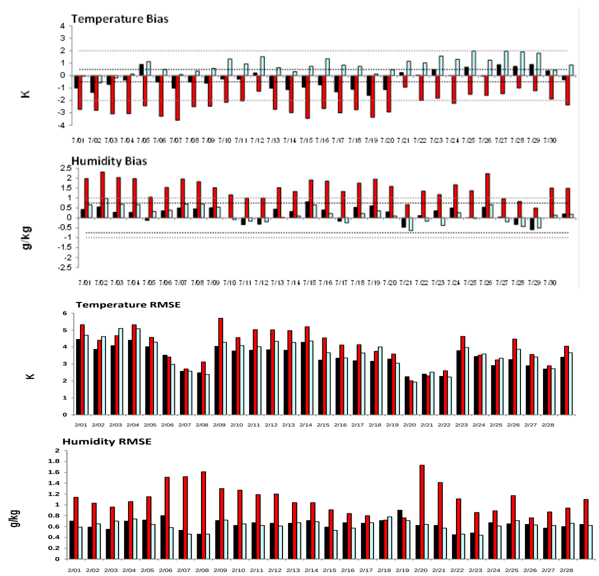

Fig. 4. Daily temperature and humidity model performance for the 4-km domain for the LSM sensitivity experiments. The top 2 images show biases from July, while the bottom 2 images show root mean square error for February.

b. PBL Model Sensitivity

To determine which PBL model should be used in the annual WRF simulations, we evaluated three PBL schemes.

1. ACM2 coupled with the Pleim-Xiu LSM (ACM2/PX).

2. MYJ coupled with the Unified Noah LSM (MYJ/Noah).

3. Quasi-Normal Scale Elimination (QNSE) scheme coupled with the Unified Noah LSM.

The QNSE scheme was tested because it is designed specifically for stability stratified conditions, similar to conditions observed during cold pool stagnation events in the Uinta Basin. During daytime hours, the QNSE PBL scheme essentially reverts to the MYJ PBL formulation. The other two PBL schemes are commonly used when developing meteorological inputs for air quality models. Again, note that in WRF, the ACM2 PBL scheme has only been tested with the Pleim-Xiu LSM, so no attempt was made to test ACM2 coupled with a different PBL scheme.

Example time series plots of observed and predicted wind speed and temperature model from the ACM2/PX and MYJ/Noah sensitivity tests for July are shown in Fig. 5 and Fig. 6. A table summarizing the model performance from the PBL sensitivity experiments is presented in Table 1.

Table 1. Model performance statistics for the WRF 4-km Domain for the February and July PBL sensitivity experiments.

Statistical Benchmarks and Model Performance for the BLM WRF 4-km Domain for February and July

		February			July		
Parameter	Statistics	ACM2/PX	MYJ/Noah	QNSE-EDMF/Noah	ACM2/PX	MYJ/Noah	QNSE-EDMF/Noah
Wind Speed (m/s)	RSME	1.83	2.22	2.2	2.16	2.48	2.54
	Bias	-0.59	0.21	0.14	-0.6	0.44	0.46
	IOA	0.56	0.55	0.54	0.59	0.61	0.6
Wind Direction (deg)	Bias	3.58	4.09	1.78	1.48	4.29	1.04
	Gross Error	58.66	59.3	60.63	55.6	55.19	55.54
Temperature (K)	Bias	-0.05	0.5	0.19	-0.34	0.85	0.09
	Gross Error	2.71	2.87	2.88	2.4	2.6	2.49
	IOA	0.89	0.87	0.86	0.94	0.93	0.93
Humidity (g/kg)	Bias	-0.1	0.11	0.15	0.2	0.17	-0.12
	Gross Error	0.52	0.5	0.51	1.29	1.39	1.19
	IOA	0.8	0.82	0.8	0.75	0.74	0.79

For July, the performance of the QNSE PBL scheme was similar to that of the MYJ scheme, as expected, since those PBL schemes use similar formulations during daytime convective conditions. Wind speed was most important difference in model performance between MYJ and ACM2 during the summer sensitivity, with ACM2 producing a persistent and relatively large negative wind speed bias. Based on both operational and diagnostic examinations of WRF performance within the Uinta Basin, we concluded that the MYJ/Noah configuration was a better choice than ACM2/PX for the summer months of the annual WRF simulations.

During February, the QNSE PBL scheme generally did not outperform the other PBL schemes, despite having a specialized formulation for stable boundary layers. Therefore, QNSE was omitted from further consideration. ACM2 generally performed better MYJ for most meteorological parameters during February both domain-wide and within the Uinta Basin study area. Therefore, the MYJ/Noah configuration was selected for the winter months of the annual WRF simulation.

A key result from these PBL and LSM sensitivity experiments was that two different WRF configurations were selected for ARMS Modeling Project annual WRF simulation, one for summer, and another for winter. We defined winter months as December through March, as these are the months in which widespread snow cover and cold pool stagnation conditions typically occur in the Uinta basin. Other months of the year are considered summer, even though some months fall outside classical definitions of summer.

ACM2/PX

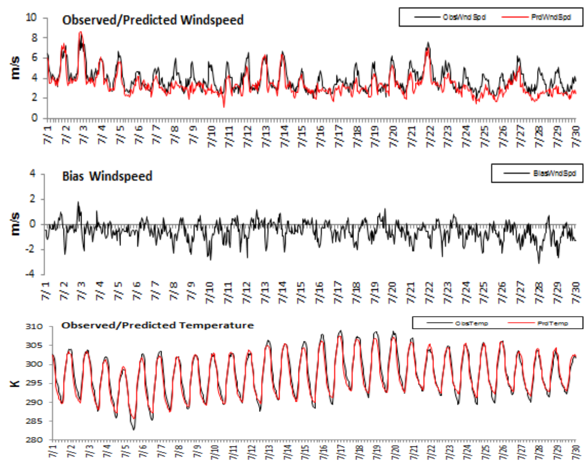

Fig. 5. Predicted (red) and observed (black) wind speed, wind speed bias, and temperature time series for the summer ACM/PX sensitivity experiment for the 4-km domain.

MYJ/Noah-Unified

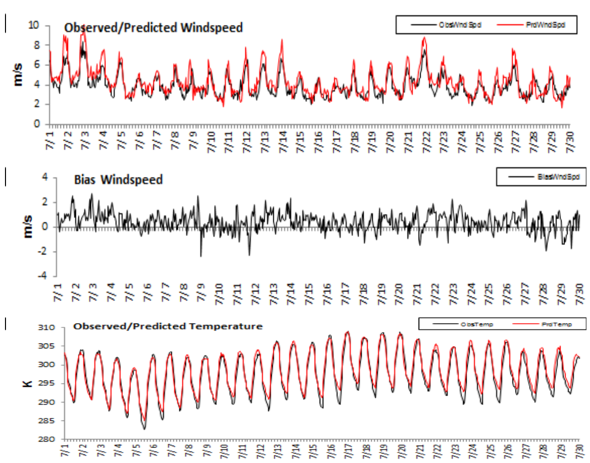

Fig. 6. Predicted (red) and observed (black) wind speed, wind speed bias, and temperature time series for the summer MYJ/Noah sensitivity experiment for the 4-km domain.

c. Data Assimilation

Although model performance for the winter MYJ/Noah configuration was reasonable for all meteorological parameters in the 4-km domain, temperature errors were unusually large within the Uinta Basin study area (Fig. 7). Although diurnal temperature patterns are well represented within the Uinta Basin, initial WRF results were several degrees too warm throughout February, despite the use of local observational nudging against special meteorological observations within the Uinta Basin. A further examination of model performance results suggested that not all available surface observations were being incorporated into the WRF data assimilation process.

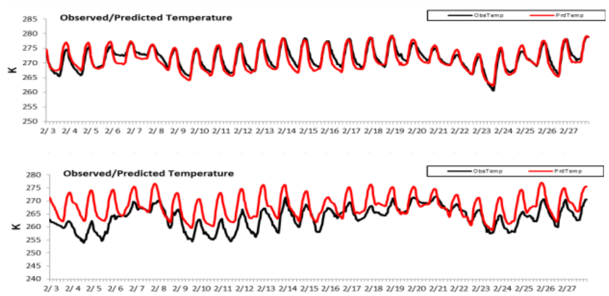

Fig. 7. Observed (black) and predicted (red) temperature time series for the 4-km domain (top) and the Uinta Basin study area (bottom) during February, 2010.

We re-examined settings, options, and log files from the WRF pre-processor, OBSGRID, which develops the files needed by the WRF data assimilation algorithms. An important function of OBSGRID is the quality control (QC) of observation data to be used in data assimilation. Among these QC checks is the Buddy Check test, which checks each observation for consistency against neighboring observations. We discovered that the Buddy Check test was rejecting valid temperature observations in areas with complex terrain, where large temperature differences can occur in short distances because of elevation differences. These rejected observations were subsequently omitted from the WRF data assimilation process.

We therefore deactivated the Buddy Check test, re-processed the observation data with OBSGRID, and then reran the February sensitivity experiment. The key results of this experiment are presented in Fig. 8. Within the Uinta Basin, model performance improved substantially for temperature, and the excessive temperature bias was eliminated. As a result, the OBSGRID Buddy Check test was deactivated when processing observation data for the WRF annual simulation.

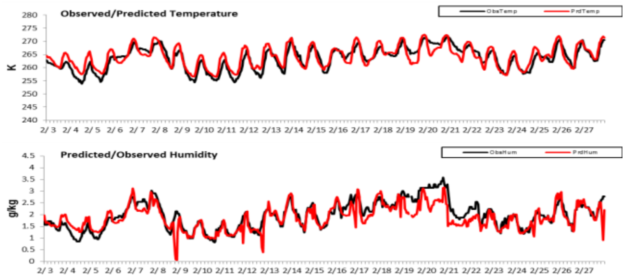

Fig. 8. Observed (black) and predicted (red) temperature (top) and water vapor mixing ratio (bottom) time series for the Uinta Basin study area for February, 2010.

Although deactivating the OBSGRID Buddy Check test improved model performance for both temperature and humidity within the Uinta Basin, model performance for humidity degraded substantially for the 4-km domain (Fig. 9). WRF captured the observed synoptic variations in moisture during February, but the observational nudging introduced a significant dry bias into the domain-wide results. Also, despite the improved statistical performance for moisture within the Uinta Basin, significant noise and large spikes were introduced into the WRF time series (Fig. 8), suggesting that the nudging introduced some imbalances in the modeled moisture fields.

To retain suitable model performance for moisture, we disabled observation nudging for relative humidity in the 4-km domain, while also disabling the Buddy Check test. As a result (Fig. 10), the moisture bias on the 4-km domain was eliminated. Although disabling the moisture nudging degraded model performance statistically within the Uinta Basin study area, the WRF time series is smoother and more realistic. Therefore, moisture nudging was disabled for the annual WRF simulation.

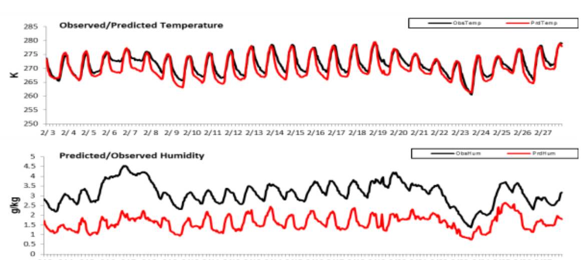

Fig. 9. Observed (black) and predicted (red) temperature (top) and water vapor mixing (bottom) ratio time series for the WRF 4-km domain for February, 2010.

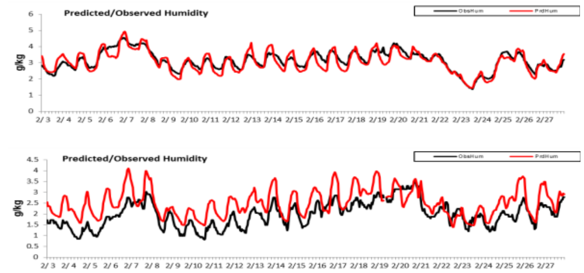

Fig. 10. Observed (black) and predicted (red) water vapor mixing ratio time series for the 4-km domain (top) and the Uinta Basin study area (bottom) for February, 2010.

4. ANNUAL WRF SIMULATION

Tables 2 and 3 summarize the configurations used for the ARMS Modeling Project annual WRF simulation. As a result of the sensitivity experiments, two configurations were selected: one for winter months, and another for summer months. With these configurations, we successfully reproduced cold-pool stagnation events in the Uinta Basin without compromising model performance for other areas and seasons.

We developed an annual WRF meteorological dataset for use in ongoing photochemical grid modeling efforts for the ARMS Modeling Project. After performing a model performance evaluation and analyzing the results in detail, we determined that the WRF outputs were suitable for use in subsequent air quality modeling. A summary of results from the annual model performance evaluation are presented in Tables 4 and 5.

Table 2. Summary of winter WRF configurations for the ARMS Modeling Project.

Parameter	36-km Grid	12-km Grid	4-km Grid
Microphysics	Lin et al., scheme	Lin et al., scheme	Lin et al., scheme
Cumulus parameterization	Kain-Fritsch scheme	Kain-Fritsch scheme	None[2]
PBL	Asymmetric Convective Model Version 2 (ACM2) scheme	ACM2 scheme	ACM2 scheme
Surface layer	Pleim-Xiu scheme	Pleim-Xiu scheme	Pleim-Xiu scheme
Land surface model (LSM)	Pleim-Xiu scheme	Pleim-Xiu scheme	Pleim-Xiu scheme
Long-wave radiation	Rapid Radiative Transfer Model (RRTM)	RRTM	RRTM
Short-wave radiation	Dudhia	Dudhia	Dudhia

[1] January, February, March, and December are defined as winter for the ARMS Study Area in 2010.

[2] Typically, cloud convection is well resolved in the 4-km grid without the need for additional cumulus parameterizations.

Table 3. Summary of summer WRF configurations for the ARMS Modeling Project.

Parameter	36-km Grid	12-km Grid	4-km Grid
Microphysics	Single moment (6-class)	Single moment (6-class)	Single moment (6-class)
Cumulus parameterization	Grell-Devenyi Ensemble Scheme	Grell-Devenyi Ensemble Scheme	None[2]
PBL	Mellor-Yamada-Janic (MYJ) scheme	MYJ scheme	MYJ scheme
Surface layer	Monin-Obukov (Janic) scheme	Monin-Obukov (Janic) scheme	Monin-Obukov (Janic) scheme
LSM	Unified Noah Land Surface Model	Unified Noah Land Surface Model	Unified Noah Land Surface Model
Long-wave radiation	RRTM	RRTM	RRTM
Short-wave radiation	Goddard	Goddard	Goddard

[1] April, May, June, July, August, September, October and November are defined as "non-winter" conditions for the ARMS Study Area in 2010.

[2] Typically, cloud convection is well resolved in the 4-km grid without the need for additional cumulus parameterizations.

Table 4. WRF annual model performance summary for the 4-km domain. Bold indicates passing benchmark for Tesche et al. (2002). Italics indicates passing benchmark for complex terrain.

		Statistical Benchmark		Average Values				
Parameter	Statistics	(Tesche et al. 2002)	Complex Terrain	Annual	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Wind speed (m/s)	RMSE	≤ 2	≤ 2.5	***1.93***	***1.71***	*2.11*	*2.10*	***1.80***
	Bias	≤ ±0.5		**-0.39**	-0.80	**-0.19**	**-0.11**	**-0.46**
	IOA	≥ 0.6		**0.73**	**0.69**	**0.79**	**0.72**	**0.72**
Wind direction (deg)	Bias	≤ ±10		**1.52**	**1.64**	**1.25**	**0.98**	**2.21**
	Gross Error	≤ 30	≤ 55	*38.70*	*38.04*	*37.76*	*40.86*	*38.15*
Temperature (K)	Bias	≤ ±0.5	≤ ±2	***0.09***	***-0.23***	***0.01***	***0.21***	***0.38***
	Gross Error	≤ 2	≤ 3.5	***1.69***	***1.96***	***1.53***	***1.76***	***1.51***
	IOA	≥ 0.8		**0.96**	**0.93**	**0.97**	**0.96**	**0.95**
Mixing ratio (g/kg)	Bias	≤ ±1	≤ ±1	***0.03***	***-0.08***	***0.36***	***-0.07***	***-0.11***
	Gross Error	≤ 2	≤ 2	***0.81***	***0.55***	***0.85***	***1.22***	***0.61***
	IOA	≥ 0.6		**0.76**	**0.75**	**0.73**	**0.77**	**0.77**

Table 5. Similar to Table 4, but for the Uinta Basin study area.

		Statistical Benchmark		Average Values				
Parameter	Statistics	(Tesche et al. 2002)	Complex Terrain	Annual	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Wind speed (m/s)	RMSE	≤ 2	≤ 2.5	***1.52***	***1.14***	***1.94***	***1.74***	***1.26***
	Bias	≤ ±0.5		**-0.42**	**-0.49**	-0.54	**-0.41**	**-0.25**
	IOA	≥ 0.6		**0.68**	0.56	**0.75**	**0.74**	**0.65**
Wind direction (deg)	Bias	≤ ±10		**1.26**	**3.24**	**-3.18**	**0.15**	**4.85**
	Gross Error	≤ 30	≤ 55	*48.56*	*53.93*	*46.87*	*43.56*	*49.89*
Temperature (K)	Bias	≤ ±0.5	≤ ±2	***0.47***	*1.12*	***-0.01***	***0.37***	***0.38***
	Gross Error	≤ 2	≤ 3.5	***1.44***	*2.24*	***1.17***	***1.18***	***1.18***
	IOA	≥ 0.8		**0.91**	**0.82**	**0.97**	**0.98**	**0.87**
Mixing ratio (g/kg)	Bias	≤ ±1	≤ ±1	***0.15***	***0.30***	***0.76***	***-0.19***	***-0.28***
	Gross Error	≤ 2	≤ 2	***0.77***	***0.56***	***0.96***	***1.02***	***0.56***
	IOA	≥ 0.6		0.54	0.55	0.47	0.55	0.57

4. CONCLUSIONS AND DISCUSSION

Multiple WRF configurations were tested to determine a preferred configuration for an annual WRF simulation in support of the ARMS Modeling project. Different WRF configurations were found to perform better depending on the season evaluated, and as a result, two configurations were used for the annual WRF simulation: one for winter months and another for summer months.

Unusually poor model performance within the Uinta Basin study area led to the discovery that the OBSGRID Buddy Check quality assurance (QA) test erroneously rejected valid observations in complex terrain, which prevented their inclusion in the WRF data assimilation process. Therefore, we deactivated the OBSGRID Buddy Check test but retained the other OBSGRID QA tests to improve model performance without sacrificing the quality of the assimilated observational data. In addition, we also turned off observational nudging for moisture to address excessive imbalances introduced by assimilating local relative humidity observations. These issues underscore the importance of carefully understanding the effect of default WRF settings on model results, and thoroughly understanding the behavior of WRF's observational data QA tests.

With the configurations developed from the sensitivity experiments, we successfully reproduced cold pool stagnation events in the Uinta Basin without compromising model performance for other areas or seasons. We subsequently applied these configurations to the annual WRF simulation, and achieved acceptable model performance. These meteorological fields are currently being used to support ongoing air quality modeling work for the ARMS Modeling Project.

5. REFERENCES

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