2022 METEOROLOGICAL MODELING TECHNICAL SUPPORT DOCUMENT (TSD)

Version 1, Jan 2025

1. Meteorological Modeling Overview

Texas Commission on Environmental Quality (TCEQ) is developing a new 2022 modeling platform (TCEQ 2022 modeling platform), which will be used in the photochemical modeling that will support various upcoming state implementation plan (SIP) revisions. The TCEQ 2022 modeling platform has a modeling episode of January 1 through December 31, 2022, and TCEQ has developed preliminary meteorological inputs for the modeling episode using the Weather Research and Forecasting (WRF) model. WRF is a numerical weather prediction (NWP) and community supported model that is a free and shared resource with distributed development and support. Meteorological modeling was conducted for the entire 2022 year using month-long model runs.[1] A Lambert Conformal Conic (LCC) map projection with geographical coordinates defined in Table 1: *Lambert Conformal Conic Map Projections* was used for the WRF modeling.

Table 1: Lambert Conformal Conic Map Projections

Projection Parameter	Projection Value
First True Latitude (Alpa):	33˚N
Second True Latitude (Beta):	45˚N
Central Longitude (Gamma):	97˚W
Projection Origin:	97˚W, 40˚N
Spheroid:	Perfect Sphere, Radius = 6370 km

TCEQ's 2022 WRF modeling is configured with two domains. The first is a 12km grid resolution domain that covers the continental United States (U.S.) and a large portion of Canada and Mexico. The second is a 4km fine grid domain covering the eastern half of Texas where the current nonattainment areas are located. Figure 1: *WRF Modeling Domains* depicts the boundaries of the WRF domains. The easting and northing ranges for each domain are defined in Table 2: *WRF Modeling Domain Definitions*.

[1] Each month-long simulation includes 24 hours of spin-up and 48 hours of spin-down. The last two weeks of December 2021 were simulated to use for photochemical model ramp-up time and only for the 12km domain.

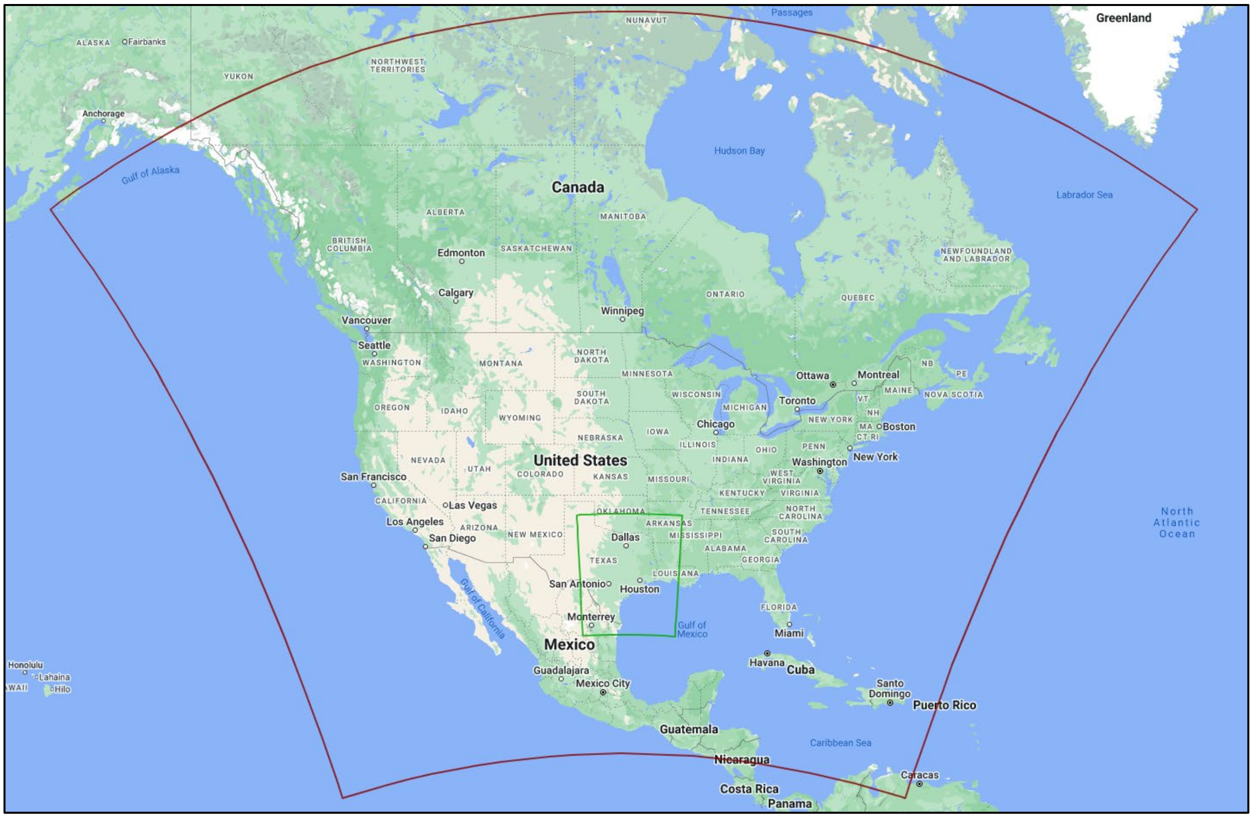

Figure 1: WRF Modeling Domains. 12 km domain (red) encompassing the continental United States and 4 km domain (green) over eastern Texas.

Table 2: WRF Modeling Domain Definitions

Domain	Easting Range (km)	Northing Range (KM)	East/West Grid Points	North/South Grid Points
nca_12km	(-3492, 3492)	(-432, 540)	583	505
txf_4km	(-3024, 3024)	(-1692, -504)	244	298

The WRF vertical layer structure is intended to provide high resolution in the lowest part of the atmosphere where pollutant mixing is critical, as shown in Figure 2: *WRF Vertical Layer Structure.*

2022 JAN-DEC (txf_4km domain)

WRF Layer	Sigma Level	Top (m AGL)	Center (m AGL)	Thickness (m)
35	0.000	20427	18431	3992
34	0.050	16435	15241	2388
33	0.100	14048	13164	1767
32	0.150	12280	11566	1428
31	0.200	10852	10245	1213
30	0.250	9639	9108	1061
29	0.300	8577	8104	947
28	0.350	7630	7202	857
27	0.400	6774	6382	783
26	0.450	5991	5630	722
25	0.500	5269	4933	671
24	0.550	4598	4285	627
23	0.600	3971	3677	589
22	0.650	3382	3104	556
21	0.700	2826	2614	424
20	0.740	2402	2248	307
19	0.770	2095	1946	298
18	0.800	1797	1700	194
17	0.820	1603	1508	190
16	0.840	1413	1320	187
15	0.860	1226	1134	184
14	0.880	1042	952	181
13	0.900	862	817	89
12	0.910	773	728	88
11	0.920	684	640	88
10	0.930	596	553	87
9	0.940	509	466	86
8	0.950	423	380	86
7	0.960	337	294	85
6	0.970	252	210	85
5	0.980	167	146	42
4	0.985	125	104	42
3	0.990	83	62	42
2	0.995	42	31	21
1	0.998	21	10	21
0	1.000	0	0	0

2022 JAN-DEC (nca_12km domain)

WRF Layer	Sigma Level	Top (m AGL)	Center (m AGL)	Thickness (m)
35	0.000	20287	18245	4085
34	0.050	16202	14982	2441
33	0.100	13761	12868	1786
32	0.150	11974	11262	1424
31	0.200	10550	9952	1197
30	0.250	9354	8834	1040
29	0.300	8314	7852	924
28	0.350	7389	6972	834
27	0.400	6555	6174	761
26	0.450	5794	5443	701
25	0.500	5093	4768	650
24	0.550	4443	4140	606
23	0.600	3836	3552	569
22	0.650	3267	2998	537
21	0.700	2730	2525	409
20	0.740	2321	2173	296
19	0.770	2025	1881	287
18	0.800	1737	1644	187
17	0.820	1550	1458	184
16	0.840	1366	1276	181
15	0.860	1186	1097	177
14	0.880	1008	921	174
13	0.900	834	791	86
12	0.910	748	705	86
11	0.920	662	620	85
10	0.930	577	535	84
9	0.940	493	451	84
8	0.950	410	368	83
7	0.960	326	285	82
6	0.970	244	203	82
5	0.980	162	142	41
4	0.985	121	101	41
3	0.990	81	61	40
2	0.995	40	30	20
1	0.998	20	10	20
0	1.000	0	0	0

Figure 2: WRF Vertical Layer Structure. Vertical layer structure for the 4km domain (left) is similar but not identical to the vertical layer structure for the 12km domain (right).

The WRF configuration and data used for modeling can be seen in Table 3: *TCEQ 2022 WRF Modeling Configuration*.

Table 3: TCEQ 2022 WRF Modeling Configuration

Parameter Description	Configuration
WRF Version	4.5.2
WPS Version	4.5
Domains	nca_12km, txf_4km
Analysis Input Data	ERA5
Topographic Inputs	GMTED2010
Sea Surface Temperature Input Data	ERA5
Land Use/Land Category Input Data	MODIS IGBP (21 class)
Nesting	None
Surface Analysis nudging	12km and 4km, for Temp, wind, and humidity
3D Analysis Nudging	12km and 4km, Temp, wind, and humidity only above PBL
Observational Nudging	None
Land Surface Model	Noah
Surface Layer Physics	Revised MM5 Scheme
Shortwave Radiation	Rapid Radiative Transfer Model (RRTM)
Longwave Radiation	Rapid Radiative Transfer Model (RRTM)
Planetary Boundary Layer Scheme	YSU
Cumulus Parameterization Option	Kain Fritsch Scheme on 12km only
Microphysics	WSM6 on 12km and 4km
Vertical Coordinate System	Hybrid

The WRF Preprocessing System (WPS) version 4.5 was used to prepare the monthly WRF model runs. WPS consists of three programs that prepare inputs to the model: geogrid, ungrib, and metgrid. An outline of WPS and how it relates to the WRF modeling system can be seen in Figure 3: *Overview of the WPS and WRF modeling framework.*

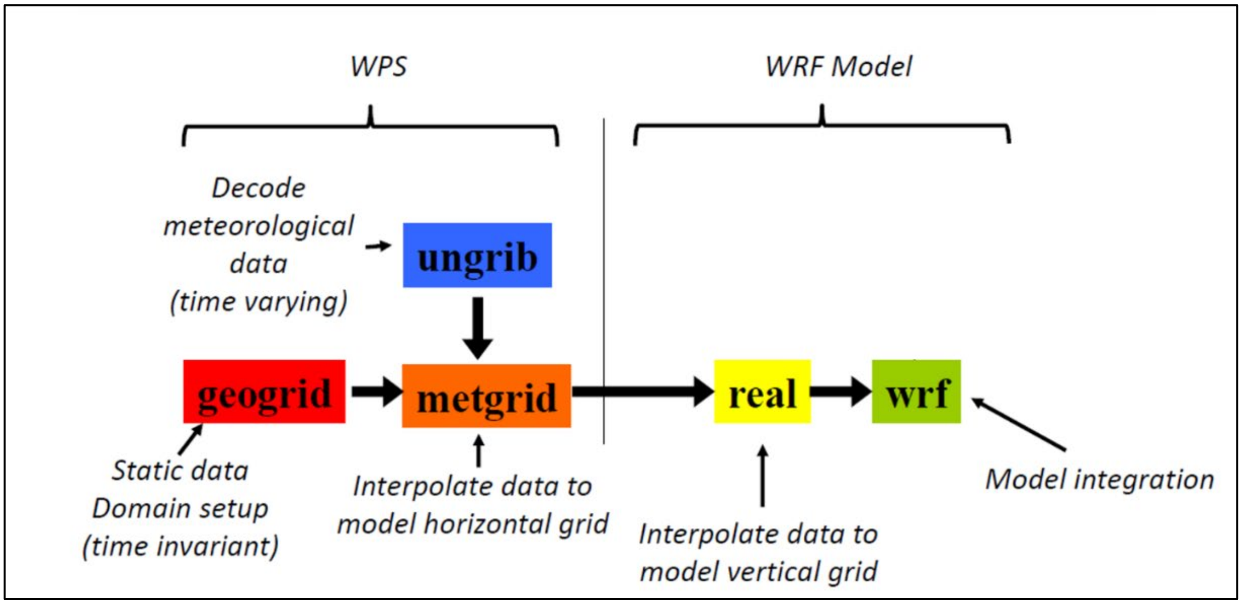

Figure 3: Overview of the WPS and WRF modeling framework. Adapted from the NCAR January 2021 Tutorial (Wang, 2021).

2. WRF Model Performance Evaluation (MPE)

2.1: Approach

The section describes the performance evaluation of the preliminary WRF meteorological model runs for the 2022 base year. This evaluation follows U.S. Environmental Protection Agency's (EPA) guidelines for the evaluation of base year meteorological fields, which has the following objectives:

- to "determine if the meteorological model output fields represent a reasonable approximation of the actual meteorology that occurred during the modeling period;" and
- to "identify and quantify the existing biases and errors in the meteorological predictions in order to allow for a downstream assessment of how the air quality modeling results are affected by issues associated with the meteorological data."

TCEQ conducted both an operational evaluation (i.e., quantitative, statistical, and graphical comparison) and a phenomenological assessment (qualitative comparison of model output to observed meteorological features) to meet these objectives.

The quantitative MPE of the 2022 WRF runs was conducted using surface observations from Continuous Air Monitoring Station (CAMS) sites across the 4km domain and includes statistical performance metrics compared with respective performance benchmarks. CAMS monitoring site locations used for MPE can be seen in Figure 4: *CAMS monitoring sites within the txf_4km modeling domain.*

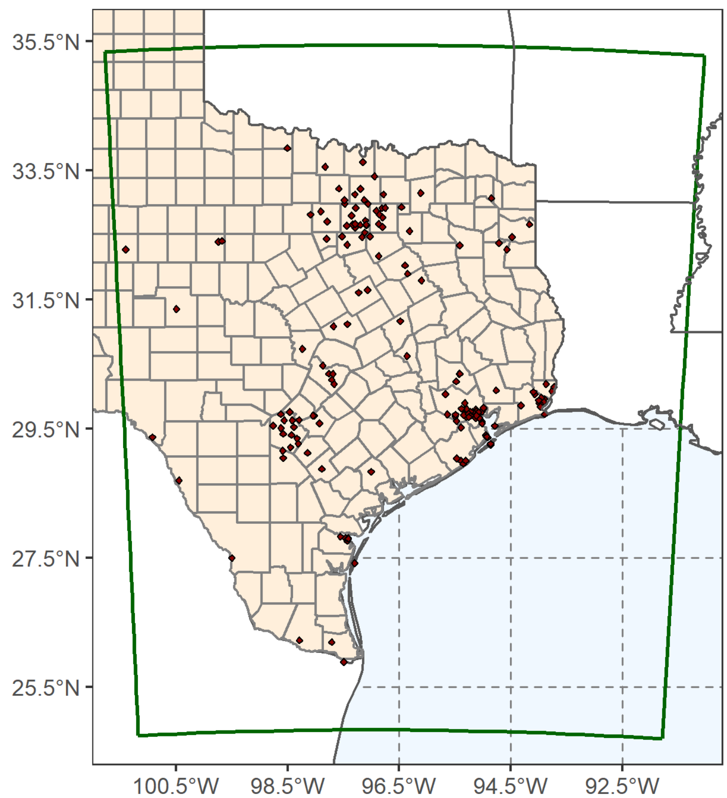

Figure 4: CAMS monitoring sites (red dots) within the txf_4km modeling domain (green boundary).

Table 4: *NWP Performance Benchmarks* lists the meteorological model performance benchmarks for simple (Emery et al., 2001) and complex (Kemball-Cook et al., 2005) situations. The simple benchmarks were created by studying well-performing meteorological model evaluation results for mostly flat terrain and simple meteorological conditions (e.g., stationary high pressure) and for modeling that was mostly conducted to support air quality modeling (e.g., ozone SIP modeling). The complex benchmarks were developed during the Western Regional Air Partnership (WRAP) regional haze modeling and are performance benchmarks for more complex conditions, such as the complex terrain of the Rocky Mountains and Alaska (Kemball-Cook et al., 2005). McNally (2009) analyzed multiple annual runs that included complex terrain conditions and suggested an alternative set of complex conditions benchmarks for temperature. These benchmarks are not to provide a pass/fail grade for the WRF model runs, but to contextualize its results within the historical literature of past NWP performance (Emery, 2001).

Table 4: NWP Performance Benchmarks

Conditions	Simple	Complex
Temperature Bias	≤ ±0.5˚K	≤ ±2.0˚K
Temperature Gross Error	≤ ±2.0˚K	≤ ±3.5˚K
Wind Speed Bias	≤ ±0.5 m/s	≤ ±1.5 m/s
Wind Speed RMSE	≤ 2 m/s	≤ 2.5 m/s
Wind Direction Bias	≤ ±10˚	≤ ±10˚
Wind Direction Gross Error	≤ 30˚	≤ 55˚
Mixing Ratio Bias	≤ ±0.8 g/kg	≤ ±1.0 g/kg
Mixing Ratio Error	≤ 2.0 g/kg	≤ 2.0 g/kg

2.2: Preliminary 4km Domain-Wide MPE

TCEQ's WRF model configuration performs well when compared to quality assured observed data from various monitoring sites within the 4km domain. The four standard meteorological parameters (wind speed, wind direction, temperature, and humidity) consistently perform within or just outside of the simple conditions benchmarks when analyzing the quarterly domain averages.

Figure 5: *Quarterly average soccer plot panel with wind speed, wind direction, temperature, and humidity performance*, Figure 6: *Quarterly average soccer plot panel with wind speed, wind direction, temperature, and humidity performance for daytime hours only*, and Figure 7: *Quarterly average soccer plot panel with wind speed, wind direction, temperature, and humidity performance for nighttime hours only* show quarterly soccer plot panels of model performance in complex and simple conditions for all hours, daytime hours, and nighttime hours, respectively. Analyzing the difference between daytime and nighttime performance can help determine if better performance is needed during times of the day when formation and/or transport of certain pollutants is important. Performance across all hours falls within the simple conditions benchmarks, except for Q2 (April, May, and June) wind speed, which has a bias slightly greater than the ±0.5 m/s simple conditions benchmark. Model performance for the four meteorological parameters averaged across all months but only for daytime hours (Figure 5) and nighttime hours (Figure 6) also shows reasonable performance. For daytime hours, Q2 wind speed and temperature fall outside of the simple conditions benchmarks, with a bias of approximately 1 m/s and 0.6 degrees Kelvin, respectively. Nighttime hours show better performance for wind speed and temperature than daytime hours, with wind direction performance showing greater bias and error for some quarters. The model also estimates wind direction well during the day when patterns within the planetary boundary layer (PBL) are more consistent, but it slightly degrades in performance during nighttime hours when the PBL breaks down and general flow is more scattered and random.

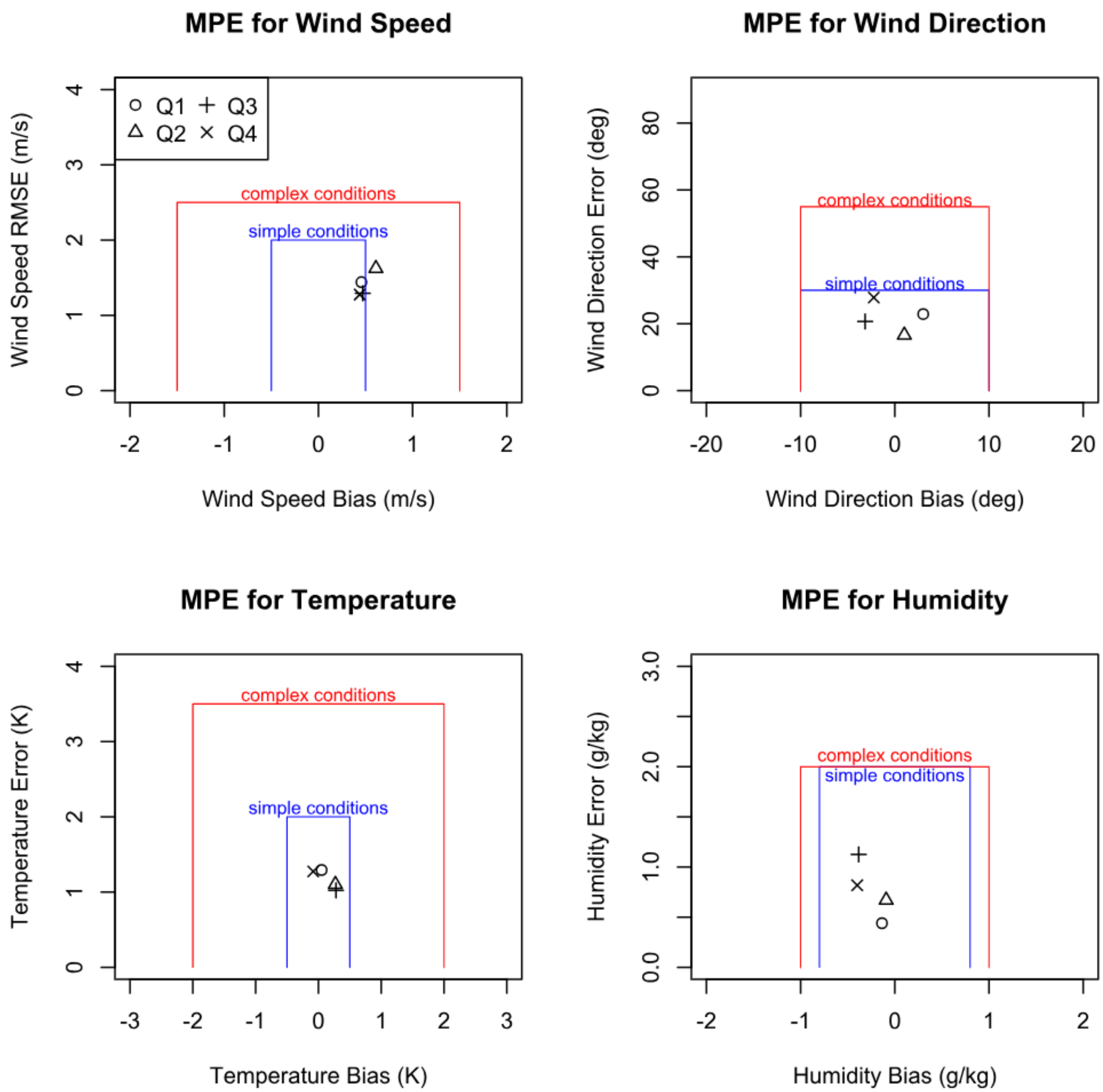

Figure 5: Quarterly average soccer plot panel with wind speed, wind direction, temperature, and humidity performance. Observed data is from quality assured CAMS data monitors within the 4km domain. Q1 consists of the months January, February, and March. Q2 consists of the months April, May, and June. Q3 consists of the months July, August, and September. Q4 consists of the months October, November, and December.

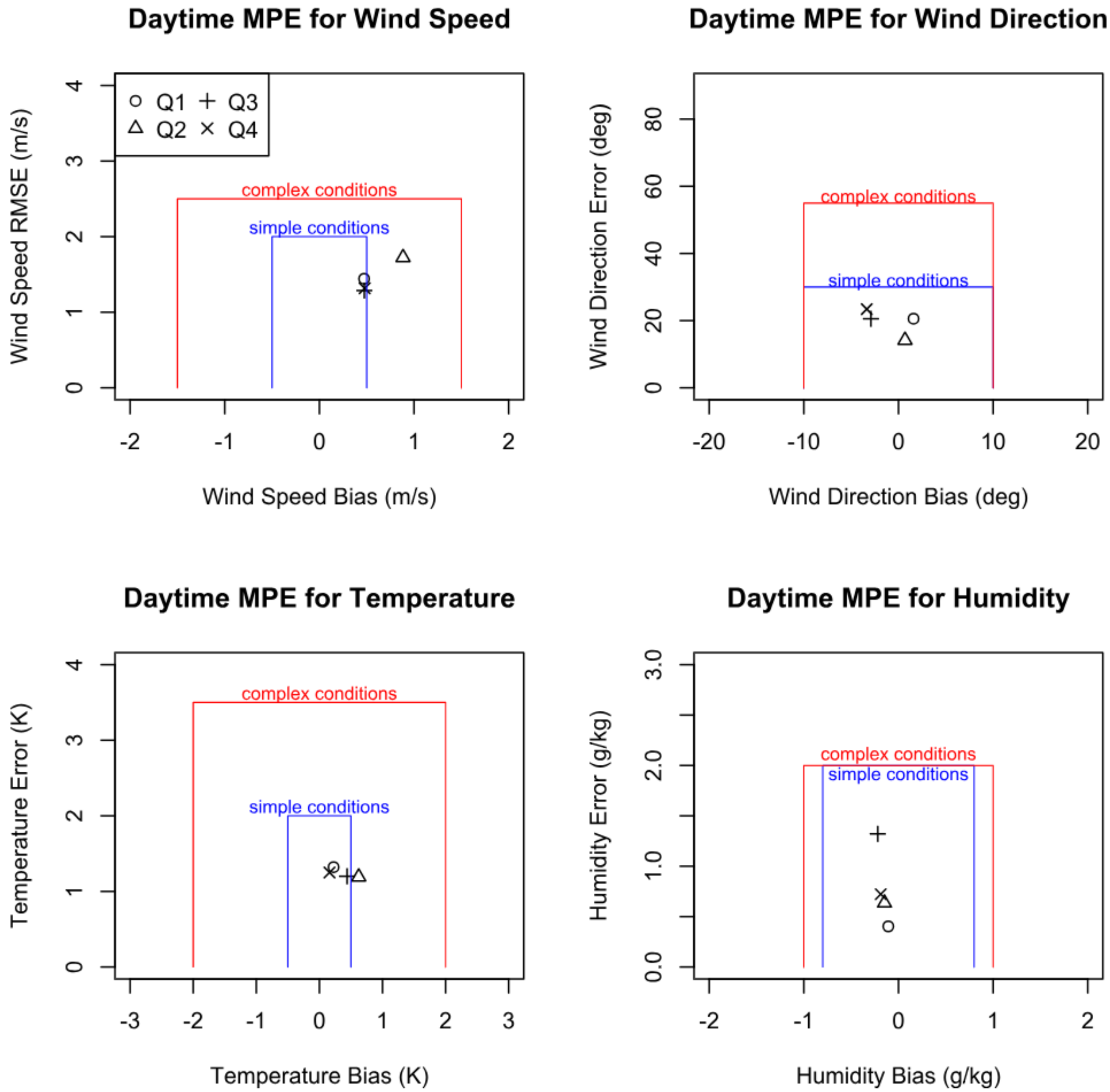

Figure 6: Quarterly average soccer plot panel with wind speed, wind direction, temperature, and humidity performance for daytime hours only. Observed data is from quality assured CAMS data monitors within the 4km domain. Q1 consists of the months January, February, and March. Q2 consists of the months April, May, and June. Q3 consists of the months July, August, and September. Q4 consists of the months October, November, and December.

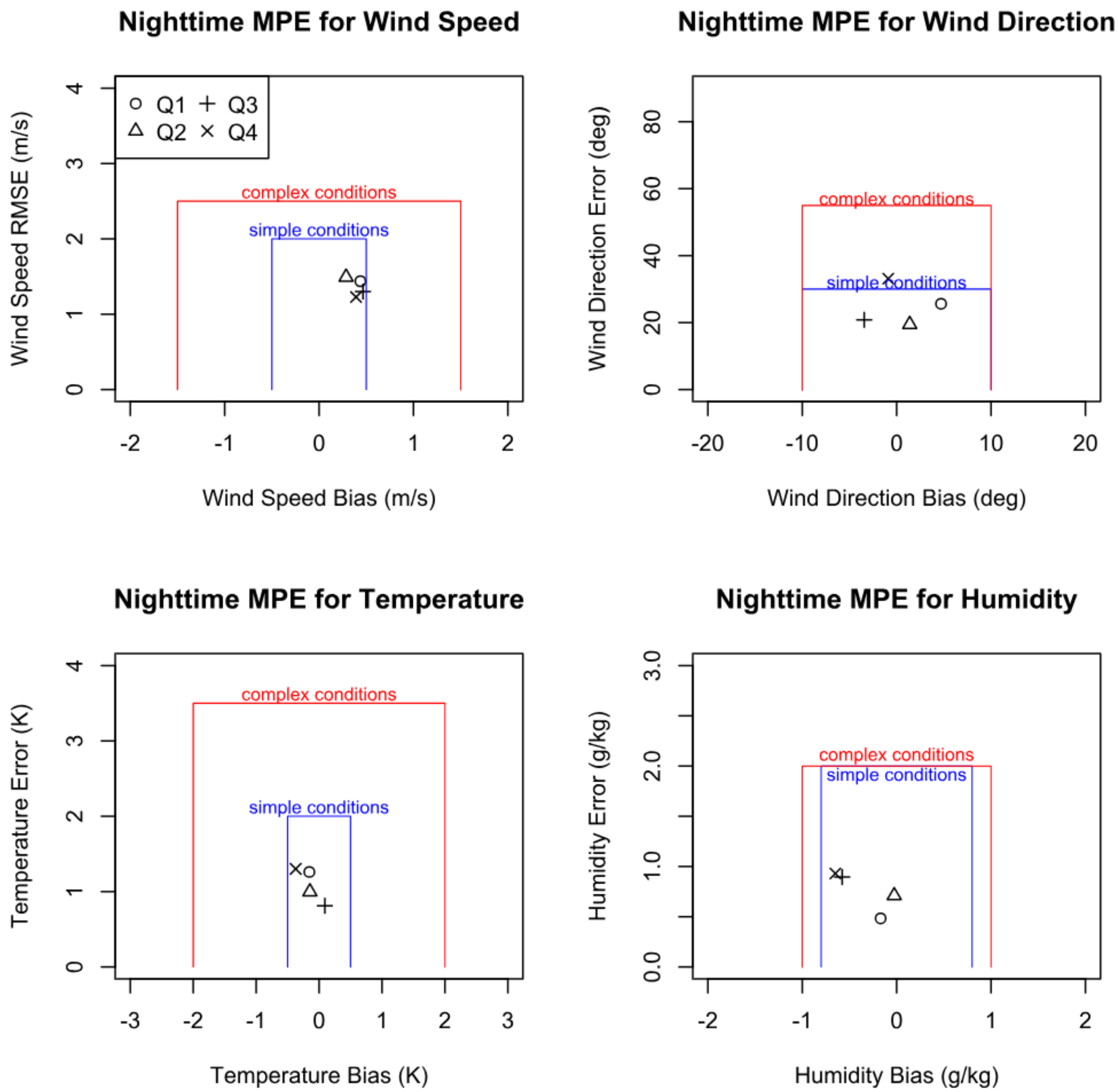

Figure 7: Quarterly average soccer plot panel with wind speed, wind direction, temperature, and humidity performance for nighttime hours only. Observed data is from quality assured CAMS data monitors within the 4km domain. Q1 consists of the months January, February, and March. Q2 consists of the months April, May, and June. Q3 consists of the months July, August, and September. Q4 consists of the months October, November, and December.

Though the 4km domain covers many different areas of Texas with varying atmospheric characteristics, generally, the model estimates temperature and wind speed well during nighttime hours when temperatures are cooler and wind speeds are slower, but it tends to overestimate these parameters during the day. This is supported by Figure 8: *July hourly temperature for the 4km domain*, where the time series of temperature for July shows WRF estimating nighttime lows well but overpredicting the daytime highs during the hot summer month. Figure 9: *January hourly temperature for* *the 4km domain* shows a temperature timeseries for a winter month. While the statistical measures in the soccer plot panels show performance for temperature is generally worse for Q1 (January, February, and March) compared to other quarters, the timeseries does show how well the model is able to replicate complicated winter diurnal temperature patterns. Despite slightly missing the timing of the highest temperature on some days or underestimating the lowest temperatures on other days, this shows the capability of the current model configuration to capture varying temperatures well.

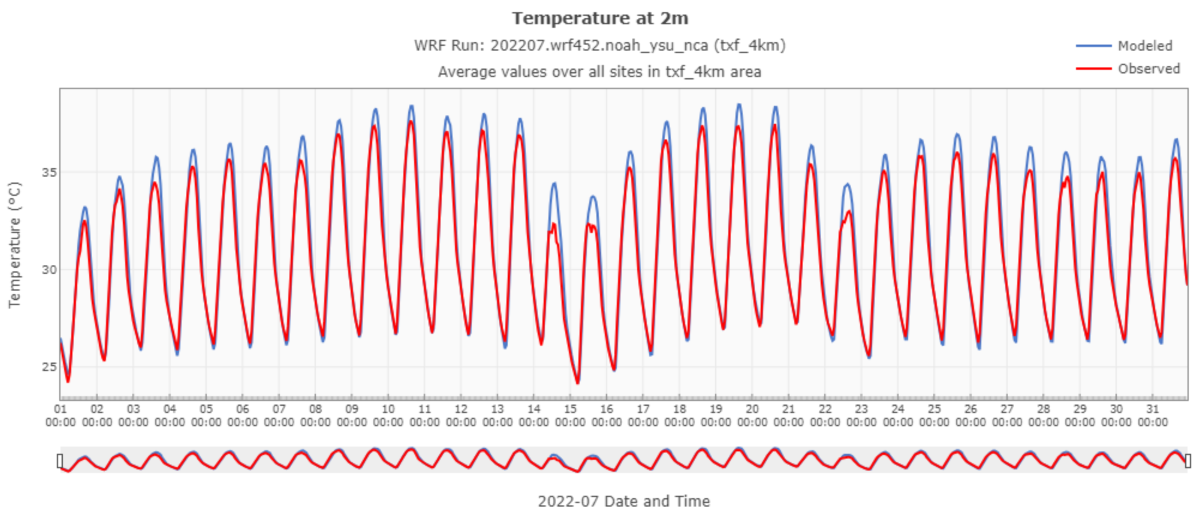

Figure 8: July hourly temperature for the 4km domain. Mean observed temperatures (red) are compared to mean modeled temperatures (blue).

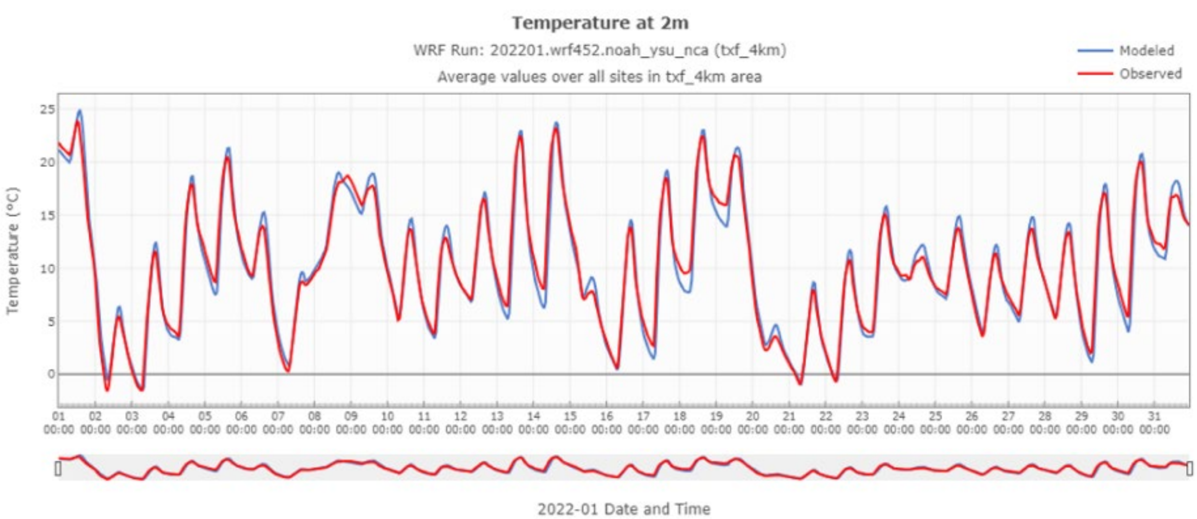

Figure 9: January hourly temperature for the 4km domain. Mean observed temperatures (red) are compared to mean modeled temperatures (blue).

Figure 10: *2022 monthly total precipitation averaged over the 4km domain* shows precipitation totals at CAMS monitoring sites compared to WRF precipitation totals at

those same locations and averaged across the 4km modeling domain. The month of May has the worst model performance and underrepresented the average precipitation total at these locations by more than 2 inches. Other months also underestimated precipitation totals at the various sites across the 4km domain. These errors are likely from WRF misrepresenting the quantity of precipitation for a given feature and possibly missing entire rain events.

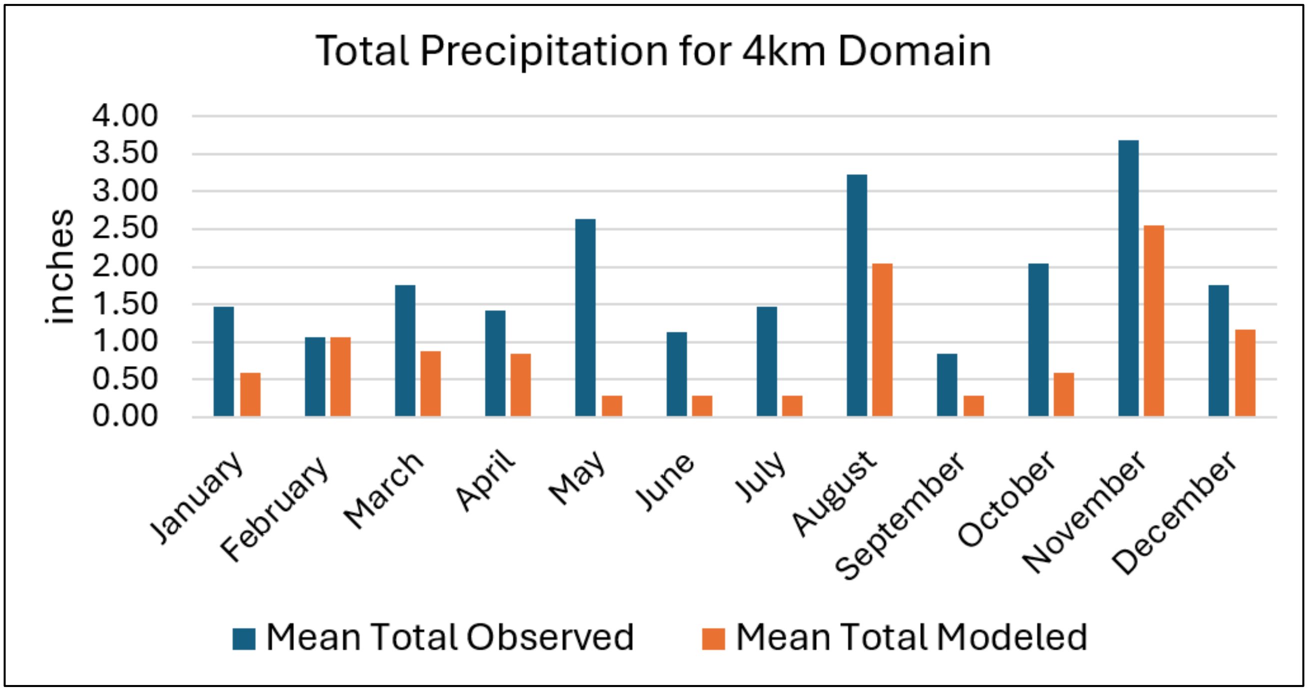

Figure 10: 2022 monthly total precipitation averaged over the 4km domain.

Overall, the preliminary WRF simulations for 2022 performed reasonably well when analyzing domain-wide statistics and looking at the standard meteorological parameters. TCEQ will continue evaluating model performance, focusing on individual nonattainment areas and additional meteorological parameters.

3. References

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