JANUS RESEARCH GROUP

Final Report

Testing and Analysis of Houston-Galveston-Brazoria (HGB) Specific WRF Configurations on TCEQ 2022 WRF 4 km Domain

TCEQ Contract No. 582-23-45974
Work Order No. 3
Revision 1.0

Deliverable 6.2

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Revision	Revision Date	Remarks
0.1	June 20, 2025	Internal Version for Review
1.0	June 23, 2025	Version Submitted to TCEQ

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List of Acronyms

AER – Atmospheric and Environmental Research
AER_BASE – AER “Base” WRF Configuration
AER_PBL – AER WRF Configuration with PBL scheme altered relative to AER_BASE
AER_MP – AER WRF Configuration with MP scheme altered relative to AER_BASE
AQRP – Air Quality Research Program
CAMS – TCEQ Continuous Air Monitoring Stations
DFW10 – Dallas Fort Worth ozone non-attainment region
ECMWF – European Center for Medium-Range Weather Forecasts
EPA – United States Environmental Protection Agency
ERA5 – ECMWF Reanalysis version 5
FCST – Modeled WRF “Forecast” fields
GHI_ACCUM – Accumulated global horizontal irradiance
HGB8 – Houston-Galveston-Brazoria ozone non-attainment region
MAE – Mean Absolute Error
MB – Mean Bias
MDA8 – Daily maximum 8-hour average of ozone
MP – Microphysics
MPAS – Model Performance Across Scales
MPE – Model Performance Evaluation
MSKF – Multiscale Kain Fritsch Scheme
NCAR – National Center for Atmospheric Research
NCEP – National Center for Environmental Prediction
NCEP-FNL – NCEP Final
NMB – Normalized Mean Bias
O3 – Ozone
OBS – Observations
PBL – Planetary Boundary Layer
RAINC – Convective Rainfall
RAINNC – Non-convective Rainfall
RAINSH – Shallow cumulus precipitation
RMSE – Root Mean Square Error
SAN4 – San Antonio ozone non-attainment region
TCEQ_BASE – Texas Commission on Environmental Quality 2022 Modeling Platform Base WRF Configuration
UH – University of Houston
WRF – Weather Research and Forecasting Model
WPS – WRF Preprocessing System

Executive Summary

Air quality modeling results are sensitive to the input meteorology (Appel et al., 2010), so it is essential to evaluate the accuracy of the meteorological inputs (EPA, 2018). Notably, meteorology (represented by 2m Temperature; Relative Humidity, Wind Speed, Wind Direction, and Surface Pressure) was found to be a significant predictor of daily maximum 8-hour average of ozone (MDA8 O3), explaining between 67 and 73% of the variability in the Dallas Fort Worth (DFW); Houston-Galveston-Brazoria (HGB); and San Antonio (SAN) regions (Dayalu et al., 2023; Mountain, M. 2022).

A recent Air Quality Research Program (AQRP) project conducted by the University of Houston (UH) tested multiple WRFv3.9.1.1 configurations at 1.3 km resolution over the Houston-Galveston-Brazoria (HGB) area (Wang et al., 2023). The UH configurations were tested over two periods in 2021 that were relevant to regional O3 air quality: July 20th through July 30th and August 20th through October 13th (Wang et al., 2023). When compared with observations and TCEQ's 2019 WRFv4.1.5 4 km resolution modeling platform, some UH configurations showed improved meteorological performance in the HGB area (Wang et al., 2023), warranting further exploration by the TCEQ. The purpose of this project was to conduct sensitivity tests for several Weather Research and Forecast (WRF) model configurations and evaluate performance benefits across different locations within TCEQ's 2022 4 km modeling domain, including Texas Eight-hour Ozone Nonattainment Areas in DFW, HGB, and SAN.

There were three major tasks to accomplish this project's objectives. The first was to review relevant scientific literature and the UH AQRP project in conjunction with the TCEQ to determine configurations and time periods to be tested across six one-month continuous WRF runs using TCEQ's 2022 4 km Eastern Texas domain. The second was to conduct the associated WRF runs and provide output and set-up files to the TCEQ. The third was to conduct a model performance evaluation (MPE), comparing results to the TCEQ 2022 base case, including analysis on high O3 event days in Texas's Eight-hour Ozone Nonattainment areas. Surface meteorological variables tested were wind speed; wind direction; air temperature; relative humidity; solar radiation; and precipitation. A recommendation on the optimal WRF configuration for TCEQ's meteorological model platform was included as part of the MPE.

Three different WRF configurations were evaluated for two different months (June 2022 and September 2022) and compared with TCEQ 2022 modeling platform WRF output ("TCEQ_BASE") from the same months. The three configurations tested in this project included a configuration similar to the optimal UH configuration ("AER_BASE"); a configuration with an altered microphysics scheme relative to AER_BASE ("AER_MP"); and a configuration with an altered Planetary Boundary Layer Height scheme relative to AER_BASE ("AER_PBL"). ***Based on comparison against observations of the six surface meteorological variables, the AER_BASE case generally displayed superior performance relative to AER_MP, AER_PBL, and the TCEQ_BASE cases.*** In addition, based on the results of the Model Performance Evaluation (MPE) it is recommended that the TCEQ retain the ERA5 initial/boundary condition data set rather than the NCEP_FNL data set used in the three AER configurations and the UH study.

All requirements established in the Quality Assurance Project Plan (QA Category III for Research Model Development or Application) for this Work Order were met and passed, satisfying the requirement to audit 10% of the data produced for quality.

1. Introduction

1.1. Project Objectives

The purpose of this project was to conduct sensitivity tests for several Weather Research and Forecast (WRF) model configurations to evaluate performance benefits across different locations within TCEQ's 4 km modeling domain, including Texas Eight-hour Ozone Nonattainment Areas. In addition, recommendations are provided as to which WRF model configuration results in the best performance for incorporation into TCEQ's 2022 modeling platform.

The objectives of this project are thus to (1) review relevant scientific literature and previous studies, including the recent AQRP project, to determine the configurations to be tested; (2) conduct six one-month continuous WRF runs in 2022 using the different configurations across TCEQ's 4 km resolution domain; and (3) evaluate model performance of key meteorological variables for each one-month WRF run and compare the results to the same month from the TCEQ 2022 base case and observational data for both the 4 km Eastern Texas domain and the eight-hour nonattainment areas of DFW, HGB, and SAN.

The Schedule of Deliverables for this project is given in Table 1.

Table 1. Schedule of Deliverables for TCEQ Work Order #3

Milestones	Planned Date
Task 1 - Work Plan	
1.1: TCEQ-approved Work Plan	December 30, 2024
1.2: TCEQ-approved QAPP	December 30, 2024
Task 2 – Progress Reports	
2.1: Monthly Progress Reports	Monthly with invoice
Task 3 – Review Previous Work and Model Set-Up	
3.1: Memo with WRF configurations and periods to be tested	March 31, 2025
Task 4 – Conduct Model Runs	
4.1: WRF output files from six one-month WRF runs and corresponding WRF set-up files.	April 30, 2025
Task 5 – Model Performance Evaluation	
5.1: Technical Memo	May 30, 2025
Task 6 – Draft and Final Reports	
6.1: Draft Report	June 13, 2025
6.2: Final Report	June 30, 2025

1.2. Background

The TCEQ is required under the Federal Clean Air Act (FCAA) to perform air quality modeling for attainment demonstration purposes. Air quality modeling includes simulations of the atmosphere using meteorological modeling. The TCEQ is currently using the community driven WRF model version 4.5.2 to generate meteorological inputs for its 2022 air quality model platform.

Air quality modeling results are sensitive to the input meteorology (Appel et al., 2010), so it is essential to evaluate the accuracy of the meteorological inputs (EPA, 2018). A recent Air Quality Research Program (AQRP) project conducted by the University of Houston (UH) tested various WRF configurations over the Houston-Galveston-Brazoria (HGB) area (Wang et al., 2023). These configurations used a 1.3 km resolution domain over the Houston area and tested different WRF settings and initialization datasets. A few of the 1.3 km WRFv3.9.1.1 UH configurations showed improved performance in the HGB area when compared to TCEQ's 4 km WRFv4.1.5 2019 model platform (Wang et al., 2023). The set of UH configurations were tested over two periods in 2021: July 20th through July 30th and August 20th through October 13th (Wang et al., 2023). For this project, the TCEQ 2022 meteorological model domain setup (WRFv4.5.2; 4 km East Texas domain) was used, testing and evaluating different WRF configurations based on one-month continuous model runs for the 4 km East Texas domain as a whole and the Eight-hour Ozone Nonattainment Areas in DFW, HGB, and SAN specifically (Figure 1).

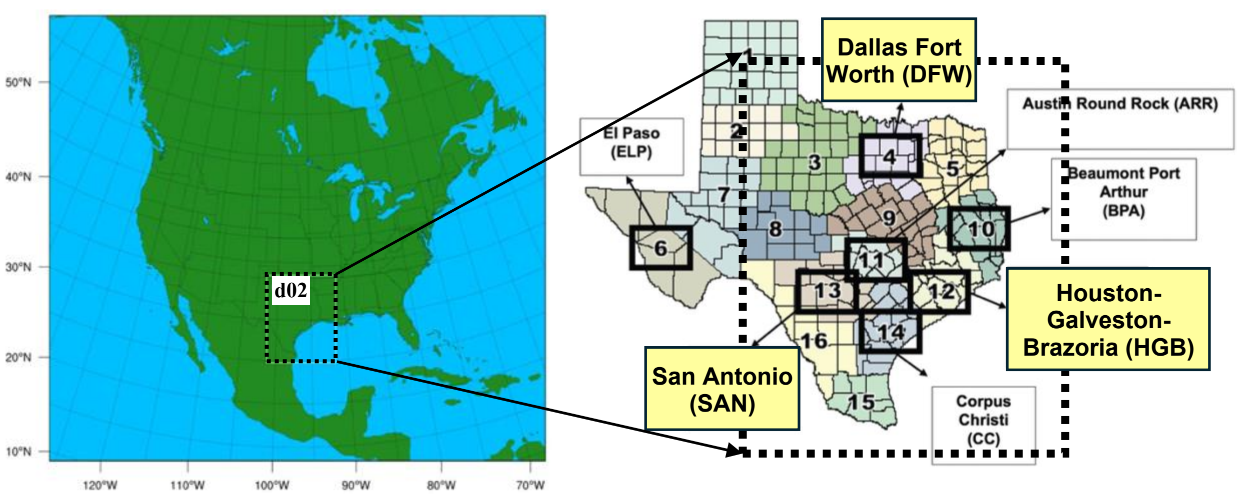


Figure 1. Study domain. Left: TCEQ-provided WRF domain configuration. Outer (d01) domain is 12km; inner (d02 East Texas domain) is 4km. Right: Zoom of d02/East Texas domain overlaid on Texas regions. Regions selected for targeted model performance evaluation on high MDA8 O3 days are highlighted in yellow (DFW, HGB, SAN). Region map adapted from Dayalu et al. (2024).

1.3. Report Outline

This Final Report highlights major activities and key findings, provides pertinent analysis, describes encountered problems and associated corrective actions, and details relevant statistics including data, parameter, or model completeness, accuracy and precision. It satisfies Deliverable 6.2 of the Work Plan for Work Order No. 3 under TCEQ Contract 582-23-45974:

Deliverable 6.2: Final Report
Deliverable 6.2 Due Date: June 30, 2025

2. Task 3: Review Previous Work and Model Set-up

In this task, AER reviewed relevant scientific literature and previous studies, including the recent Wang et al. (2023) AQRP project, to determine the configurations to be tested. AER also coordinated with the TCEQ project manager to obtain TCEQ's 2022 meteorological model platform domain parameters, the TCEQ base-case configuration ("TCEQ_BASE"), and other relevant information on configurations beyond the TCEQ_BASE case. Modifications made to WRF configuration files, including namelists, are detailed in Appendix A.

2.1. WRF Configurations Tested

In coordination with the TCEQ project manager, AER selected three configurations for testing and evaluation. The three 36-level WRF configurations "AER_BASE", "AER_PBL", and "AER_MP" were each run continuously for each of the months of June 2022 and September 2022. The final configurations are displayed in Table 2. June and September 2022 were selected as they both presented a series of high ozone days, with June 2022 facing more weather fluctuations relative to September 2022. Details including sample namelist files for WRF Preprocessing system (namelist.wps); WRF OBSGRID (namelist.oa); and WRF REAL (namelist.input) are provided in Appendix A of this report.

Table 2. Final three AER WRF configurations. The TCEQ 2022 modeling platform base ("TCEQ_BASE") and Wang et al. (2023) Nudged2 ("Wang_n2") schemes are provided for reference. The AER base configuration ("AER_BASE") is selected to closely resemble Wang_n2. AER's remaining proposed configurations reflect changes relative to AER_BASE in one of: microphysics (AER_MP); and Planetary Boundary Layer (AER_PBL). Red Font: altered schemes relative to AER_BASE.

Simulation Name	WRF version	IC/BC Meteorology	PBL	Microphysics	Cumulus on 12-km domain
TCEQ_BASE	4.5.2	ERA5	YSU	WSM6	Kain-Fritsch
Wang_n2	3.9.1	NCEP_FNL	MYNN	Morrison 2M	New Tiedtke
AER_BASE	4.5.2	NCEP FNL	MYNN	P3	New Tiedtke
AER_MP	4.5.2	NCEP_FNL	MYNN	Thompson aerosol-aware	New Tiedtke
AER_PBL	4.5.2	NCEP FNL	MYNN-2.6 w/EDMF option	P3	New Tiedtke

As shown in Table 2, the AER_BASE configuration was selected to most closely resemble the Wang_n2 configuration (Wang et al., 2023). Note that Wang et al. (2023) used the two-moment Morrison microphysics scheme in their study. Active development on that scheme ceased in 2014 (Morrison, personal communication) and the developers have since released the Predicted Particle Properties (P3) parameterization (Morrison and Milbrandt 2015; Milbrandt et al. 2021). AER used P3 in AER_BASE as the closest approximation to the Morrison 2M scheme. The P3 parameterization addresses the many issues inherent in dividing ice hydrometeors into multiple classes by having a single ice category, with variations in particle riming as a new prognostic variable. Significant success has been shown in improving precipitation rates and diurnal accumulations over other microphysics schemes (Wang et al. 2021).

For each of the sensitivity tests proposed by AER (red font, Table 2) the following justifications are provided:

- **AER_MP altered microphysics scheme:** For a sensitivity test, AER recommended the Thompson aerosol-aware microphysics parameterization (Thompson and Eidhammer 2014). This parameterization is used by the High-Resolution Rapid Refresh (HRRR) v4 model that has been operational since 2020.
- **AER_PBL altered PBL scheme:** MYNN-2.6 with EDMF option is the most up-to-date version of the MYNN scheme and activates mass flux in MYNN (email communication with Joseph Olson, MYNN developer). It also includes a non-local flux component which would help increase mixing, potentially alleviating the low boundary layer height biases noted in Wang et al. (2023).

In addition to analysis nudging to NCEP_FNL, surface grid nudging with OBSGRID was implemented to regrid the NCEP surface observational weather dataset only (https://rda.ucar.edu/datasets/d461000/). As the TCEQ Continuous Air Monitoring station (CAMS) observational data was used in the Model Performance Evaluation (MPE), these data were not included in the OBSGRID nudging. Of note, the Wang et al. (2023) study erroneously used CAMS data in both OBSGRID nudging and evaluation such that the evaluation results were not entirely independent of the nudging data. The current work eliminated that potential issue by using the CAMS data for independent evaluation only.

Note that the number of vertical levels (36) was retained in the AER configurations to remain consistent with the TCEQ_BASE configuration. While the selection of the number of vertical levels for the purposes of the current scope of work is not anticipated to appreciably change meteorological statistics of interest, for future development AER recommends the TCEQ increase vertical levels to 50 to align with current best practices.

As part of this task, a Technical Memo with WRF configurations and periods to be tested was provided to the TCEQ as Work Order Deliverable 3.1, delivered to the TCEQ on 19 March 2025.

3. Task 4: Conduct Model Runs

A downloader file containing instructions and links to download the six months of relevant WRF output files from the AER AWS S3 bucket was provided to the TCEQ via email on 17 April 2025 as a zip file (P2708_3_DELIVERABLE_4_1_582-23-45974.zip). The zip file contained a readme file with instructions; a python download script; a readme file; and the download manifest. Together, these were used by the TCEQ to automatically download relevant files for two months (June, Sept 2022) and three configurations (AER_BASE, AER_PBL, AER_MP). Given the size of the files, only the d02 files were provided as relevant for download and analysis. The following file categories (all listed in the manifest) have been provided for each month/configuration combination: wrfout*d02*; wrfrst*d02*; xtrm*d02*; namelist.input; namelist.wps; namelist.oa. The download manifest is provided as Appendix B.

4. Task 5: Model Performance Evaluation – Comparison of AER_BASE, AER_MP, AER_PBL, and TCEQ_BASE configurations with observations

Previous work used Generalized Additive Models (GAMs) to predict MDA8 O3 concentrations for several TX counties from 2012 to 2021 (Dayalu et al., 2023; Mountain, M. 2022). Meteorology (represented by 2m Temperature; Relative Humidity, Wind Speed, Wind Direction, and Surface Pressure) was found to be a significant predictor of MDA8 O3, explaining between 67 and 73% of the variability in the Dallas Fort Worth (DFW); Houston-Galveston-Brazoria (HGB); and San Antonio (SAN) regions. In this section, we compare meteorological model-observation mismatch among the AER configurations and the TCEQ_BASE configuration. Given the dominant role of meteorology in predicting MDA8 O3, we conclude with recommendations on the optimal WRF configuration to ingest into future modeling platforms. (Note that in this work, solar radiation and precipitation replace surface pressure as an MDA8 O3 predictor.)

Based on Model Performance Evaluation (MPE) results across multiple meteorological variables and averaging spatial and temporal scales, we recommend the AER_BASE configuration for ingestion into future modeling platforms. Notably, the AER_BASE configuration is the nearest approximation to the Wang et al. (2023) "Nudged2" configuration (Table 2).

Surface temperature, relative humidity, solar radiation, wind speed, wind direction, and 24-h precipitation have all been evaluated for the three configurations in June and September 2022. All variables were evaluated with the MET PointStat tool where Continuous Air Monitoring Site (CAMS) observations were present. 24-h precipitation was evaluated using the GridStat tool and the PRISM data set.

In this section, we compare model-observation mismatch among the AER_BASE, AER_MP, and AER_PBL configurations for each of the six meteorological variables. Comparisons are conducted for the 4 km domain as a whole and for each of the HGB8, DFW10, and SAN4 MDA8 O_3 non-attainment regions including for specific non-attainment dates (Table 3). In addition, we evaluate differences among configurations at monthly, daily and hourly timescales.

A selection of TCEQ_BASE results is provided for reference. Note that the TCEQ_BASE runs used ERA5 rather than NCEP_FNL for initial/boundary conditions and analysis nudging. As such, the direct comparisons with the AER configurations are limited to a high-level daily average comparison over the 4km domain as a whole for each meteorological variable. Our final recommendation for an optimal configuration is based only on comparisons among the AER configurations.

The AER model configurations have similar performances when averaged monthly and across the 4km domain. However, there are significant differences at daily and/or hourly timescales, including regional variation in performance, with the AER_PBL configuration consistently having significantly higher model-observation mismatch at daily and hourly timescales.

Table 3. High Ozone dates for targeted MPE. Relevant meteorological variables evaluated on the high ozone days both in aggregate and spatiotemporally separated for these locations and dates. Unless otherwise specified, region results are limited to sites located in the region's non-attainment counties/non-attainment adjacent counties. HGB8 = Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, Waller; DFW10 = Collin, Dallas, Denton, Ellis, Johnson, Kaufman, Parker, Rockwall, Tarrant, Wise; SAN4 = Bexar, Comal, Guadalupe, Wilson.

Date	Region	CAMS Site ID	8h O_3 (ppb)
2022-06-20	HGB8	417	97
		001	96
		554	92
2022-06-29	SAN4	501	88
		622	80
2022-06-30	DFW10	056	100
		070	93
2022-09-12 and 2022-09-13	DFW10	056	74
		062	71
		013	75
2022-09-13	SAN4	058	72
2022-09-21	HGB8	053	92
		417	88

Table 4. Point Stat MPE d02 summary statistics for June 2022, for each of the three AER WRF configurations “BASE”, “MP”, “PBL”. WRF Modeled = FCST; CAMS Observations = OBS; Pearson R = R; Normalized Mean Bias = NMB; Mean Bias = MB; Mean Absolute Error = MAE; Root Mean Square Error = RMSE; % Error relative to OBS = % Error.

	Variable	*Units*	*FCST*	*OBS*	*R*	*NMB*	*MB*	*MAE*	*RMSE*	*% Error*
BASE	Temp	K	303.1	302.5	0.94	0.002	0.676	1.312	1.67	0.22
MP			303.1		0.94	0.002	0.667	1.309	1.67	0.22
PBL			303.3		0.93	0.003	0.885	1.639	2.05	0.29
BASE	WSPD	m/s	3.570	2.710	0.68	0.317	0.860	1.258	1.59	32
MP			3.564		0.68	0.315	0.854	1.254	1.59	32
PBL			3.589		0.68	0.324	0.879	1.266	1.59	32
BASE	WDIR	deg	151.0	152.1	0.70	0.001	0.107	28.259	45.53	0.07
MP			151.1		0.70	0.001	0.157	28.325	45.66	0.10
PBL			151.1		0.70	0.000	-0.001	28.451	45.75	0.00
BASE	RH	%	58.58	62.93	0.90	-0.069	-4.346	7.417	9.49	-6.9
MP			58.67		0.90	-0.068	-4.259	7.351	9.44	-6.8
PBL			58.34		0.89	-0.073	-4.584	7.980	10.14	-7.3
BASE	Solar-All	L/min	0.46	0.41	0.95	0.120	0.049	0.084	0.16	12
MP			0.46		0.96	0.121	0.049	0.080	0.16	12
PBL			0.46		0.95	0.120	0.049	0.083	0.16	12
BASE	Solar-NonZero	L/min	0.70	0.62	0.93	0.120	0.075	0.128	0.20	12
MP			0.70		0.93	0.121	0.075	0.123	0.20	12
PBL			0.70		0.93	0.120	0.075	0.127	0.20	12
BASE	1-h Precip	mm	0.069	0.046	0.10	0.509	0.023	0.106	1.03	51
MP			0.062		0.08	0.342	0.016	0.100	0.98	34
PBL			0.065		0.08	0.412	0.019	0.105	1.06	41

Table 5. Point Stat MPE d02 summary statistics for September 2022, for each of the three AER WRF configurations "BASE", "MP", "PBL". WRF Modeled = FCST; CAMS Observations = OBS; Pearson R = R; Normalized Mean Bias = NMB; Mean Bias = MB; Mean Absolute Error = MAE; Root Mean Square Error = RMSE; % Error relative to OBS = % Error.

	Variable	*Units*	*FCST*	*OBS*	*R*	*NMB*	*MB*	*MAE*	*RMSE*	*% Error*
BASE	Temp	K	300.4	299.8	0.93	0.002	0.653	1.325	1.75	0.22
MP			303.1		0.93	0.002	0.665	1.334	1.75	0.22
PBL			303.3		0.92	0.002	0.713	1.586	2.00	0.24
BASE	WSPD	m/s	2.557	1.874	0.61	0.365	0.684	1.018	1.27	36
MP			3.564		0.61	0.365	0.682	1.017	1.27	36
PBL			3.589		0.62	0.373	0.699	1.016	1.26	37
BASE	WDIR	deg	125.1	117.6	0.69	0.025	3.735	36.45	54.4	3.18
MP			151.1		0.69	0.024	3.605	36.47	54.4	3.07
PBL			151.1		0.69	0.023	3.507	36.49	54.3	2.98
BASE	RH	%	58.27	63.91	0.91	-0.088	-5.646	7.790	10.3	-8.8
MP			58.67		0.91	-0.090	-5.766	7.870	10.4	-9.0
PBL			58.34		0.90	-0.086	-5.471	8.305	10.8	-8.6
BASE	Solar-All	L/min	0.36	0.34	0.96	0.065	0.022	0.054	0.12	6
MP			0.46		0.96	0.067	0.023	0.055	0.12	7
PBL			0.46		0.96	0.063	0.021	0.054	0.12	6
BASE	Solar-	L/min	0.61	0.58	0.94	0.065	0.037	0.093	0.16	6
MP	Non-zero		0.70		0.94	0.067	0.039	0.094	0.16	7
PBL			0.70		0.94	0.063	0.036	0.093	0.16	6
BASE	1-h Precip	mm	0.039	0.036	0.01	0.183	0.007	0.075	1.03	18
MP			0.062		0.01	-0.065	-0.002	0.069	0.95	-7
PBL			0.065		0.01	0.119	0.004	0.073	1.03	12

4.1. Temperature-2m (K)

Monthly averaged surface air temperature biases for June and September 2022 are shown in Figures 2 and 3. While the aggregate differences among configurations are small, AER_PBL shows the greatest deviation and spread in months relative to observations. Spatial patterns are largely consistent across configurations, with DFW showing smallest bias in June and SAN showing smallest bias in September. Overall, WRF modeled surface temperatures biases are small (about 1 K; Tables 4-5) but biased high relative to observations.

Diurnal averages are shown for June 2022 (Figure 4a) and Sept 2022 (Figure 4b). Averages are calculated for the entire 4km domain and across sites in or near non-attainment locations in each of HGB, DFW, and SAN. At diurnal scales, the deviation of AER_PBL from observations becomes large and significant. AER_PBL generally overestimates daytime temperatures relative to both observations AER_BASE, and AER_MP. Outside of daylight hours, AER_PBL generally underestimates temperatures relative to observations, AER_BASE, and AER_MP. These results hold for high ozone days as well.

Comparison of daily averaged 4 km domain-wide results generally indicate better model-observation agreement in June 2022 (Figure 5a) versus September 2022 (Figure 5b). As before, the AER_PBL configuration consistently has the highest model-observation mismatch and this is most pronounced during June 2022. In general, AER_MP and AER_BASE models perform similarly relative to temperature observations in both months. All AER configurations have temperatures that are biased high relative to both observations and the TCEQ_BASE case.

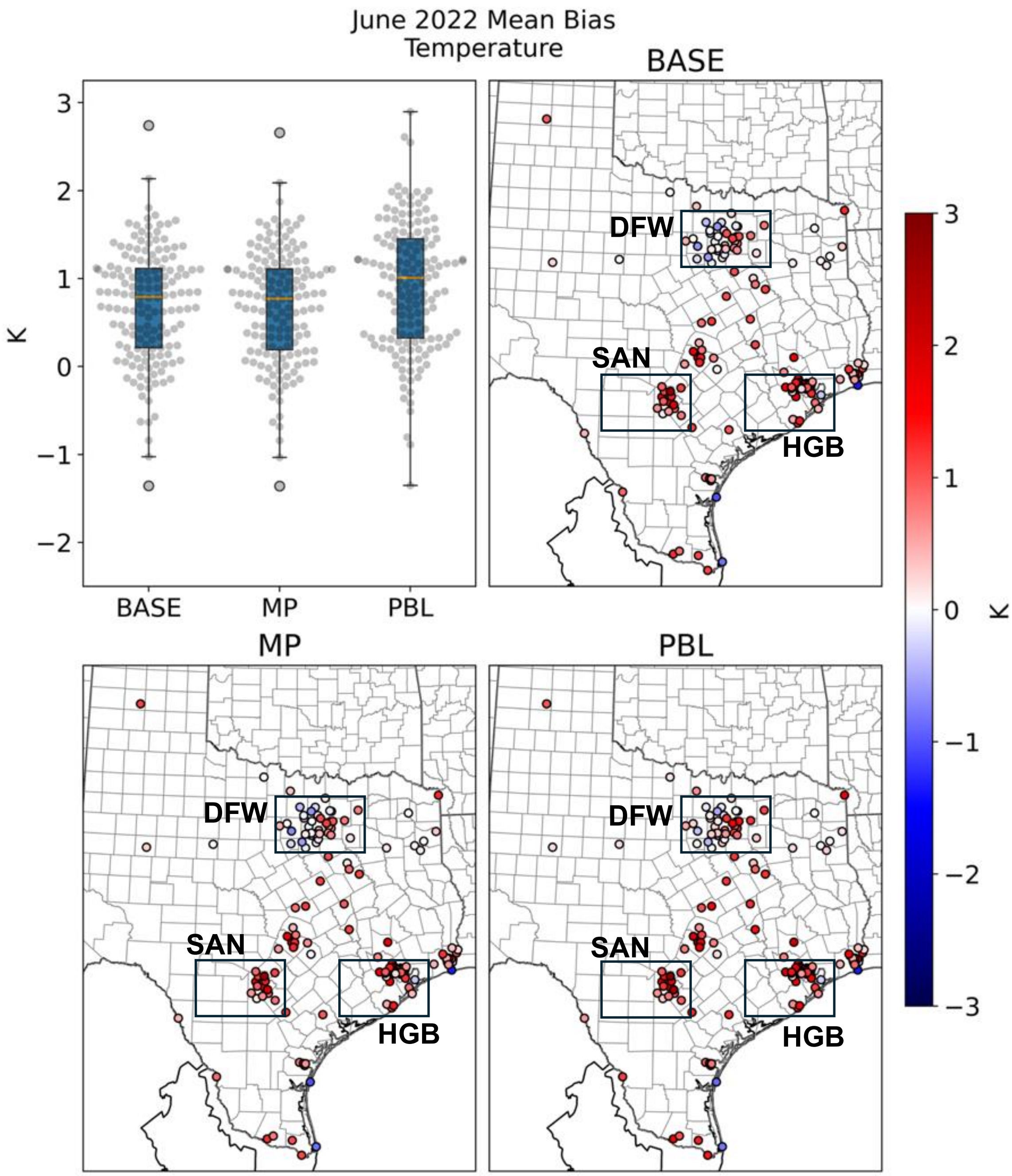


Figure 2. d02 Surface Temperature Mean Bias (K) relative to CAMS observations for June 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

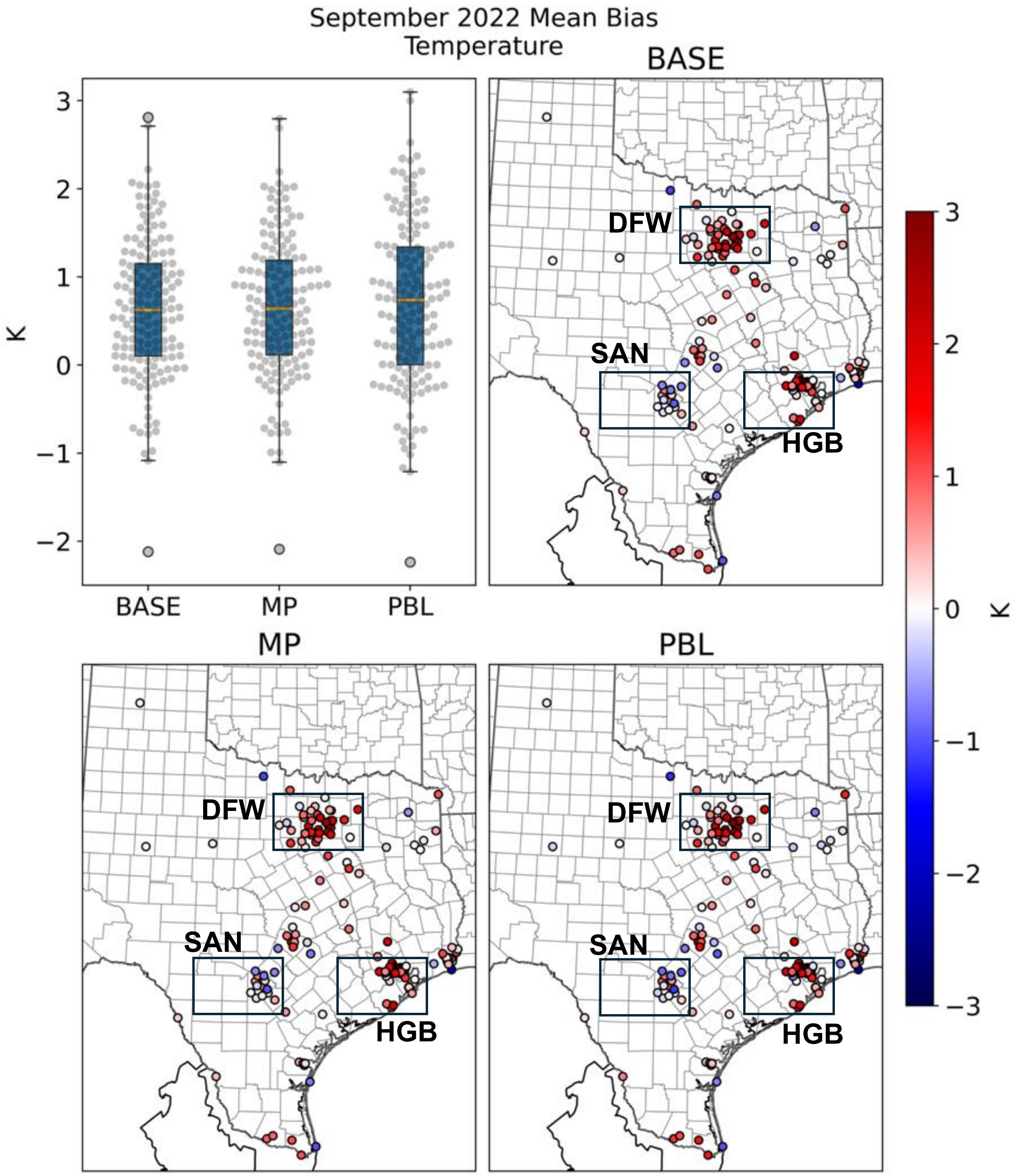


Figure 3. d02 Surface Temperature Mean Bias (K) relative to CAMS observations for September 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

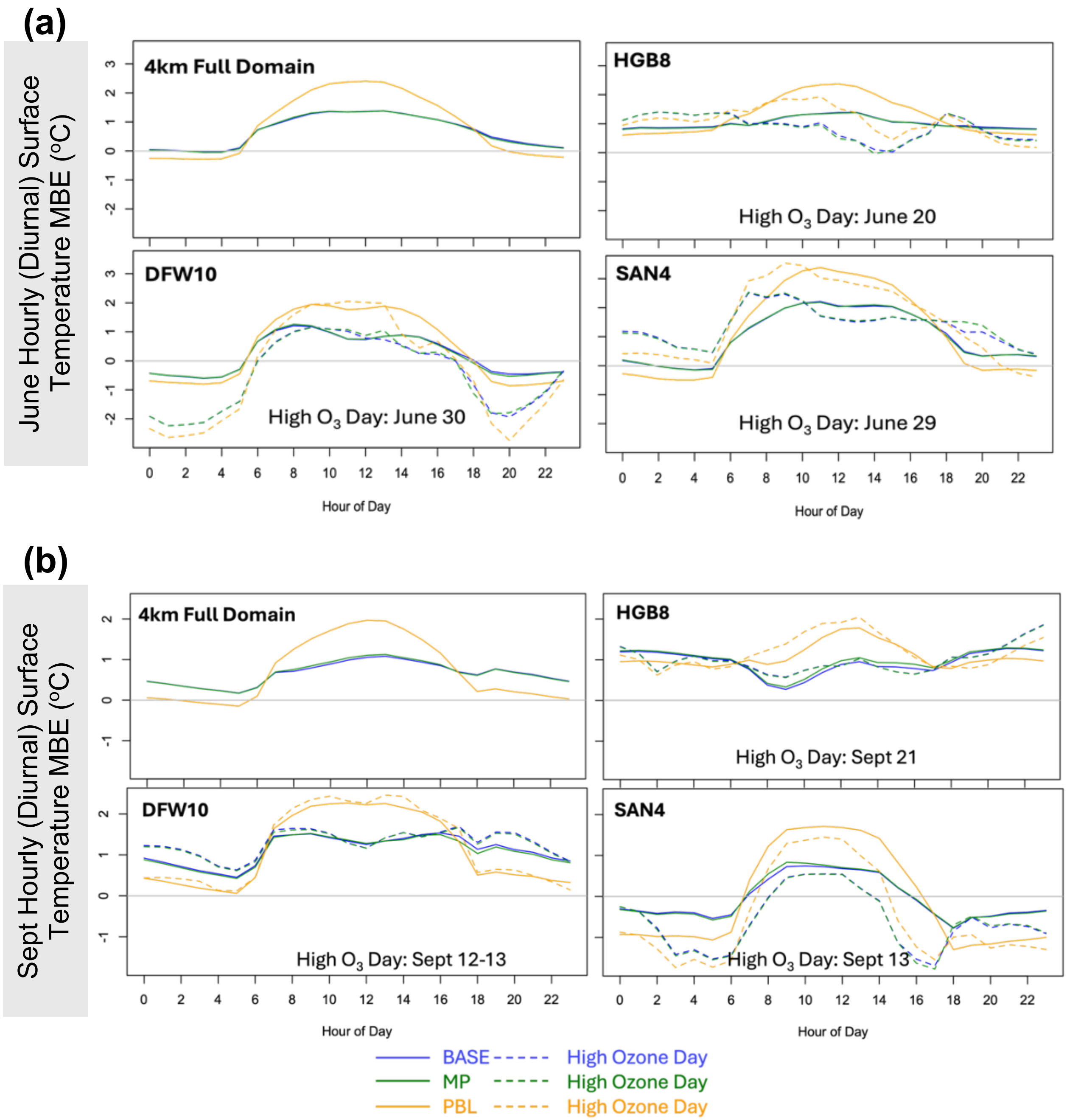


Figure 4. Diurnally averaged Mean Bias Errors (MBE) in Surface Temperature for the three AER WRF configurations for (a) June 2022 and (b) September 2022. For each month, the MBE is averaged for the full 4km domain; the HGB8 non-attainment region; the DFW10 non-attainment region; and the SAN4 non-attainment region. The dashed lines provide MBE results for the specified High O3 day. Note differences in y-axis scales for panels (a) and (b).

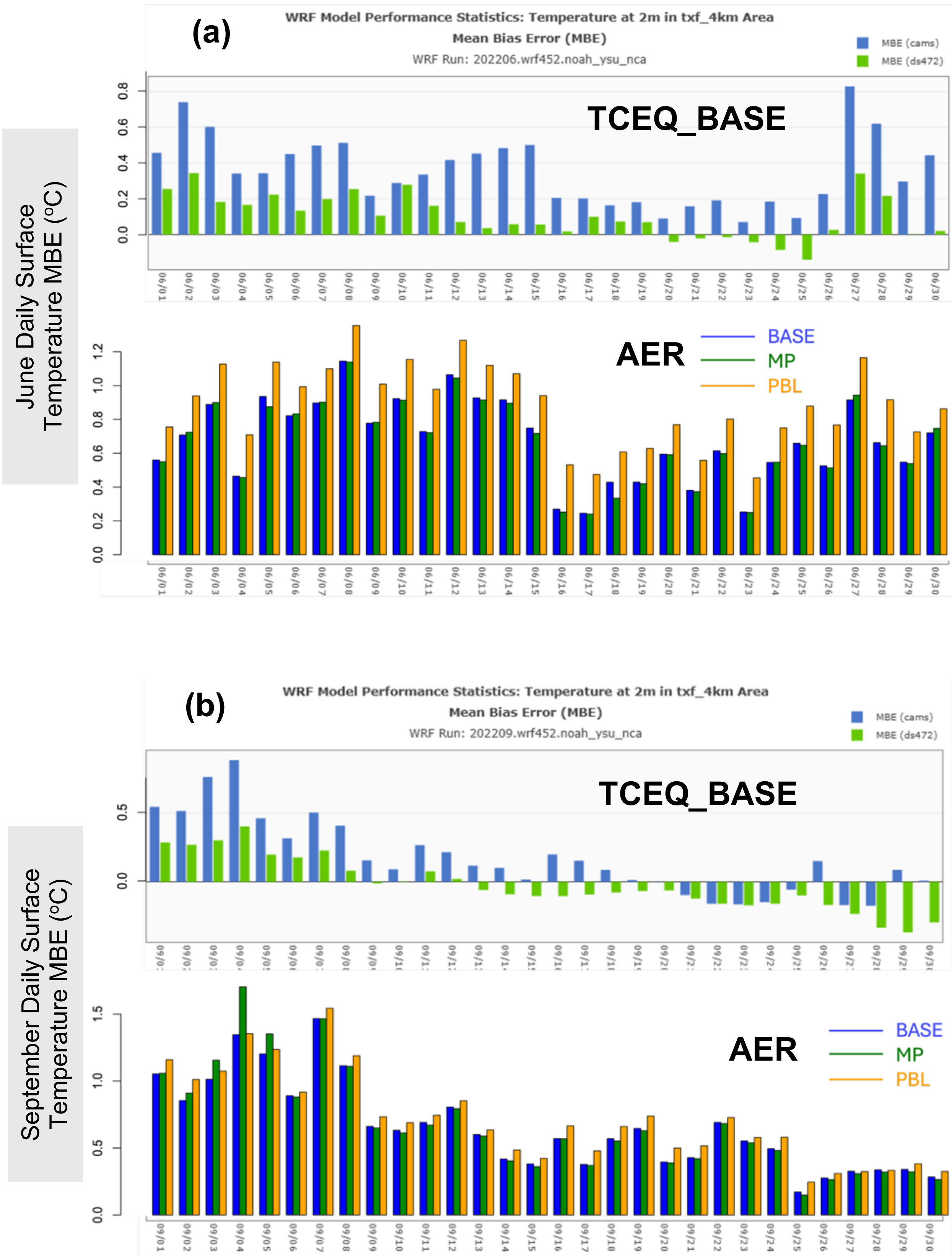


Figure 5. Daily averaged Mean Bias Errors (MBE) in Surface Temperature for TCEQ_BASE and the three AER WRF configurations for (a) June 2022 and (b) September 2022. For a more direct comparison of AER MBE with TCEQ_BASE MBE, the TCEQ_BASE data shaded in blue provides the comparison with CAMS data.

4.2. Relative Humidity (%)

Overall, Relative Humidity (RH) is biased low relative to observations in all tested configurations. Averaged across the domain, RH is typically 7% lower than observations in June 2022 and ~9% lower in September 2022 (Tables 4-5). Once again, no significant differences were observed among configurations when averaged across the domain and over each of the months (Figures 6 and 7). As with surface temperature, all WRF configurations exhibited the smallest RH model-observation mismatch in DFW in June 2022 (Figures 6 and 7).

Given that the overall sample size is small, and no observations were available in the SAN region, the diurnal comparison was restricted to the 4km domain only (Figure 8). Diurnal biases were largest during the 0600 LST to 1600 LST time window, underestimating RH by 5-10% depending on model configuration. As with Temperature, AER_PBL exhibited the largest bias, underestimating RH by up to 10% relative to observations (resulting in up to a 60% difference when compared to AER_BASE and AER_MP MBE).

Modeled and CAMS measured daily averages are shown in Figure 9ab. AER daily averages for each month are comparable to those estimated by the TCEQ_BASE configuration. Overall, the AER configurations consistently underestimated RH for both months relative to CAMS observations.

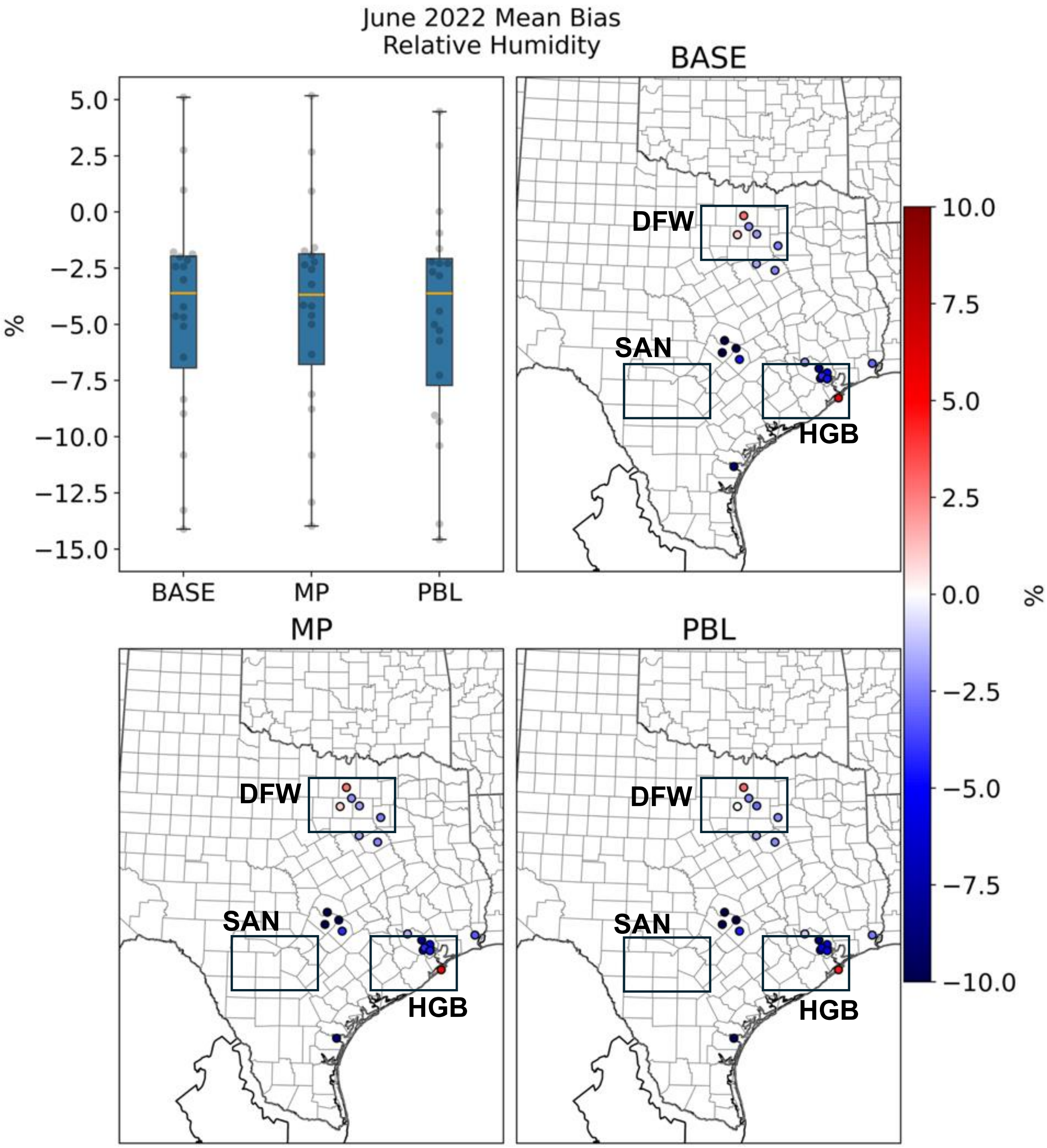


Figure 6. d02 Relative Humidity Mean Bias (%) relative to CAMS observations for June 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

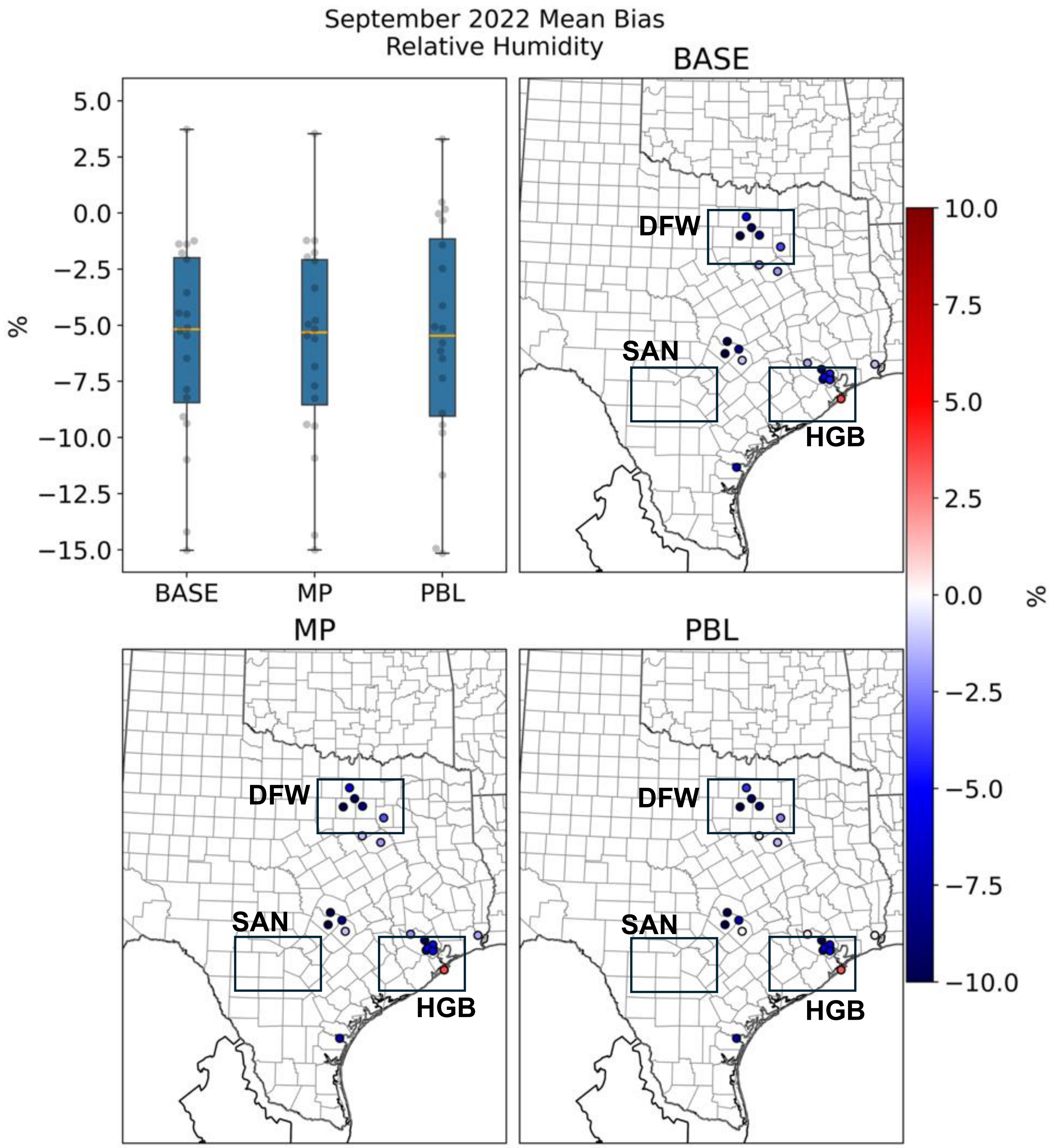


Figure 7. d02 Relative Humidity Mean Bias (%) relative to CAMS observations for September 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

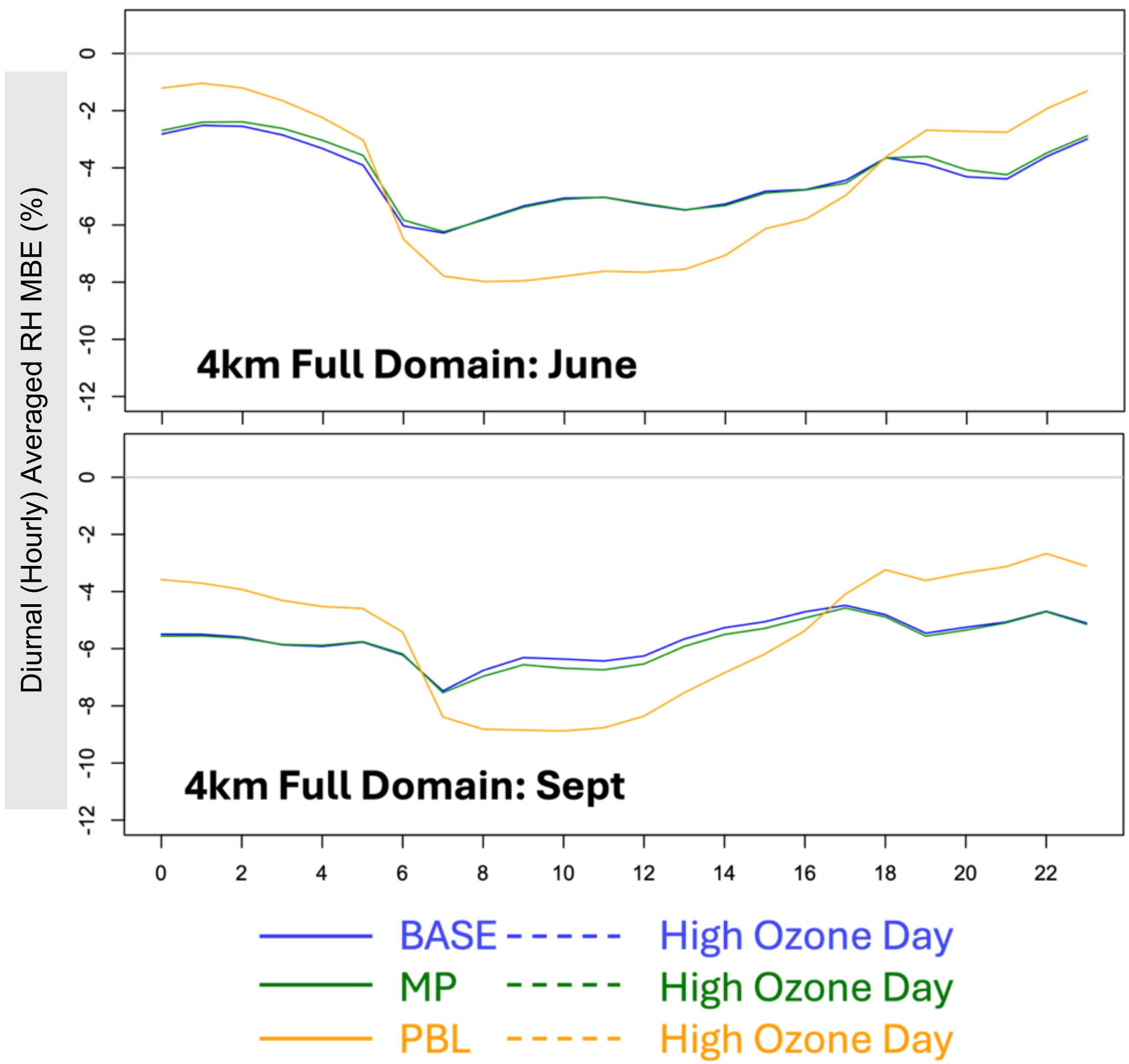


Figure 8. Diurnally averaged Mean Bias Errors (MBE) in Relative Humidity (%) for the three AER WRF configurations for (a) June 2022 and (b) September 2022. For each month, the MBE is averaged for the full 4km domain.

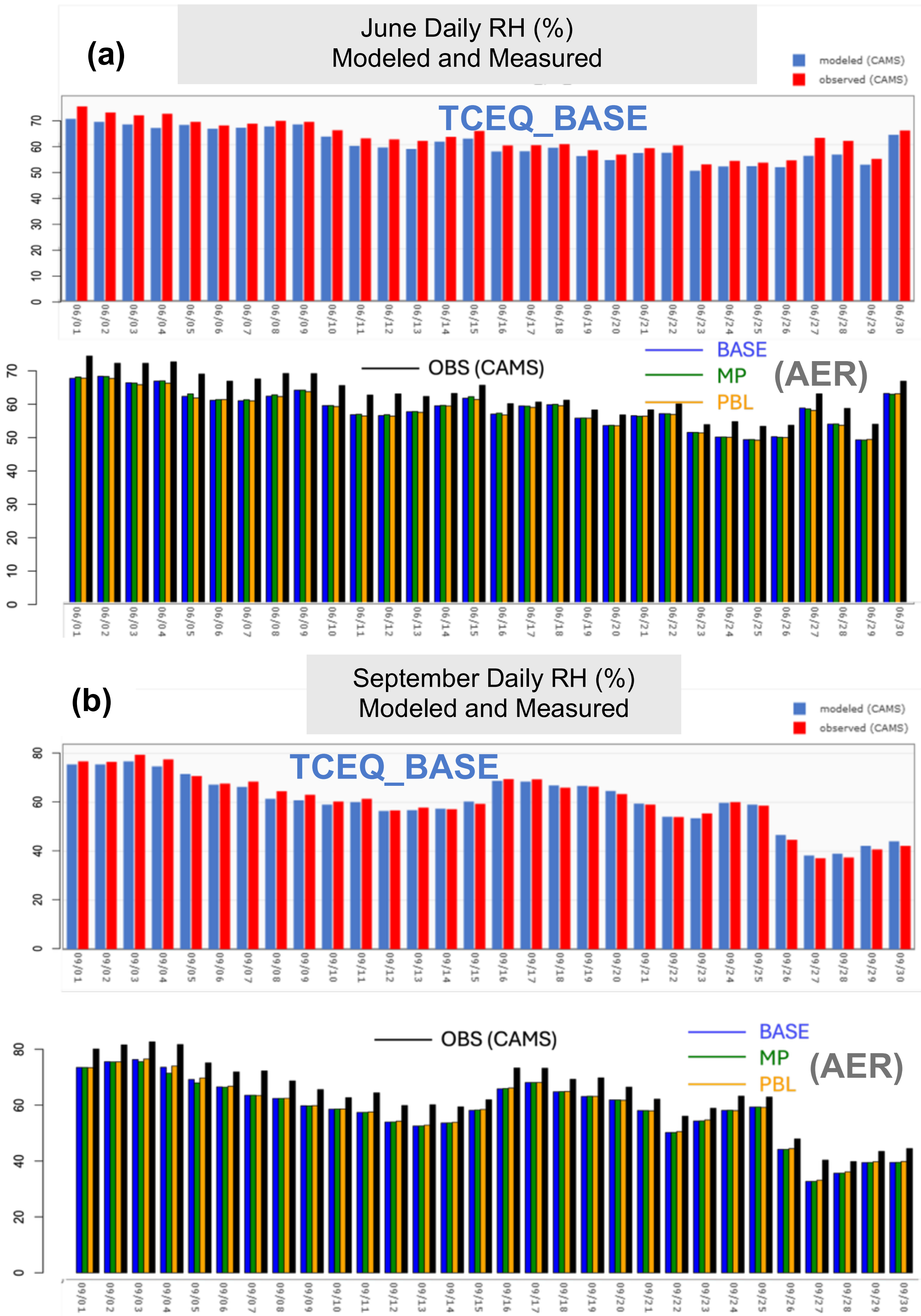


Figure 9. Daily averaged Relative Humidity (%) for TCEQ_BASE and the three AER WRF configurations for (a) June 2022 and (b) September 2022. Comparison for all models is with CAMS data.

4.3. Solar Radiation (as Langleys per minute, L/min; and as W/m^2)

No significant differences were observed among configurations at any averaging timescale (i.e., monthly, daily, diurnal).

When averaged over the domain and for each month, Solar Radiation is biased high relative to observations – typically 0.05 L/min (35 W/m^2) higher in June 2022 and 0.025 L/min (17 W/m^2) higher in September 2022 (Figures 10 and 11). Generally, model-observation mismatch was a factor of 2 smaller in September 2022 (modeled radiation ~6% higher than observations) versus June 2022 (modeled radiation ~12% higher than observations) (Tables 4-5). No distinct regional patterns were observed. Note that only one site provided observations for the SAN region.

Diurnal analysis (Figures 12ab) shows similar performance across configurations for the 4km domain and individual regions. SAN results should be viewed with caution as there was only a single site used in the analysis. Of note, modeled radiation was significantly underestimated at peak insolation hours by all model configurations on the DFW10 high O_3 date of 30 June and at ~1000LST in the HGB8 area. Outside of these specific high O_3 dates (and not considering the single SAN site), diurnal analysis mirrors the monthly average results of overestimating solar radiation throughout the day, with peak MBE between 50 and 100 W/m^2.

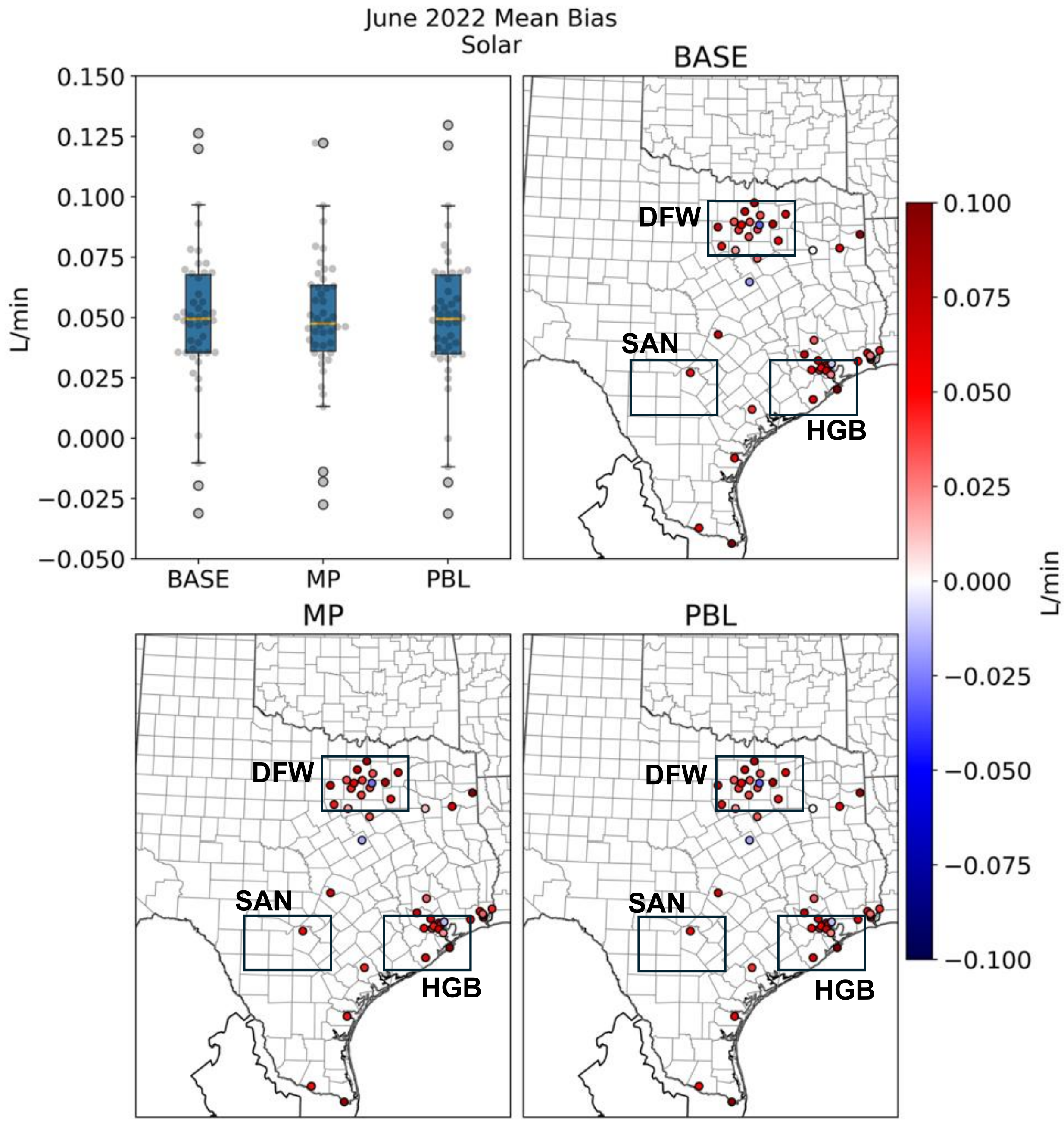


Figure 10. d02 Solar Radiation Mean Bias (Langleys/min) relative to CAMS observations for June 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

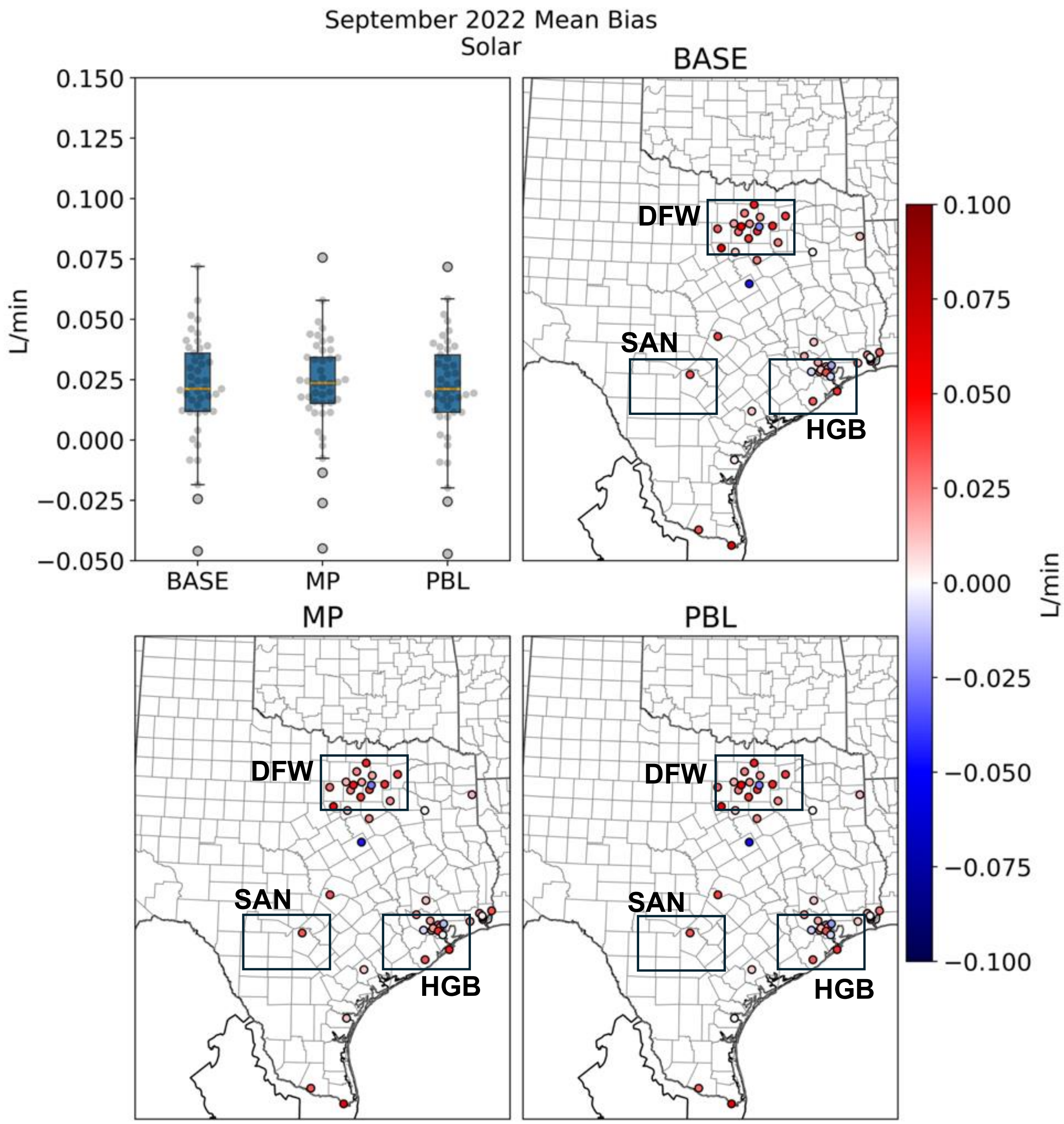


Figure 11. d02 Solar Radiation Mean Bias (Langleys/min) relative to CAMS observations for September 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

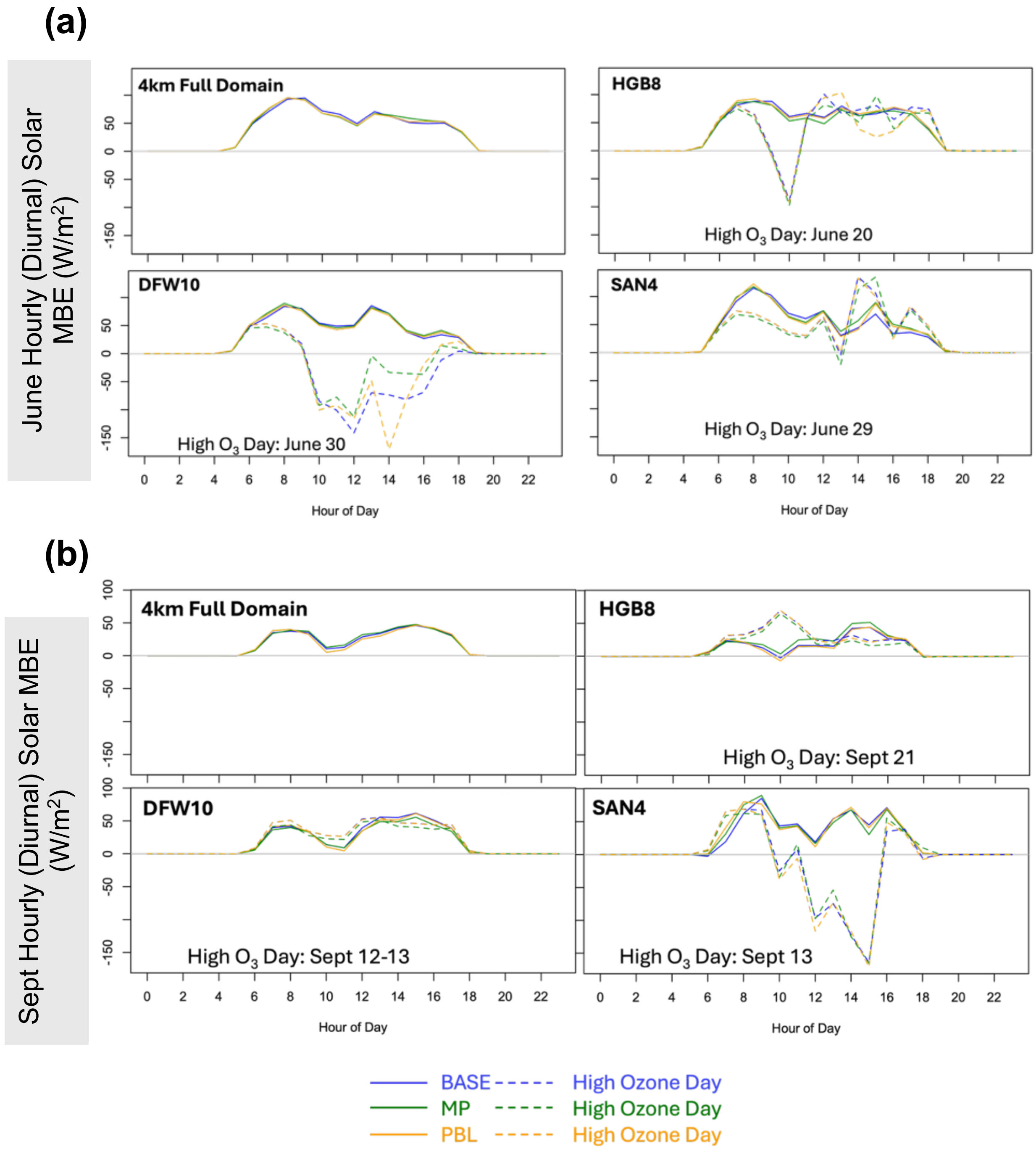
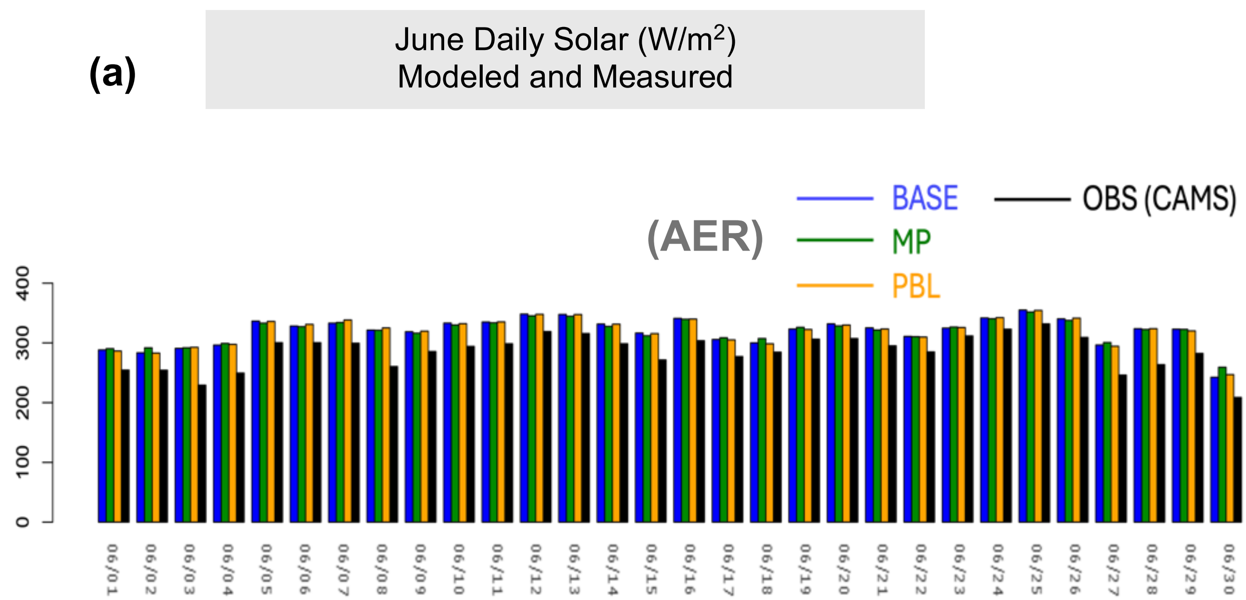


Figure 12. Diurnally averaged Mean Bias Errors (MBE) in Solar Radiation (W/m²) for the three AER WRF configurations for (a) June 2022 and (b) September 2022. For each month, the MBE is averaged for the full 4km domain; the HGB8 non-attainment region; the DFW10 non-attainment region; and the SAN4 non-attainment region. The dashed lines provide MBE results for the specified High O3 day. Note differences in y-axis scales for panels (a) and (b). Note that SAN4 region reported solar radiation from only a single site.



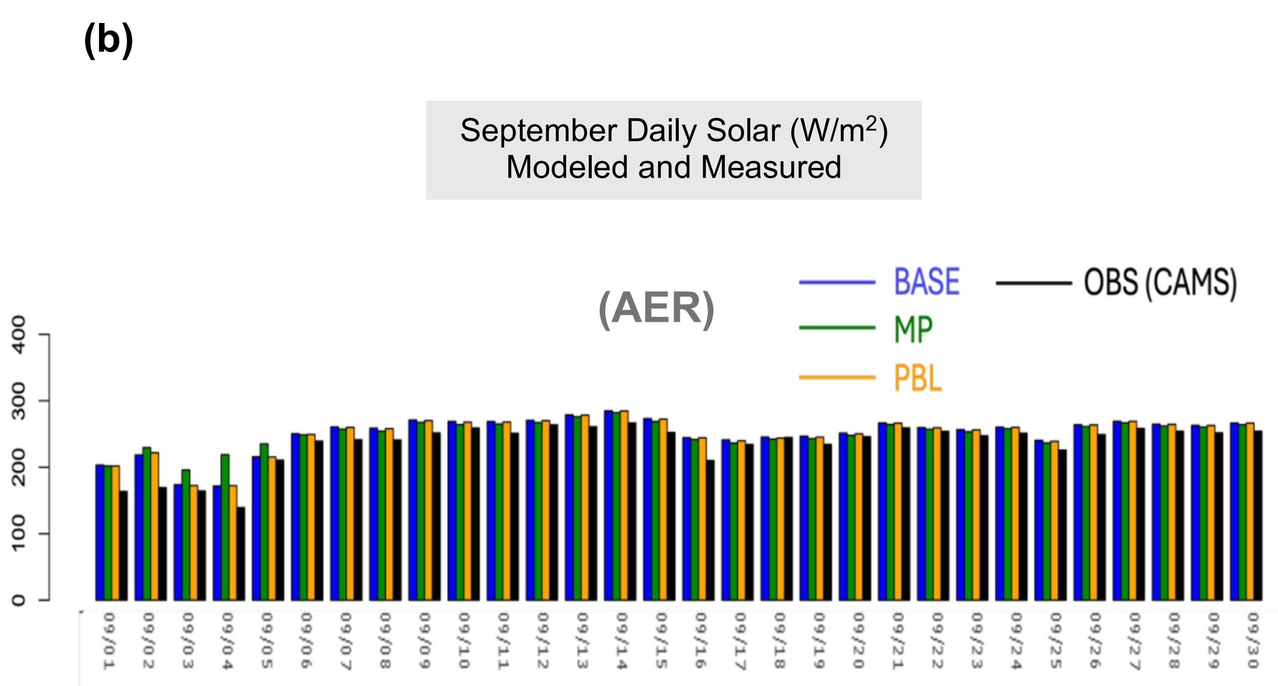


Figure 13. Daily averaged Solar Radiation (W/m²) for the three AER WRF configurations for (a) June 2022 and (b) September 2022. Comparison for all models is with CAMS data.

4.4. Wind Speed

Overall, surface wind speed had similar high biases (about 0.7 to 0.9 m/s) relative to observations across all configurations for both June and September 2022 (Figures 8 and 9). Once again, no significant differences were observed among configurations when averaged over the whole month and across the 4km domain. Generally, the DFW region exhibited the smallest model-observation mismatch in June 2022 relative to other regions.

Diurnally, all model configurations performed similarly relative to observations (Figures 16a,b). Diurnal windspeed biases were significantly lower in September than in June.

Daily averages of surface windspeed were comparable with TCEQ_BASE (Figure 17a,b). The patterns in biases were also correlated for both months between the TCEQ_BASE output and the AER configurations.

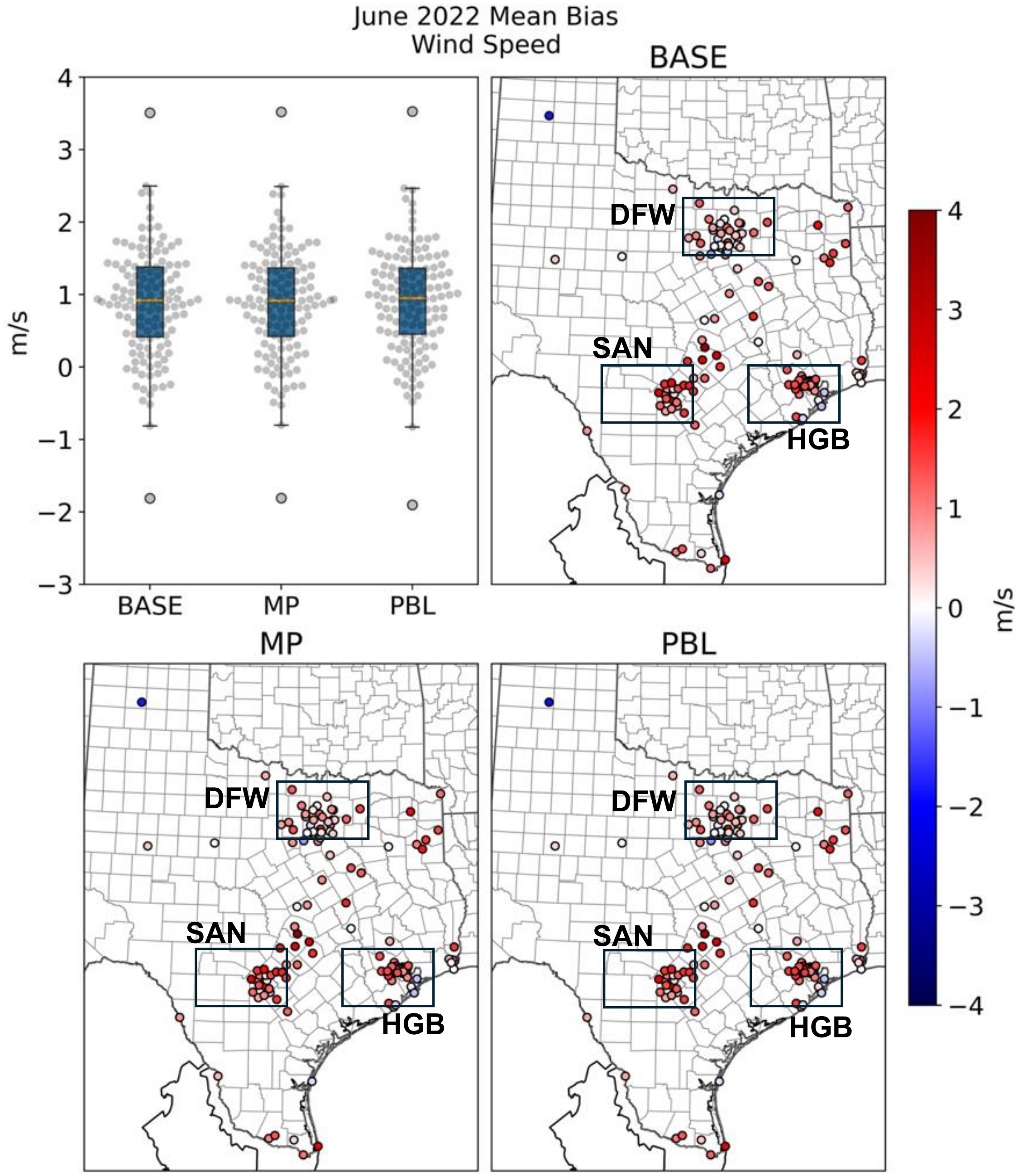


Figure 14. d02 Wind Speed Mean Bias (m/s) relative to CAMS observations for June 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

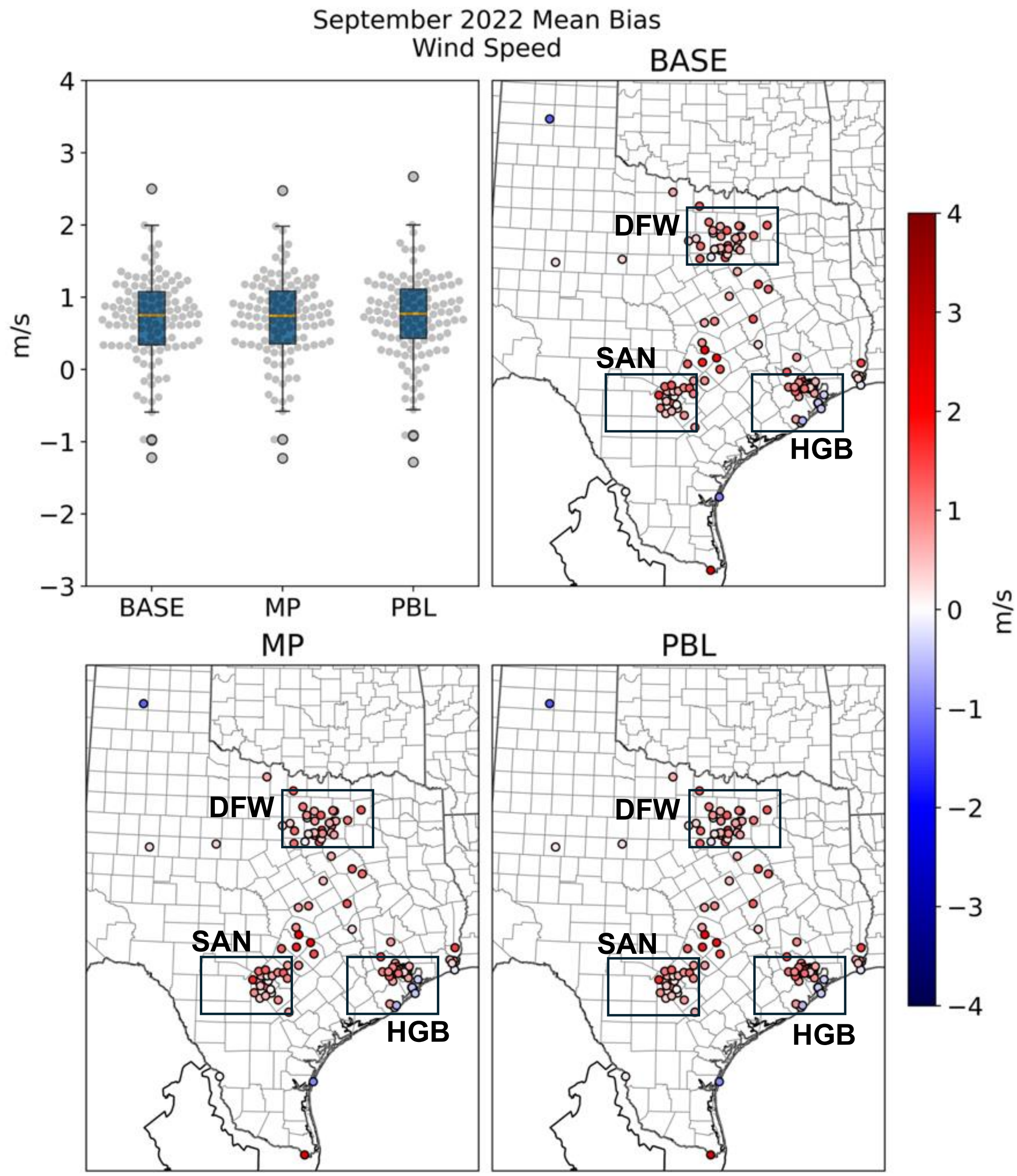


Figure 15. d02 Wind Speed Mean Bias (m/s) relative to CAMS observations for September 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

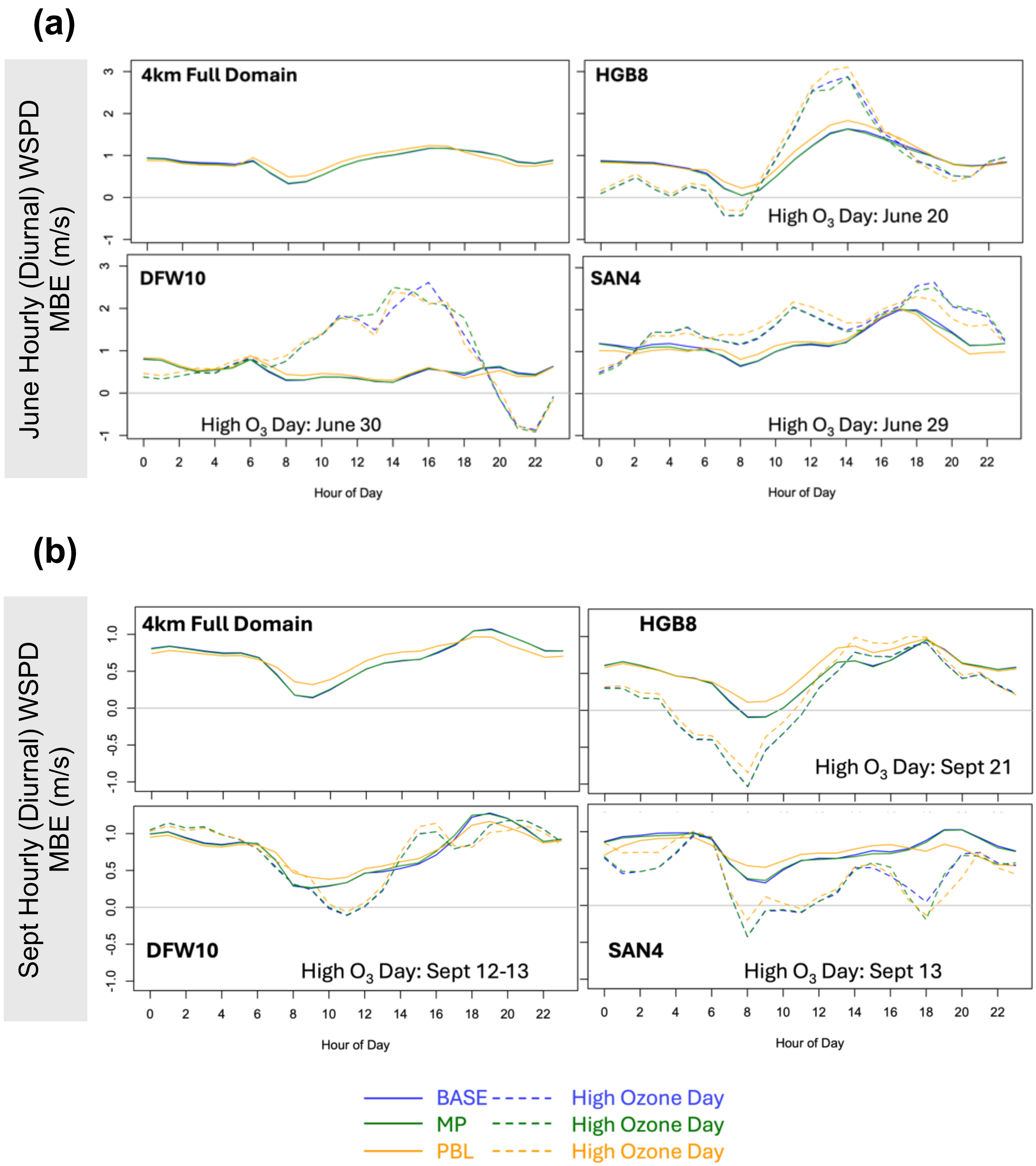


Figure 16. Diurnally averaged Mean Bias Errors (MBE) in Windspeed (m/s) for the three AER WRF configurations for (a) June 2022 and (b) September 2022. For each month, the MBE is averaged for the full 4km domain; the HGB8 non-attainment region; the DFW10 non-attainment region; and the SAN4 non-attainment region. The dashed lines provide MBE results for the specified High O3 day. Note differences in y-axis scales for panels (a) and (b).

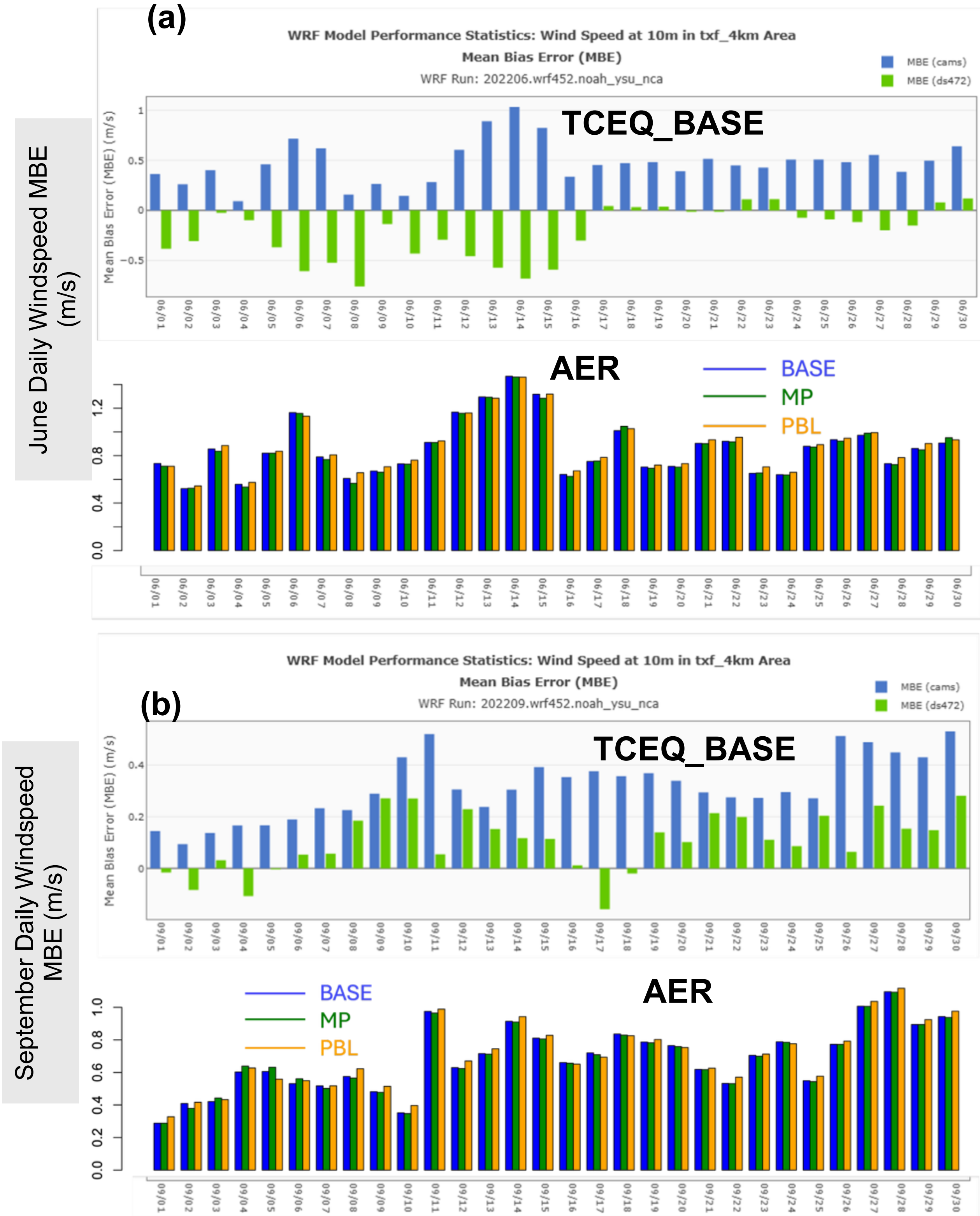


Figure 17. Daily averaged Mean Bias Errors (MBE) in Surface Windspeed for TCEQ_BASE and the three AER WRF configurations for (a) June 2022 and (b) September 2022. For a more direct comparison of AER MBE with TCEQ_BASE MBE, the TCEQ_BASE data shaded in blue provides the comparison with CAMS data.

4.5. Wind Direction

When averaged across the domain and for each month, wind direction biases were similar across all AER WRF configurations. There were no distinct regional patterns (Figures 18 and 19). Relative to observations, wind direction had better agreement in June 2022 (errors of about 0 degrees relative to observations), than in September 2022 (about 5 degrees). Wind direction analysis was not conducted diurnally or as daily averages.

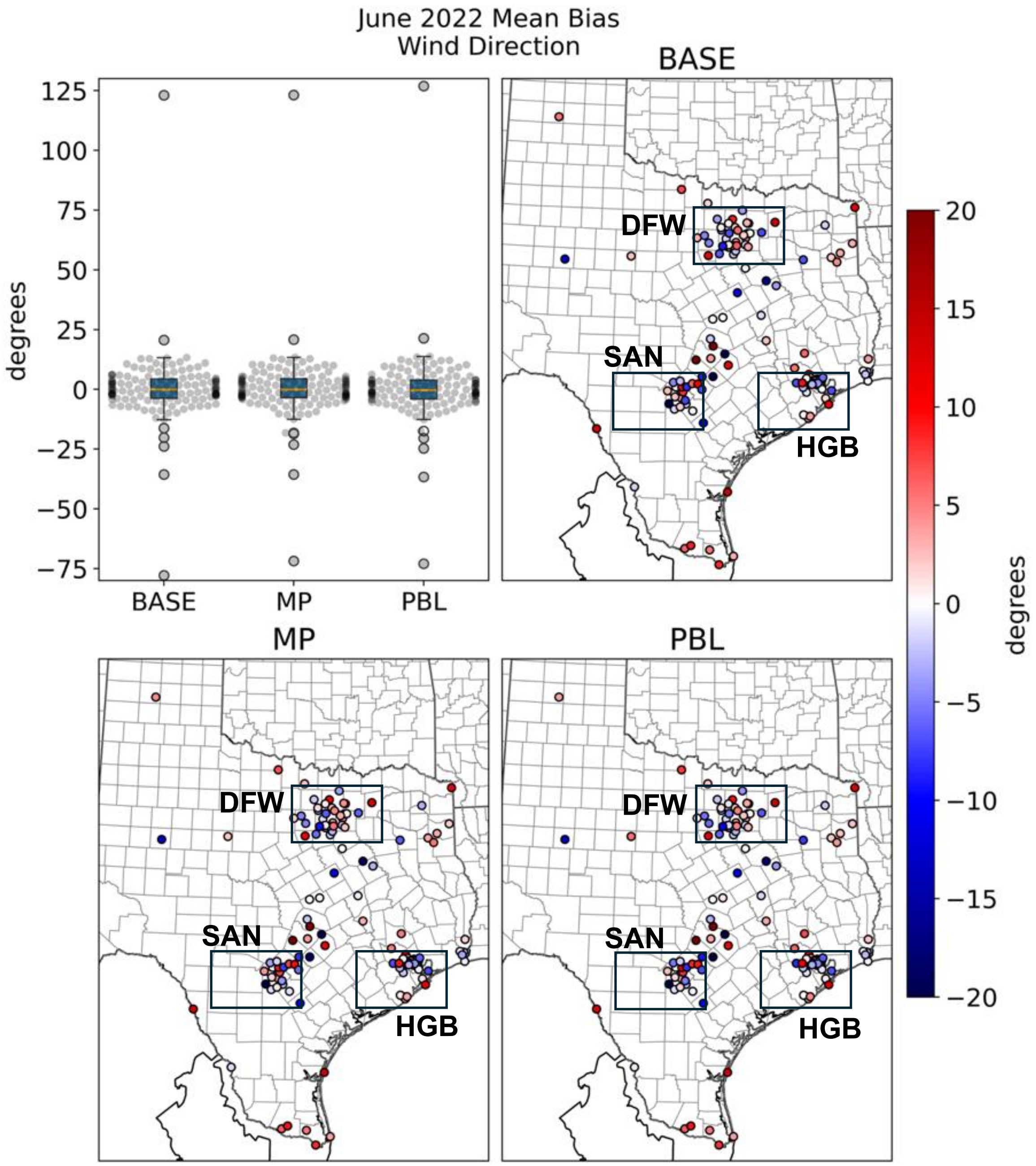


Figure 18. d02 Wind Direction Mean Bias (deg) relative to CAMS observations for June 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

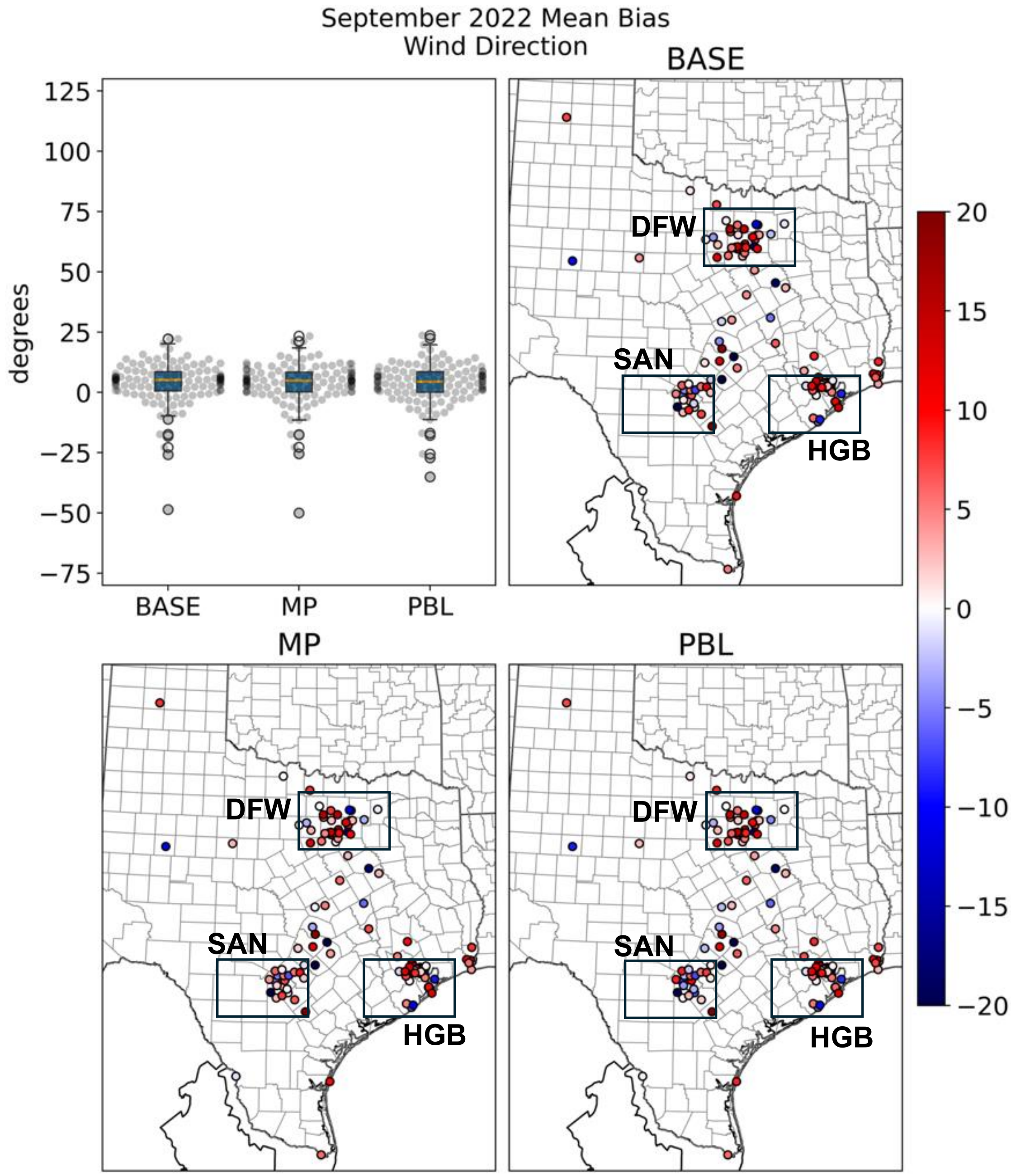


Figure 19. d02 Wind Direction Mean Bias (deg) relative to CAMS observations for September 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

4.6. Precipitation- 1hr and 24h

1-h Precipitation biases vary across configurations with the smallest bias exhibited by the AER_MP configuration (+34% error relative to observations in June 2022; -7% error relative to observations in September 2022) (Table 4, 5; Figures 12-13). In both months, AER_BASE and AER_PBL precipitation is biased high relative to observations with significantly smaller errors in September (12-18%) than in June (41-51%).

While the results from the point precipitation data set are based on a small sample size ($n < 30$) they are corroborated by the 24h accumulated precipitation analysis using GridStat and the larger PRISM data set (Figure 24). Biases in the DFW, HGB, and SAN regions are significantly smaller and biased low in September 2022 versus larger and biased high in June 2022. However, we note that the bias pattern varies for other regions of the d02 domain. Namely, June 2022 has small and low biases in the southern portion of the d02 domain and large and low biases in the north; the pattern shifts in September with large and low biases exhibited in the south, and small biases in the north.

Maps of total precipitation as estimated by the PRISM data set, the AER configurations, and TCEQ_BASE are provided for June 2022 (Figure 23) and September 2022 (Figure 24). Generally, TCEQ_BASE underestimates precipitation throughout the domain in both months relative to PRISM and the AER configurations. The AER_MP configuration notably underestimates (relative to AER_BASE, AER_PBL, and TCEQ_BASE) the high precipitation feature along the Gulf of Mexico coast near the HGB area. The higher land total precipitation feature in the PRISM dataset suggests that the AER_MP configuration is underestimating a real precipitation feature.

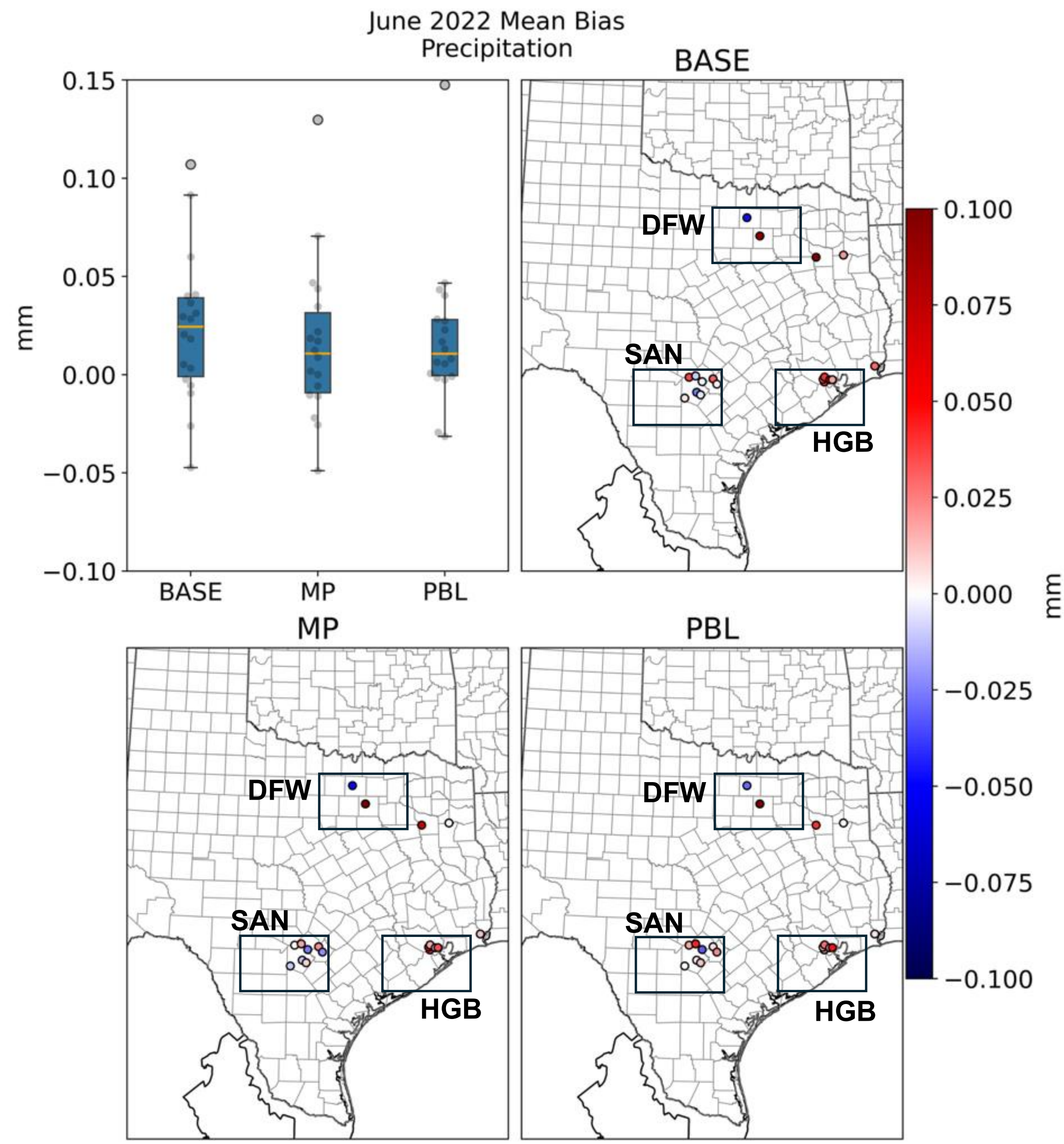


Figure 20. d02 1-h Precipitation (mm) relative to CAMS observations for June 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

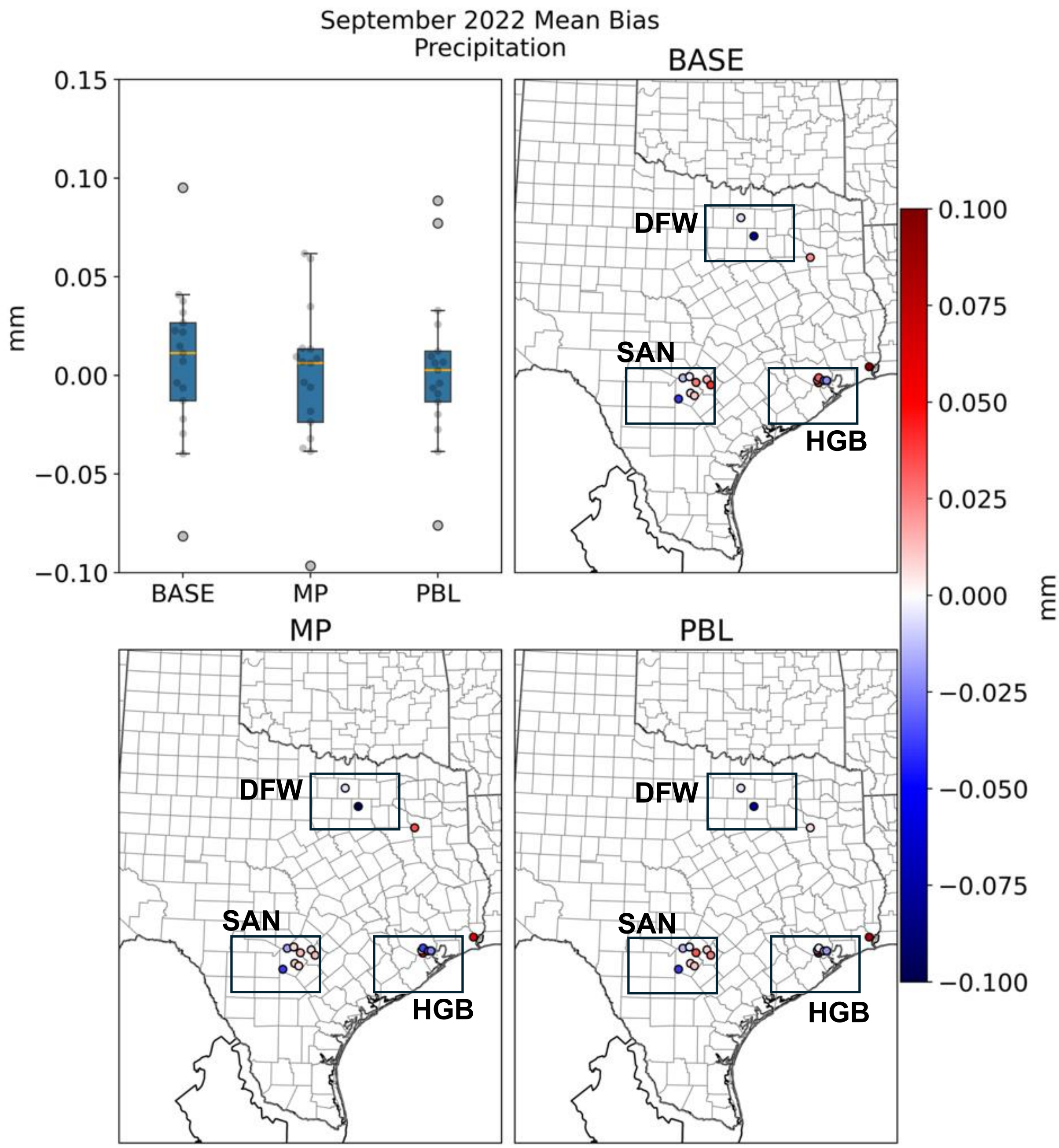


Figure 21. d02 1-h Precipitation (mm) relative to CAMS observations for September 2022, across three AER WRF configurations (BASE, MP, PBL). Approximate DFW, SAN, and HGB regions are highlighted for reference.

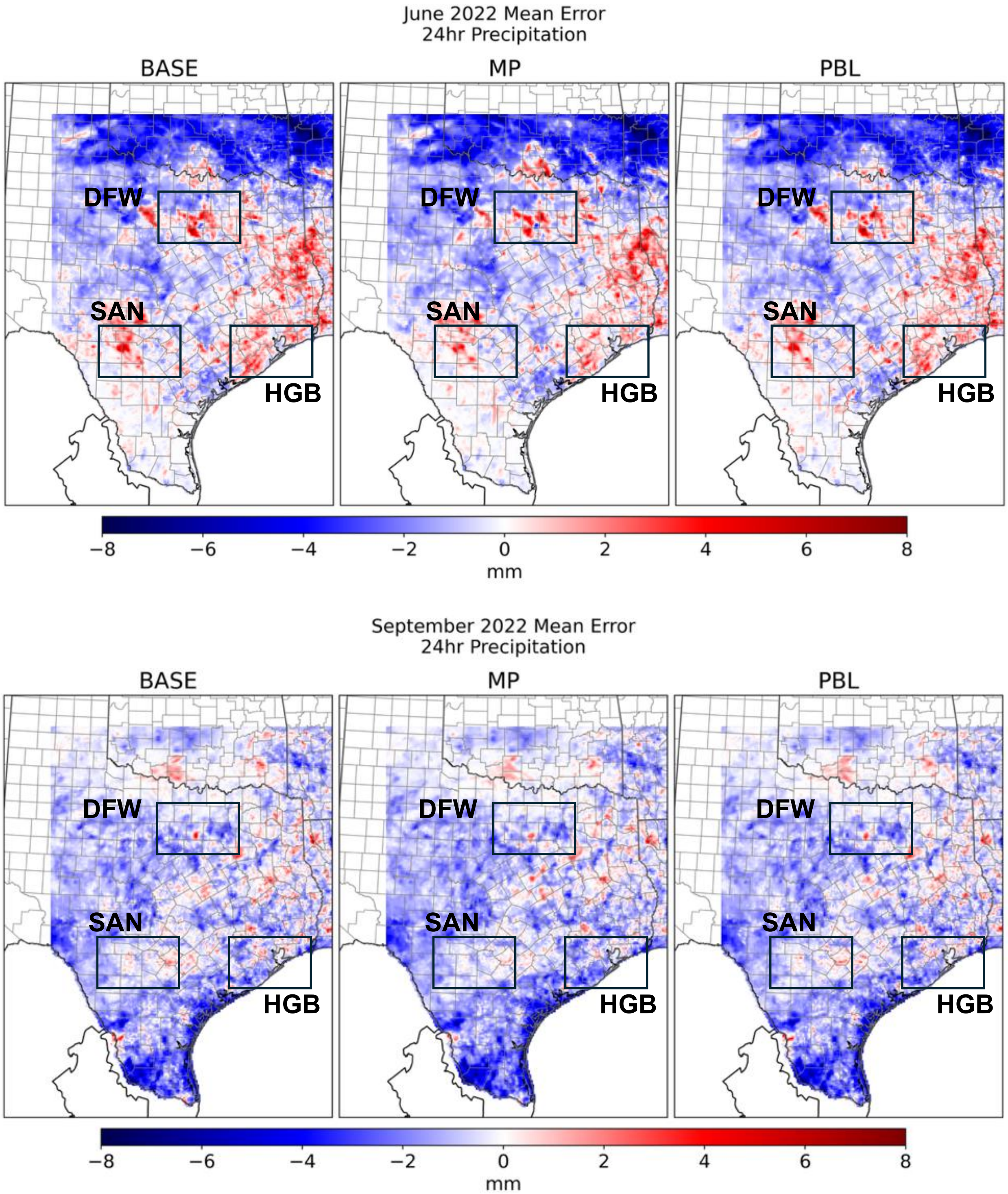


Figure 22. 24-h Precipitation biases (mm) evaluated for each AER WRF configuration relative to PRISM output for (top): June 2022 and (bottom) September 2022. Approximate DFW, SAN, and HGB regions are highlighted for reference.

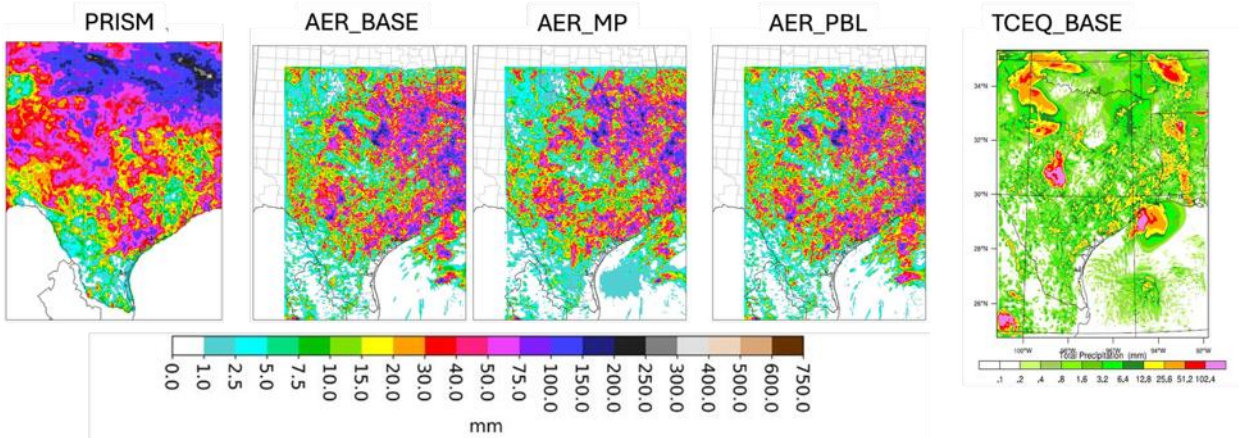


Figure 23. June 2022 Total Precipitation (mm) estimated by PRISM data set and each of the AER WRF configurations. TCEQ_BASE June 2022 Total Precipitation (mm) is provided for reference. Note different scales between TCEQ_BASE and all other output.

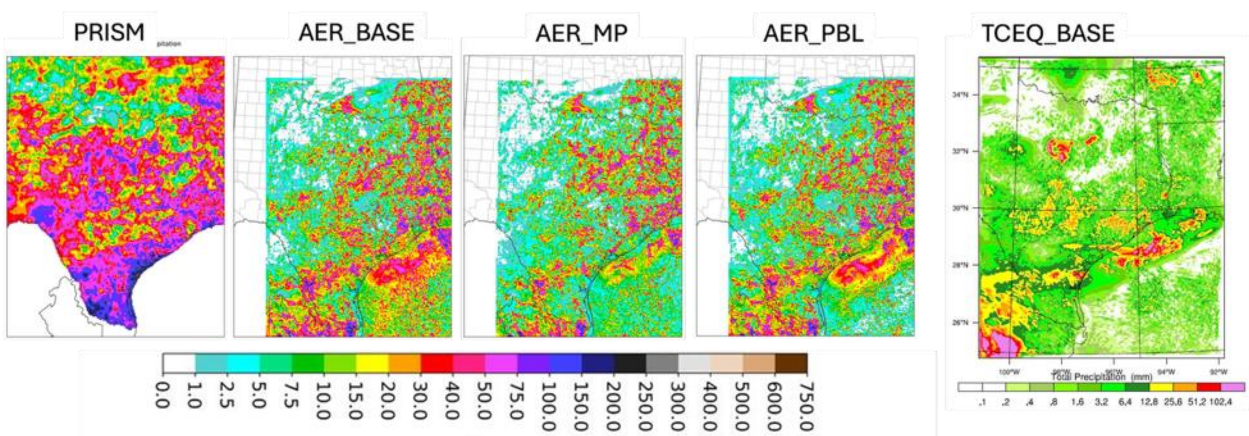


Figure 24. September 2022 Total Precipitation (mm) estimated by PRISM data set and each of the AER WRF configurations. TCEQ_BASE September 2022 Total Precipitation (mm) is provided for reference. Note different scales between TCEQ_BASE and all other output.

5. Issues and Resolutions

Task 4

- **Issue.** The first attempt at running a month-long (June 2022) simulation of the AER_BASE failed midway through the model month. This was due to development of unstable updrafts in the P3 microphysics scheme (updrafts >60 m/s).
- **Resolution.** While `use_adaptive_time_step = .true.` works for the wrfout files, the internal time code for WRF does not handle the timing outputs and mean calculations due to these time differences for the xtrm files needed for model performance evaluation. Thus, in accordance with standard TCEQ practice, a decrease timestep from 60 to 30 was used. We also slightly increased the `epssm` variable from 0.1 to 0.2, which dampens 3D divergence in vertical

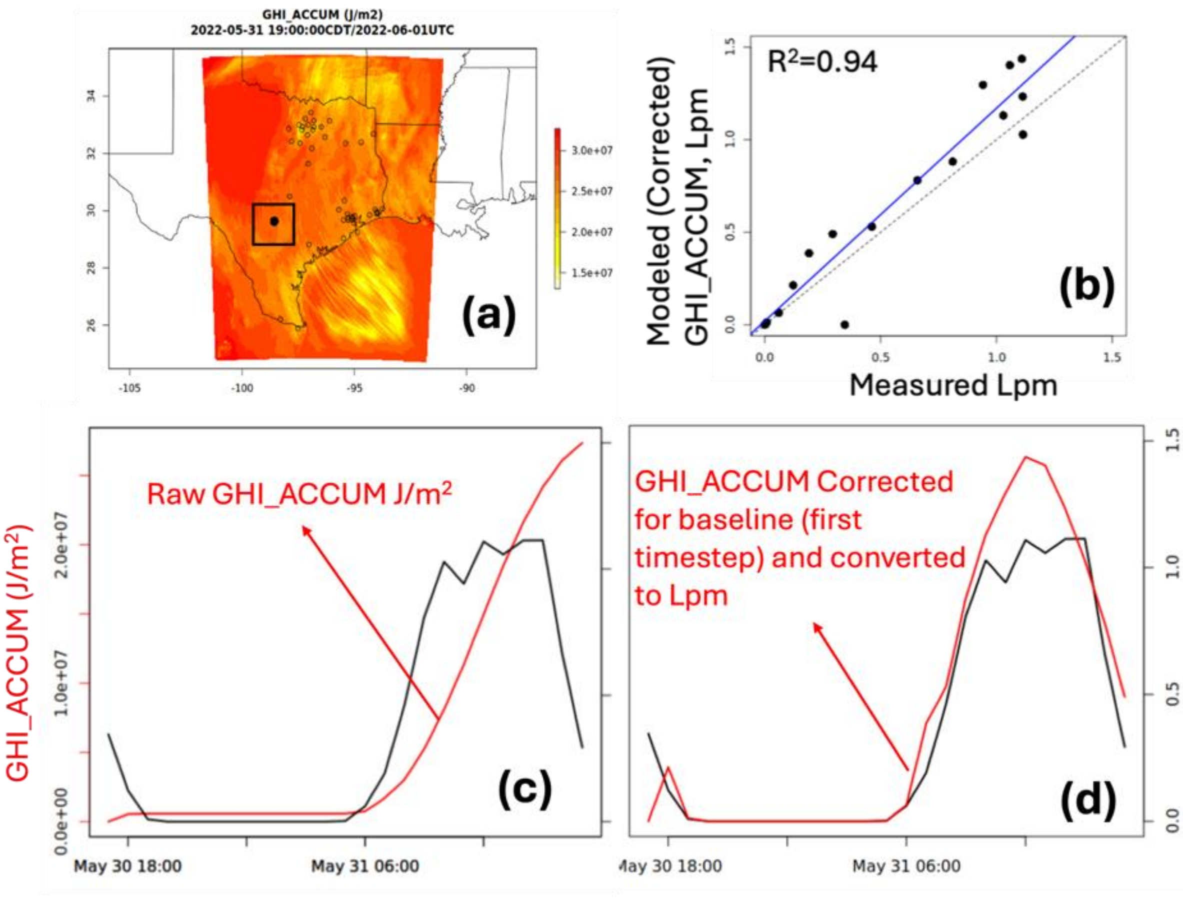


Figure 25. Results from comparison of WRF modeled with CAMS measured solar irradiance for a 24 hour period beginning 5-31-2022 01 UTC. (a) modeled and baseline-corrected GHI_ACCUM on 6-01-2022 00UTC with CAMS locations overlaid; example evaluation site is highlighted by bounding box. (b) Modeled vs. Observed solar irradiance in Langleys per minute; dotted line is 1:1, solid blue line is best fit RMA regression. (c) original hourly modeled GHI_ACCUM (red) in J/m² indicates cumulative sum at each time step. Observations (black) are in Lpm. (d) baseline-corrected GHI_ACCUM (red) in Lpm at each timestep plotted with observed irradiance.

pressure gradient. These two changes led to successful completion of the June 2022 AER_BASE month-long run. With these changes, the other five model runs: June 2022 AER_MP, AER_PBL and Sep 2022 AER_BASE, AER_MP, AER_PBL were also completed.

Task 5

- **Issue.** The WRF variable "GHI_ACCUM", or accumulated global horizontal irradiance in J/m^2, is used to compare with observations obtained in Langleys per minute at the CAMS locations. However, we noticed that GHI_ACCUM at each hour is cumulatively summed over the course of the entire run.
- **Resolution:** Prior to evaluation with observations, the GHI_ACCUM at each time step needs to account for the baseline value at model start and the prior timestep's value. Then, the (non-cumulative) GHI at each timestep is converted to Langleys per minute (1 Langley = 41840 J/m^2). Figure 25 summarizes the correction process and preliminary model-observation comparison at a sample CAM site on an example day (5-31-2022 01UTC to 6-01-2022 00UTC).

6. Quality Assurance

Analysis of all plots and statistics in this report provided a subjective assessment that algorithms were correctly implemented. The processing and analysis scripts used in this project were inspected by a team member not involved in their creation for accuracy. All automated calculations and at least 10% of manual calculations were inspected for correctness. This meets the requirement of Level III QAPPs that 10% of the data must be inspected.

As the quality of the information, including secondary data was not evaluated by EPA, the below disclaimer applies to all project deliverables:

Disclaimer: The information contained in this report or deliverable has not been evaluated by EPA for this specific application.

7. Conclusions

Here we summarize the conclusions of our project, with reference to the corresponding report section.

- Comparability among AER configurations depended on spatial and temporal averaging scales.
  - Generally, monthly averages spatially aggregated across the entire 4 km domain did not reveal significant differences among the configurations.
  - Spatially disaggregated monthly averages revealed regional variations in performance. However, regional variations were consistent among configurations, indicating that no region appeared to benefit from one configuration over another.

  - When monthly averages were broken down by hour of day, differences among configurations were sometimes significant. Relative to observations at peak daytime hours, AER_PBL overestimated surface temperature and underestimated RH significantly more than AER_BASE and AER_MP. In addition, AER_PBL surface wind speed biases were generally higher than AER_BASE and AER_MP.
- The AER configurations all performed similarly regardless of temporal and spatial averaging choices and – except for the DFW10 and HGB8 June high ozone days – showed good agreement with observations.
- Systematic offsets between variables modeled by the AER configurations and the TCEQ_BASE configuration were likely due to choice of initial/boundary and analysis nudging data sets. With the possible exception of solar radiation, results suggest that ERA5 (TCEQ_BASE) might lead to better agreement with CAMS observations than NCEP_FNL (AER configurations, Wang et al., 2023 "Nudged2" configuration). Note that Wang et al. (2023) WRF configuration results are possibly confounded by their use of CAMS data in both observational nudging and evaluation.
- Based on performance across multiple meteorological variables and averaging spatial and temporal scales, we recommend the AER_BASE configuration for ingestion into future TCEQ modeling platforms. The AER_BASE configuration is the closest configuration to the Wang et al. (2023) "Nudged2" configuration ("Wang_n2" in Table 2). In addition, we recommend retaining the TCEQ_BASE ERA5 selection for initial and boundary conditions (and analysis nudging) instead of the NCEP_FNL dataset. (Section 4)

8. Recommendations for Future Work

- This work did not test the impacts of IC/BC and analysis nudging data sets, and systematic performance offsets among the TCEQ_BASE (ERA5) and AER (NCEP_FNL) configurations warrant testing the impacts of the IC/BC and nudging data. As the AER_BASE configuration performed optimally relative to the remaining AER configurations, future work can compare an AER_BASE_ERA5 run with TCEQ_BASE.
- In addition, it is recommended that vertical levels are increased from 36 to 50 to align with current best practices.
- This work did not test the impact of WRF configurations on PBL height estimation. It is recommended that future work involves a comprehensive assessment of PBL estimated across the BASE and PBL configurations relative to evaluation using radar techniques (Henderson et al., 2024).
- This work focused on evaluating WRF performance at the surface. We recommend future work evaluates WRF performance at upper levels. Specifically, we recommend a comparison across configurations and observations of vertical profiles using Skew-T diagrams or similar for a specific time and location.

- In the longer term, there will be a transition to using a Model for Prediction Across Scales (MPAS) system for regional modeling. Therefore, it will be useful to have a comparison of WRF and MPAS outputs where both frameworks use similar physics packages.

9. References

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https://aqrp.ceer.utexas.edu/research/projects/fy-2022-2023/44-project-number-22-008.

WRFv4.5.2 namelist variables. https://github.com/wrf-model/WRF/blob/release-v4.5.2/run/README.namelist. Accessed 6 March 2025.

Appendix A: WRF Configuration Details

A1. WRF preprocessing System (WPS) namelist.wps

Common Across AER_BASE, AER_MP, AER_PBL June 2022 Example

```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2022-05-31_00:00:00', '2022-05-31_00:00:00',
 end_date = '2022-07-03_00:00:00', '2022-07-03_00:00:00',
 interval_seconds = 3600,
 io_form_geogrid = 2,
/
&geogrid
 parent_id         =   1,   1,   1,
 parent_grid_ratio =   1,   3,   3,
 i_parent_start    =   1, 256, 202,
 j_parent_start    =   1, 112, 135,
 s_we              =   1,   1,   1,
 e_we              = 583, 244, 244,
 s_sn              =   1,   1,   1,
 e_sn              = 505, 298, 229,
 geog_data_res = 'default','default','default',
 dx = 12000,
 dy = 12000,
 map_proj = 'lambert',
 ref_lat   =  40.0,
 ref_lon   = -97.0,
 truelat1  =  33.0,
 truelat2  =  45.0,
 stand_lon = -97.0,
 geog_data_path = '/rd-data/WRF_code/GEOG_v422/WPS_GEOG/'
/
&ungrib
 out_format = 'WPS',
 prefix = 'NCEP_SST'
/
&metgrid
 fg_name = 'NCEP', 'NCEP_SST'
 io_form_metgrid = 2,
 opt_metgrid_tbl_path = '/fsx-tceq/WRFv4.5.2/WPS/metgrid/'
/
&mod_levs
 press_pa = 201300 , 200100 , 100000 ,
             95000 ,  90000 ,
             85000 ,  80000 ,
             75000 ,  70000 ,
             65000 ,  60000 ,
             55000 ,  50000 ,
             45000 ,  40000 ,
             35000 ,  30000 ,
             25000 ,  20000 ,
             15000 ,  10000 ,
              5000 ,   1000

/
```

A2. WRF OBSGRID namelist.oa

Common Across AER_BASE, AER_MP, AER_PBL June 2022 Example

```
&record1
 start_year                   =  2022
 start_month                  =     5
 start_day                    =    31
 start_hour                   =    00
 end_year                     =  2022
 end_month                    =     7
 end_day                      =     3
 end_hour                     =    00
 interval                     =  3600
/

&record2
 grid_id                      = 2 !1or2
 obs_filename                 = './SURFACE_OBS/SURFACE_OBS'
 remove_data_above_qc_flag    = 32768
 remove_unverified_data       = .TRUE.
/
 obs_filename                 = '../JAN00/obs'
 trim_domain                  = .TRUE.
 trim_value                   = 5

&record3
 max_number_of_obs            = 100000
 fatal_if_exceed_max_obs      = .TRUE.
/

&record4
 qc_test_error_max            = .TRUE.
 qc_test_buddy                = .TRUE.
 qc_test_vert_consistency     = .FALSE.
 qc_test_convective_adj       = .FALSE.
 max_error_t                  = 8
 !max_error_dewpoint           = 20
 max_error_uv                 = 4
 max_error_z                  = 4
 max_error_rh                 = 20
 max_error_p                  = 600
 max_buddy_t                  = 6
 !max_buddy_dewpoint           = 20
 max_buddy_uv                 = 4
 max_buddy_z                  = 4
 max_buddy_rh                 = 20
 max_buddy_p                  = 800
 buddy_weight                 = 0.75
 max_p_extend_t               = 1300
 max_p_extend_w               = 1300
 !rinblw                       = 24 !DOES NOT EXIST IN NAMELIST.OA
 !qc_psfc                      = .TRUE.
 !use_p_tolerance_one_lev      = .TRUE.
 !max_p_tolerance_one_lev_qc   = 700
/
```

```
&record5
 print_obs_files             = .TRUE.
 print_found_obs             = .FALSE.
 print_header                = .FALSE.
 print_analysis              = .FALSE.
 print_qc_vert               = .FALSE.
 print_qc_dry                = .FALSE.
 print_error_max             = .FALSE.
 print_buddy                 = .FALSE.
 print_oa                    = .FALSE.
/

&record7
 use_first_guess             = .TRUE.
 f4d                         = .TRUE.
 intf4d                      =  3600
 lagtem                      = .FALSE.
/

&record8
 smooth_type                 =  1
 smooth_sfc_wind             =  0
 smooth_sfc_temp             =  0
 smooth_sfc_rh               =  0
 smooth_sfc_slp              =  0
 smooth_upper_wind           =  0
 smooth_upper_temp           =  0
 smooth_upper_rh             =  0
/

&record9
 oa_type                     = 'Cressman'
 radius_influence            = 0,
 mqd_minimum_num_obs         = 30
 mqd_maximum_num_obs         = 1000
 oa_min_switch               = .TRUE.
 oa_max_switch               = .TRUE.
 !oa_3D_option                = 1
 !oa_3D_type                  = 'Cressman'
 !scale_cressman_rh_decreases = .TRUE.
 !radius_influence_sfc_mult   = 0.4
 !oa_psfc                     = .FALSE.
 !max_p_tolerance_one_lev_oa  = 700
/

&plot_sounding
 file_type                   = 'raw'
 read_metoa                  = .TRUE.
/
 file_type                   = 'used'
```

A3. WRF REAL namelist.input

AER_BASE June 2022 Example

```
&time_control
 run_days                             = 0,
 run_hours                            = 0,
 run_minutes                          = 0,
 run_seconds                          = 0,
 start_year                           = 2022, 2022, 2022,
 start_month                          = 05, 05, 05,
 start_day                            = 31, 31, 31,
 start_hour                           = 00, 00, 00,
 end_year                             = 2022, 2022, 2022,
 end_month                            = 07, 07, 07,
 end_day                              = 03, 03, 03,
 end_hour                             = 00, 00, 00,
 interval_seconds                     = 3600,
 input_from_file                      = .true., .true., .true.,
 history_interval                     = 60, 60, 60,
 frames_per_outfile                   = 24, 24, 24,
 restart_interval                     = 1440,
 auxinput1_inname                     = "metoa_em.d<domain>.<date>",
 iofields_filename                    = chase_d02.txt, chase_d02.txt,
 ignore_iofields_warning              = .true.,
 io_form_auxhist7                     = 2,
 auxhist7_outname                     = chases_files.d<domain>.<date>,
 auxhist7_interval                    = 60, 60,
 frames_per_auxhist7                  = 1, 1,
 output_diagnostics                   = 1,
 auxhist3_outname                     = xtrm_60min.d<domain>.<date>
 auxhist3_interval                    = 60, 60,
 frames_per_auxhist3                  = 24, 24,
 io_form_auxhist3                     = 2,
 auxinput4_inname                     = "wrflowinp_d<domain>",
 auxinput4_interval                   = 60,
 io_form_auxinput4                    = 2,
 !nocolons                            = .true.,
/

 &domains
 time_step                            = 30,
 time_step_fract_num                  = 0,
 time_step_fract_den                  = 1,
 max_dom                              = 2,
 e_we                                 = 583,   244,
 e_sn                                 = 505,   298,
 s_vert                               = 1,     1,     1,
 e_vert                               = 36,    36,    36,
 num_metgrid_levels                   = 34,
 eta_levels                           = 1.000, 0.9975, 0.995, 0.990, 0.985,
                                        0.980, 0.970, 0.960, 0.950,
                                        0.940, 0.930, 0.920, 0.910,
                                        0.900, 0.880, 0.860, 0.840,
                                        0.820, 0.800, 0.770, 0.740,
                                        0.700, 0.650, 0.600, 0.550,
                                        0.500, 0.450, 0.400, 0.350,
```

```
                                     0.300, 0.250, 0.200, 0.150,
                                     0.100, 0.050, 0.000,
 dx                                = 12000,  4000,
 dy                                = 12000,  4000,
 grid_id                           = 1,     2,     3,
 parent_id                         = 0,     1,     1,
 i_parent_start                    = 1,   256,   202,
 j_parent_start                    = 1,   112,   135,
 parent_grid_ratio                 = 1,     3,     3,
 parent_time_step_ratio            = 1,     3,     3,
 feedback                          = 0,
 smooth_option                     = 0
/

&physics
 mp_physics                        = 50,   50,    50,
 ra_lw_physics                     = 4,     4,     4,
 ra_sw_physics                     = 4,     4,     4,
 radt                              = 4,     4,     4,
 sf_sfclay_physics                 = 1,     1,     1,
 sf_surface_physics                = 2,     2,     2,
 bl_pbl_physics                    = 5,     5,     5,
 bldt                              = 0,     0,     0,
 topo_wind                         = 1,     1,     1,
 cu_physics                        = 16,    0,     0,
 cudt                              = 0,     0,     0,
 ifsnow                            = 0,
 kf_edrates                        = 0,     0,     0,
 icloud                            = 1,
 surface_input_source              = 3,
 num_soil_layers                   = 4,
 pxlsm_modis_veg                   = 0,
 pxlsm_smois_init                  = 0,
 sf_urban_physics                  = 0,     0,     0,
 mp_zero_out                       = 1,
 num_land_cat                      = 21,
 sst_update                        = 1,
 aer_opt                           = 3,
 swint_opt                         = 1,
 usemonalb                         = .true.,
 rdlai2d                           = .true.,
 prec_acc_dt                       = 60, 60,
 do_radar_ref                      = 1
 /



&noah_mp
 opt_soil                         = 3,
 opt_pedo                         = 1,
/

&diags
solar_diagnostics                 = 1,
/

&fdda
```

```
 grid_fdda                            = 1, 1,  1,
 gfdda_inname                         = "wrffdda_d<domain>",
 gfdda_interval_m                     = 60,  60,   60,
 gfdda_end_h                          = 999,   999,   999,
 fgdt                                 = 0,     0,     0,
 if_no_pbl_nudging_uv                 = 1,     1,     1,
 if_no_pbl_nudging_t                  = 1,     1,     1,
 if_no_pbl_nudging_q                  = 1,     1,     1,
 if_zfac_uv                           = 0,     0,     0,
 k_zfac_uv                            = 10,   10,     10,
 if_zfac_t                            = 0,     0,     0,
 k_zfac_t                             = 10,   10,     10,
 if_zfac_q                            = 0,     0,     0,
 k_zfac_q                             = 10,   10,     10,
 guv                                  = 0.0003,     0.0003,     0.0003,
 gt                                   = 0.0003,     0.0003,     0.0003,
 gq                                   = 0.0003,     0.0003,     0.0003,
 if_ramping                           = 1,
 dtramp_min                           = 60.0,
 io_form_gfdda                        = 2,
 grid_sfdda                           = 1, 1, 1,
 sgfdda_inname                        = "wrfsfdda_d<domain>",
 sgfdda_end_h                         = 999,  999,  999,
 sgfdda_interval_m                    = 60, 60, 60,
 io_form_sgfdda                       = 2,
 guv_sfc                              = 0.0003, 0.0003, 0.0003,
 gt_sfc                               = 0.0003, 0.0003, 0.0003,
 gq_sfc                               = 0.0003, 0.0003, 0.0003,
 rinblw                               = 24., 24., 24.,
 pxlsm_soil_nudge                     = 0,
 /


&dynamics
 w_damping                            = 1,
 diff_opt                             = 1,
 km_opt                               = 4,
 base_temp                            = 290.
 damp_opt                             = 0,
 zdamp                                = 5000.,  5000.,  5000.,
 dampcoef                             = 0.01,   0.01,   0.01,
 khdif                                = 0,      0,      0,
 kvdif                                = 0,      0,      0,
 non_hydrostatic                      = .true., .true., .true.,
 moist_adv_opt                        = 1,      1,      1,
 scalar_adv_opt                       = 1,      1,      1,
 smdiv                                = 0.1,    0.1,    0.1,
 emdiv                                = 0.01,   0.01,   0.01,
 epssm                                = 0.2,    0.2,    0.2,
 time_step_sound                      = 0,      0,      0,
 h_mom_adv_order                      = 5,      5,      5,
 v_mom_adv_order                      = 3,      3,      3,
 h_sca_adv_order                      = 5,      5,      5,
 v_sca_adv_order                      = 3,      3,      3,
 tke_adv_opt                          = 1,      1,      1,
 use_baseparam_fr_nml                 = .t.
 /
```

```
&bdy_control
spec_bdy_width                    = 5,
spec_zone                         = 1,
relax_zone                        = 4,
specified                         = .true., .false., .false.,
nested                            = .false., .true., .true.,
/

&grib2
/

&namelist_quilt
nio_tasks_per_group = 0,
nio_groups = 1,
/
```

AER_MP (Differences Only, Relative to AER_BASE)

```
&domains
wif_input_opt                     = 1,
num_wif_levels                    = 30

&physics
mp_physics                        = 28,   28,    28,
use_aero_icbc                     = .F.,
```

AER_PBL (Differences Only, Relative to AER_BASE)

```
&physics
sf_sfclay_physics                 = 5,     5,     5,
bl_mynn_closure                   = 2.6,
tke_budget                        = 0,     0,
bl_mynn_tkeadvect                 = .false., .false.
icloud_bl                         = 1,
bl_mynn_cloudmix                  = 1,     1,
bl_mynn_mixlength                 = 2,
bl_mynn_cloudpdf                  = 2,
bl_mynn_edmf                      = 1,     1,
bl_mynn_edmf_mom                  = 1,     1,
bl_mynn_edmf_tke                  = 0,     0,
scalar_pblmix                     = 1,     1,
```

A4: Customizations to Registry.EM_COMMON file

The following additions have been made to the WRFv4.5.2 default Registry.EM_COMMON file to output these variables in the regular wrfout history files.

```
state   real    GSW             ij     misc        1        -     rhd        "GSW"
 "NET SHORT WAVE FLUX AT GROUND SURFACE"                          "W m-2"
state   real    diffuse_frac    ij     misc        1        -     rhd        "DIFFUSE_FRAC"
 "DIFFUSE FRACTION OF SURFACE SHORTWAVE IRRADIANCE"               ""
state   real    swddir          ij     misc        1        -     rhd        "SWDDIR"
 "Shortwave surface downward direct irradiance"                   "W m-2" ""
state   real    swddirc         ij     misc        1        -     rhd        "SWDDIRC"
 "Clear-sky Shortwave surface downward direct irradiance"         "W m-2" ""
state   real    swddni          ij     misc        1        -     rhd        "SWDDNI"
 "Shortwave surface downward direct normal irradiance"            "W m-2" ""
state   real    swddnic         ij     misc        1        -     rhd        "SWDDNIC"
 "Clear-sky Shortwave surface downward direct normal irradiance" "W m-2" ""
state   real    swddif          ij     misc        1        -     rhd        "SWDDIF"
 "Shortwave surface downward diffuse irradiance"                  "W m-2" ""
```

A5: wrfout file output variables

The variables produced by a one-day test run of WRF, with the AER_BASE configuration, that are relevant to the desired verifications are displayed in Tables 1 and 2 below. The first table shows variables from the wrfout file. The second table shows variables from the xtrm_60min file, a custom file that includes time-averaged and maximum variables calculated over the preceding hour.

Verification was conducted using the TCEQ-provided CAMs data. Per https://www.tceq.texas.gov/cgi-bin/compliance/monops/daily_summary.pl and the copied screenshot image below, measurements provided by CAMs are averaged over hourly periods.

The table below contains hourly averages for all the pollutants and meteorological conditions measured at Camp Bullis C58 for **Friday, June 10, 2022**. All times shown are in CST.

Parameter Measured	Morning											
	Mid	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Ozone	16	13	9	8	***6***	7	7	9	12	17	22	28
Wind Speed	6.3	4.0	2.6	2.5	2.4	5.6	5.0	5.6	5.7	6.3	6.3	5.4
Resultant Wind Speed	5.9	3.8	2.5	2.3	2.2	5.1	4.4	4.8	4.8	5.3	4.2	3.2
Resultant Wind Direction	162	161	143	159	163	186	198	196	221	202	208	193
Maximum Wind Gust	13.3	10.5	5.3	6.5	8.8	14.5	13.6	13.1	13.8	14.8	15.5	13.0
Std. Dev. Wind Direction	20	21	18	21	24	23	27	30	32	31	46	**52**
Outdoor Temperature	79.3	77.9	76.5	75.8	***75.3***	75.4	76.2	78.9	80.6	83.6	86.2	88.6
Solar Radiation	***0.000***	0.000	0.000	0.000	0.000	0.004	0.116	0.442	0.569	1.023	1.240	1.397
Parameter Measured	Mid	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
	Morning											

Afternoon												Paramet Measur
Noon	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	
31	41	**48**	47	47	46	42	34	21	23	21	16	Ozone
4.8	5.7	7.4	6.3	5.1	6.1	5.2	2.4	***0.9***	**8.7**	7.0	5.1	Wind Spe
3.2	3.8	6.4	5.1	3.4	4.9	4.6	2.3	***0.8***	**8.1**	6.7	4.8	Resultant Wind Spe
193	198	180	182	176	168	160	143	**296**	***137***	150	157	Resultant Wind Direction
13.4	16.3	17.2	17.3	13.0	16.2	11.5	8.3	***2.5***	**20.7**	19.6	14.3	Maximum Wind Gus
47	47	30	35	46	36	29	18	23	21	***17***	19	Std. Dev. Wind Direction
91.0	93.3	95.9	97.1	97.8	**98.1**	97.3	93.9	85.5	87.4	85.6	83.9	Outdoor Temperat
1.363	**1.430**	1.284	1.058	0.774	0.451	0.172	0.018	0.000	0.000	0.000	0.000	Solar Radiation
Noon	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	Paramet Measure
Afternoon												

The observations include mean wind speed, direction, and temperature over 60-minute periods, a maximum wind gust over the same time period, and mean solar radiation. The following WRF variables were used for validation.

TCEQ CAMs variable	WRF output
Mean wind speed (miles h^{-1})	SPDUV10MEAN (m s^{-1})
Mean wind direction (degrees)	U10MEAN, V10MEAN, converted to direction
Mean temperature (F)	T2MEAN (K)
Mean Relative Humidity (%)	Derived (T2MEAN, Q2MEAN, PSFC)
Mean solar radiation (Langleys min^{-1})	ACSWDNB (J m^{-2}), divided by time period

WRF accumulated solar radiation at the surface accumulates over the course of the entire monthly simulation. After correcting for this accumulation, the actual amount accumulated at each individual hourly timestep in J/m^2 is converted to Langleys per minute using a conversion factor of 41840 J/m^2/Langley and 60 minutes/hr. Langleys per minute are then convertible to W/m2 using the conversion factor of 11.63 W/m^2 = 1 Langley/hr.

Precipitation analysis was conducted using grid-stat comparison using PRISM gridded data, obtained via the PRISM web site: https://prism.oregonstate.edu/recent/. The PREC_ACC_NC variable calculates hourly precipitation accumulation within WRF. These were summed to daily (monthly) intervals for verification with the daily (monthly) PRISM data.

Table A1: wrfout file variables.

Type	Name	Description	Units
float	PSFC	SFC PRESSURE	Pa
float	RAINNC	ACCUMULATED TOTAL GRID SCALE PRECIPITATION	mm
float	SWDOWN	DOWNWARD SHORT WAVE FLUX AT GROUND SURFACE	W m-2
float	ACSWDNB	ACCUMULATED DOWNWELLING SHORTWAVE FLUX AT BOTTOM	J m-2
float	SWDNB	INSTANTANEOUS DOWNWELLING SHORTWAVE FLUX AT BOTTOM	W m-2
float	PREC_ACC_NC	ACCUMULATED GRID SCALE PRECIPITATION OVER prec_acc_dt PERIODS OF TIME (60minutes)	mm

Table A2: xtrm_60min file variables.

Type	Name	Description	Units
float	T2MEAN	MEAN TEMPERATURE AT 2M HEIGHT IN DIAGNOSTIC OUTPUT INTERVAL (60 min)	K
float	Q2MEAN	MEAN WATER VAPOR MIX. RAT. AT 2M HEIGHT IN DIAGNOSTIC OUTPUT INTERVAL (60 min)	kg kg-1
float	SPDUV10MEAN	MEAN WIND SPEED AT 10M HEIGHT IN DIAGNOSTIC OUTPUT INTERVAL (60 min)	m s-1
float	U10MEAN	MEAN U AT 10M HEIGHT IN DIAGNOSTIC OUTPUT INTERVAL (60 min)	m s-1
float	V10MEAN	MEAN V AT 10M HEIGHT IN DIAGNOSTIC OUTPUT INTERVAL (60 min)	m s-1

Appendix B: Download Manifest for Deliverable 4.1 WRF d02 output and set-up files.

```
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-05-31_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-01_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-02_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-03_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-04_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-05_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-06_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-07_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-08_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-09_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-10_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-11_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-12_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-13_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-14_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-15_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-16_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-17_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-18_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-19_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-20_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-21_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-22_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-23_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-24_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-25_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-26_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-27_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-28_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-29_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-06-30_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-07-01_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-07-02_00:00:00
202206_AER_BASE/WRFOUT_D02/wrfout_d02_2022-07-03_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-01_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-02_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-03_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-04_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-05_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-06_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-07_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-08_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-09_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-10_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-11_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-12_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-13_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-14_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-15_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-16_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-17_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-18_00:00:00
202206_AER_BASE/WRFRST_D02/wrfrst_d02_2022-06-19_00:00:00
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