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Ozone Source Apportionment Modeling for New Mexico Environmental Department – CAMx 2022v2 Base Case Model Performance Evaluation – Draft Final

CAMx 2022v2 4 km Base Case Model Performance Evaluation – Draft Final





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EXECUTIVE SUMMARY

In 2025–2026, the New Mexico Environment Department (NMED) contracted with Ramboll to conduct a Regional Ozone Source Apportionment Study. The study is being conducted in two phases. Phase I was performed from April through June 2025 during Fiscal Year 2025 (FY2025). Phase I included 2022v1 base case and 2026v1 ozone source apportionment modeling using the EPA 2022v1 12 km photochemical grid model (PGM) platform based on the Comprehensive Air-quality Model with extensions (CAMx) (Ramboll, 2025a,b).

Under Phase II (FY2026; July 1, 2025 – June 30, 2026), Ramboll developed a higher-resolution CAMx 2022v2 12/4 km modeling platform using EPA 2022v2 emissions and is conducting CAMx 2022v2 and 2032 12/4 km base case and ozone source apportionment modeling. Ozone source apportionment modeling is being conducted and reported for the full 4 km modeling domain, which includes all of New Mexico and portions of adjacent states. Although results are obtained for the entire New Mexico 4 km domain, the focus is on ozone contributions within the New Mexico portion of the Permian Basin where the largest ozone increases have occurred in recent years.

This report documents the development of the NMED Phase II CAMx 2022v2 12/4 km modeling platform and its model performance evaluation.

Permian Basin Ozone Concentrations

Figure ES-1 displays the ozone monitoring sites within the New Mexico 4 km modeling domain and the 2005–2024 trends in ozone design values (DVs) at the three ozone monitoring sites located in the New Mexico portion of the Permian Basin in southeastern New Mexico: Carlsbad City and Carlsbad Caverns in Eddy County, and Hobbs in Lea County. In August 2018, U.S. EPA designated ozone nonattainment areas for the 70 ppb 2015 ozone National Ambient Air Quality Standard (NAAQS) based on observed 2014–2016 ozone DVs, which at the Carlsbad City and Hobbs monitoring sites were 67 ppb and 66 ppb, respectively. This resulted in Eddy and Lea Counties being designated as attainment areas under the 2015 ozone NAAQS.

Since 2017, ozone concentrations in the Permian Basin have increased, coincident with increases in oil and gas (O&G) production in the region. By 2018, ozone DVs began exceeding the 2015 ozone NAAQS (Figure ES-1, right panel).

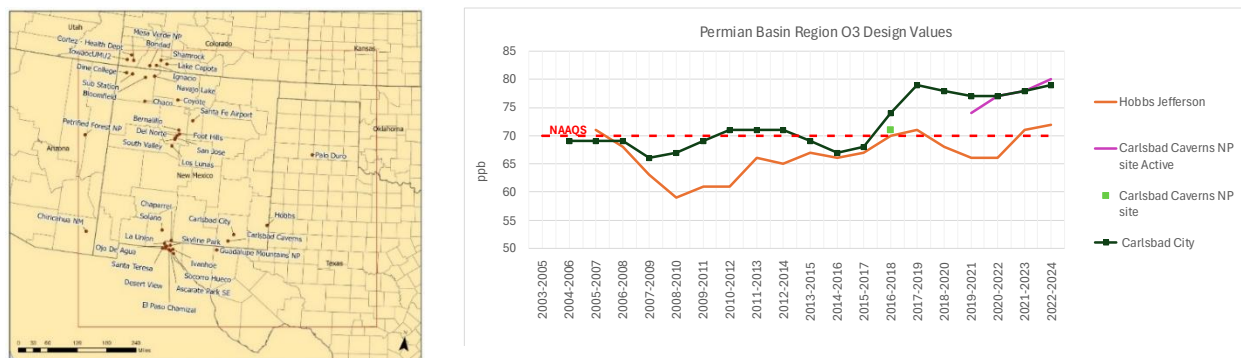


Figure ES-1. Locations of ozone monitoring sites within the New Mexico 4 km modeling domain (left) and trends in observed ozone Design Values at monitoring sites within the New Mexico portion of the Permian Basin (right).

Development of a CAMx 2022v2 12/4 km Modeling Platform

A CAMx 2022v2 12/4 km modeling platform was developed for the summer 2022 (May-through mid-October) modeling period. The 12 km grid resolution domain covered the continental U.S. (CONUS; 12US2 domain) and the 4 km grid resolution domain included New Mexico and portions of adjacent states, including the Permian Basin in Texas (Figure ES-1, left panel). Meteorological inputs for the CAMx 2022v2 12/4 km platform were based on a 2022 simulation of the Weather Research and Forecasting (WRF) meteorological model (Ramboll, 2025c). Boundary conditions (BCs) for the lateral boundaries of the 12 km CONUS domain were based on output from a CAMx 2022v2 North American 36 km domain simulation, whose BCs were based on a 2022 simulation of the Hemispheric CMAQ global chemistry model. Emissions for the CAMx 2022v2 12/4 km platform were based on the National Emissions Collaborative ([NEC](#)) [2022v2 Emissions Modeling Platform](#) (EMP; EPA 2025). EPA processed the 2022v2 inventories to generate PGM model-ready emission inputs for the 12 km CONUS domain that were used directly in the NMED CAMx 2022v2 12/4 km modeling platform. The EMP 2022v2 emissions were processed using the Sparse Matrix Operator Kernel Emissions (SMOKE) model to generate 2022 hourly gridded speciated CAMx emissions inputs for the 4 km New Mexico domain and the summer of 2022.

CAMx 2022v2 12/4 km Model Performance Evaluation

A CAMx 2022v2 12/4 km base case simulation was conducted, and the 4 km modeling results were compared with concurrent routine ozone and NO_x measurements as part of a model performance evaluation. The modeling results were also evaluated against special field studies' ozone precursor measurements and satellite data.

Routine Ozone and NO_x Model Performance Evaluation

The Phase II CAMx 2022v2 4 km ozone model performance was compared with the Phase I CAMx 2022v1 12 km results and was found to exhibit a larger ozone underestimation bias, particularly in the Permian Basin. The cause of the lower ozone concentrations in the CAMx 2022v2 4 km results was traced to EPA's correction of an error in oil and gas drilling and fracking engine emissions, for which NO_x emissions were overstated by 74% in the 2022v1 emissions inventory.

Ozone normalized mean bias (NMB) and normalized mean error (NME) metrics were evaluated against commonly used ozone performance goals (NMB $\leq \pm 5\%$ and NME $\leq 15\%$) and performance criteria (NMB $\leq \pm 15\%$ and NME $\leq 25\%$). Figure ES-2 presents the CAMx

2022v2 4 km NMB and NME performance metrics for maximum daily average 8-hour (MDA8) and hourly ozone concentrations at monitoring sites within the New Mexico 4 km domain. NMB symbols are shown in grey when the performance goal is achieved and in yellow (overestimation) or green (underestimation) when the NMB fall between the performance goal and performance criteria. MDA8 and hourly ozone NMB values at nearly all sites in the New Mexico 4 km domain meet the bias performance criteria, and many sites meet the bias performance goal. MDA8 ozone NME meets the error performance criterion at all sites and meets the performance goal at more than 80% of sites in the New Mexico 4 km domain.

Within the New Mexico portion of the Permian Basin, MDA8 ozone NMB falls between the performance goal and performance criterion with an underestimation bias except for the Carlsbad Caverns sites that just barely exceeds the bias performance criterion. MDA8 ozone NME meets the performance goal at the Hobbs site but falls between the performance goal and performance criterion at the two Eddy County sites. Similar results are observed for hourly ozone, although the hourly ozone NMB at Hobbs meets the performance goal.

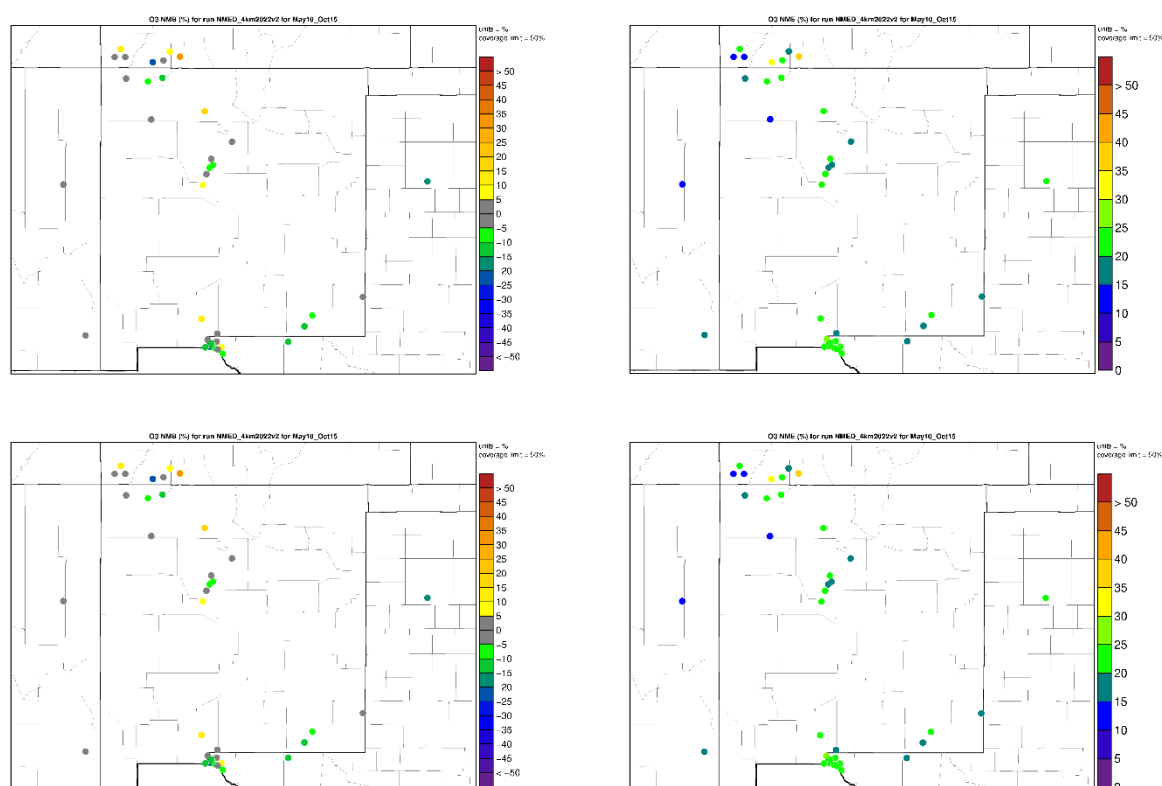


Figure ES-2. Spatial distribution of CAMx 2022v2 4 km NMB (left) and NME (right) MDA8 (top) and hourly (bottom) ozone performance statistics for the May 10 through October 15, 2022 modeling period.

Figure ES-3 presents scatter plots and performance statistics for MDA8 ozone at four monitoring sites in the Permian Basin. CAMx 2022v2 4 km exhibits normalized mean bias (NMB) underestimation of -15.7% at the Carlsbad City site and -14.6% at the Carlsbad Caverns site in Eddy County, New Mexico, with most data points falling below the 1:1 line of perfect agreement (Figure ES-3, top panels). The Hobbs site in Lea County shows an NMB of -9.5% , and Guadalupe Mountains National Park, located just south of Eddy County in

Texas, shows an NMB of -11.4% (Figure ES-3, bottom panels). At both of these sites, the underestimation bias falls between the bias performance goal and performance criterion.

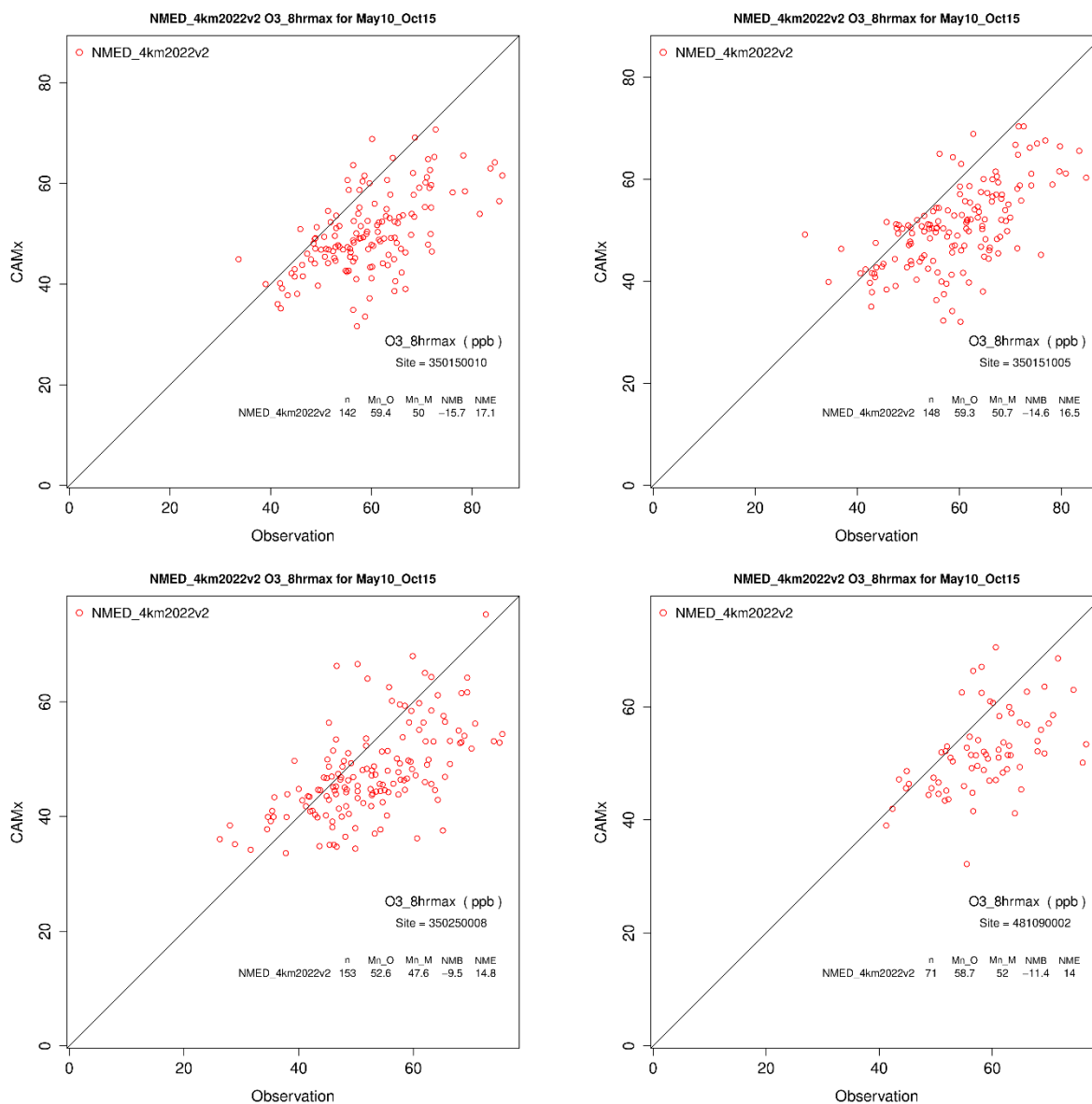


Figure ES-3. Scatter plots of predicted (CAMx 2022v2 4 km) and observed MDA8 ozone concentrations at monitoring sites in the Permian Basin: Carlsbad Cavern (350150010; top left), Carlsbad City (350151005; top right), Hobbs (350250008; bottom left) and Guadalupe Mountains National Park (481090002; bottom right).

Ground-level (tropospheric) ozone formation results from photochemical reactions between volatile organic compounds (VOCs) and oxides of nitrogen (NO_x) in the presence of sunlight. The photolysis of NO_2 is the key atmospheric process for ozone formation in the troposphere, when ultraviolet radiation splits NO_2 into nitric oxide (NO) and a highly reactive oxygen atom [$\text{O}(^3\text{P})$]. The oxygen atom rapidly reacts with molecular oxygen (O_2) to form ozone (O_3). The ozone titration reaction ($\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2$) can rapidly convert ozone back to NO_2 , resulting in no net ozone formation. However, VOCs generate reactive radical species that convert NO to NO_2 without destroying ozone leading to a net increase in ozone concentrations. As a result, both NO_x and VOCs are required for ozone formation. As part of this evaluation, we compared predicted and observed hourly ozone and NO_2 concentrations, as it provides insight into the model's ability to represent observed ozone formation processes.

Figure ES-4 presents a time series of predicted and observed hourly ozone and NO_2 concentrations at the Carlsbad City site for July 13–15, 2022. The model generally reproduces the observed morning and early afternoon increase in hourly ozone concentrations; however, later in the afternoon the modeled ozone increase levels off, while observed ozone continues to rise (e.g., see July 15 in Figure ES-4). Vertical lines in Figure ES-4 indicate the approximate afternoon time when modeled and observed hourly ozone concentrations begin to diverge. At these times, modeled hourly NO_2 concentrations approach zero, while measured NO_2 remains higher, which may allow observed ozone formation to continue while insufficient modeled NO_2 limits simulated ozone production. Several factors may contribute to the modeled ozone increase leveling off and to lower modeled afternoon ozone and NO_2 concentrations than observed, including:

- Understated NO_x or VOC or both emissions in the inventory.
- Excessive vertical mixing in the model that dilutes near-surface ozone concentrations and its precursors (e.g., NO_2).
- Insufficient elevated ozone aloft available that is entrained into the mixed layer and mixed down to the surface as afternoon mixing heights increase.
- Observed NO_2 concentrations near the instrument detection limit.
- Interference in NO_2 measurements from other reactive nitrogen species (e.g., PAN, PNA, NO_3^- , HNO_3).

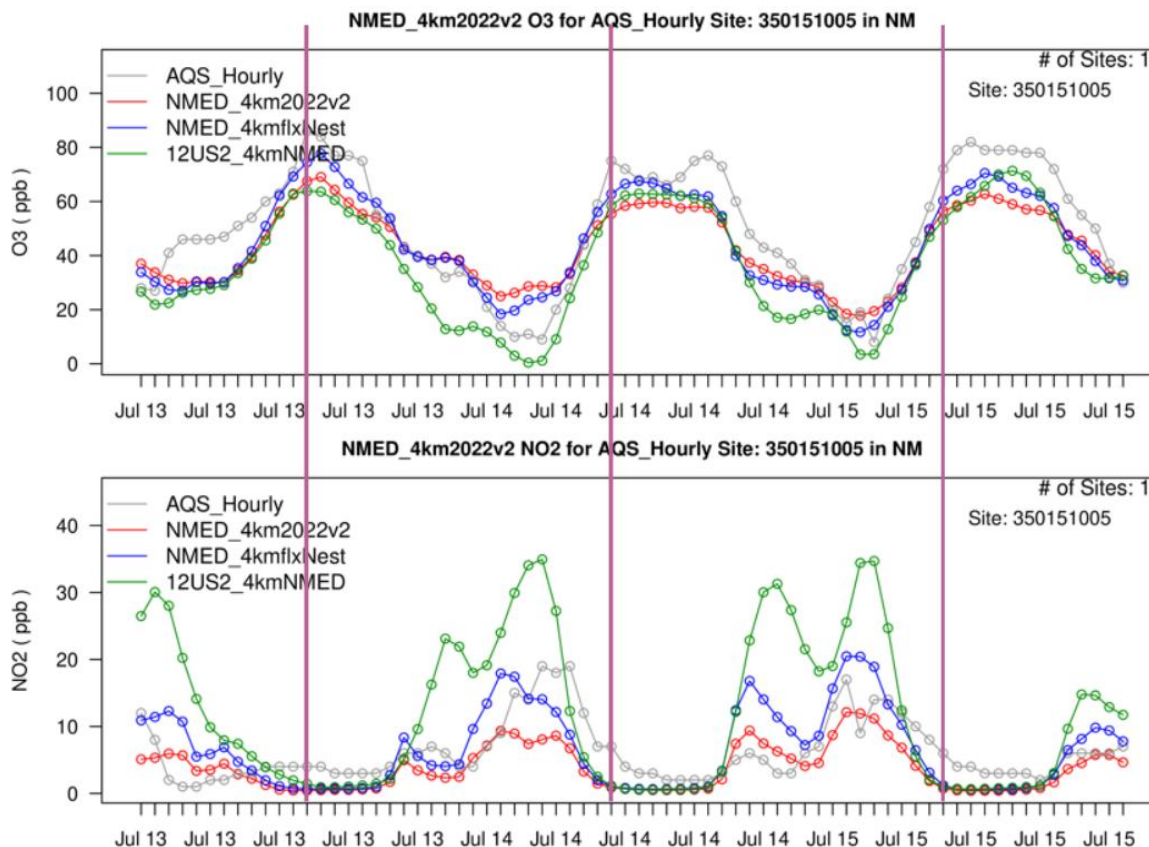


Figure ES-4. Predicted and observed hourly ozone (top) and NO₂ (bottom) concentrations at the Carlsbad City monitoring site on July 13-15, 2022 for the current Phase II CAMx 2022v2 4 km (red), Phase I CAMx 2022v1 12 km (green), and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

CAMx 2022v2 4 km Ozone Precursor Evaluation Against Special Field Study Data

The CAMx 2022v2 4 km modeling results were evaluated against VOC and NO_x observations collected during the 2021 Carlsbad Caverns Air Quality Study (CarCavAQS) and the Health Effects Institute (HEI) 2023 measurements collected in Loving, New Mexico (LNM) by Boulder AIR. Figure ES-5 (left panel) shows the locations of the Carlsbad City, LNM, and Carlsbad Caverns monitoring sites; the Carlsbad Caverns site is located slightly farther west than shown in the figure. These sites are located near oil and gas (O&G) activities, as indicated by the cyan symbols representing active well locations and red symbols representing satellite-detected flaring, with the LNM site situated closer to O&G activity than the Carlsbad Caverns site.

Because the special field measurement studies were conducted in different years (2021 and 2023) than the modeling period (2022), a model evaluation based on matched time and location concentration comparisons, as performed for ozone and NO₂, was not possible. Instead, frequency distributions of predicted and observed ozone precursor concentrations were compared matched by location and under- or over-prediction was assessed by evaluating differences in the mean and median values of the predicted and observed frequency distributions. An additional challenge in evaluating the field study VOC data is that the CAMx model employs a lumped chemical mechanism, in which explicit VOC species

are mapped to lumped species based on their reactivity, whereas the field studies measured numerous explicit VOC species. As a result, the CAMx 2022v2 4 km simulation was evaluated for eight explicit VOC species represented in the model's chemical mechanism that were also measured in the field studies, as shown in the right panel of Figure ES-5. This summary presents evaluation results for ethane, propane, and benzene from the CarCavAQS and LNM studies; results for the remaining VOC species are provided in the main body of the report. Ethane and propane are indicators of O&G production, and comparisons of modeled and measured concentrations provide information on the accuracy of the Permian Basin O&G VOC emissions inventory. Benzene is a marker for gasoline combustion and may provide insight into the accuracy of the mobile-source VOC emissions inventory.

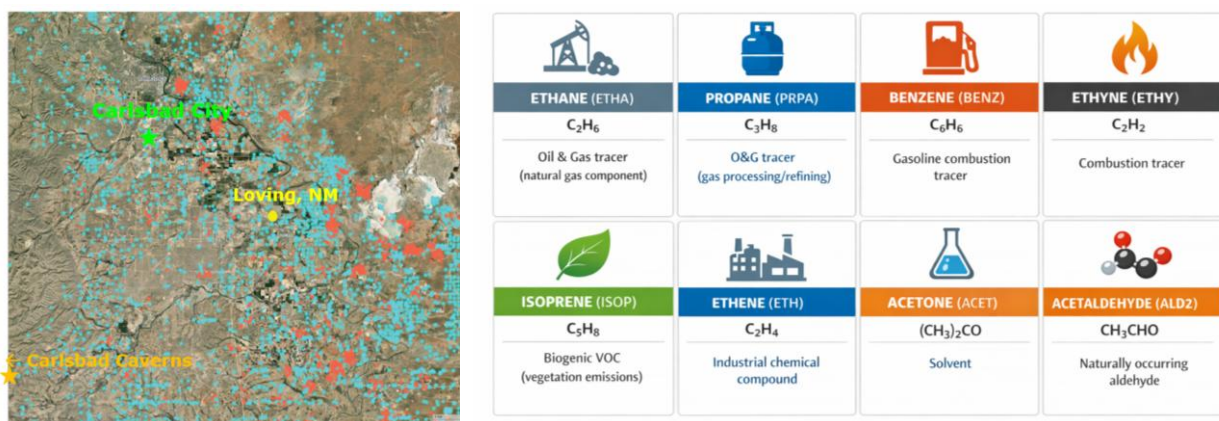


Figure ES-5. Locations of Carlsbad City, Loving, NM and Carlsbad Caverns monitoring sites (left) and 8 explicit VOC species used in the special field study model evaluation (right).

Figures ES-6 and ES-7 compare distributions of predicted and observed hourly ethane (ETHA) and propane (PRPA) concentrations using box-and-whisker plots for the CAMx 2022v2 4 km base case and the 2021 CarCavAQS and 2023 HEI LNM field studies, respectively. In the box-and-whisker plots, the box represents the interquartile range (IQR), spanning the 25th to 75th percentiles, and the whiskers extend to the highest and lowest values within 1.5 times the IQR. Circles above and below the whiskers indicate outliers, and the line within each box denotes the median.

At the Carlsbad Caverns site (Figure ES-6), observed ETHA and PRPA concentrations are substantially higher than modeled values, with the 25th percentile of the observed distribution approximately corresponding to the 75th percentile of the modeled distribution. The maximum modeled ethane concentration (approximately 15 ppb) is below the 75th percentile of the observed ethane concentrations (approximately 19 ppb).

Similar differences between modeled and observed ETHA and PRPA concentrations are seen at the LNM site, consistent with the CarCavAQS results, only with observed and modeled concentrations at LNM substantially higher than at Carlsbad Caverns. (Figure ES-7).

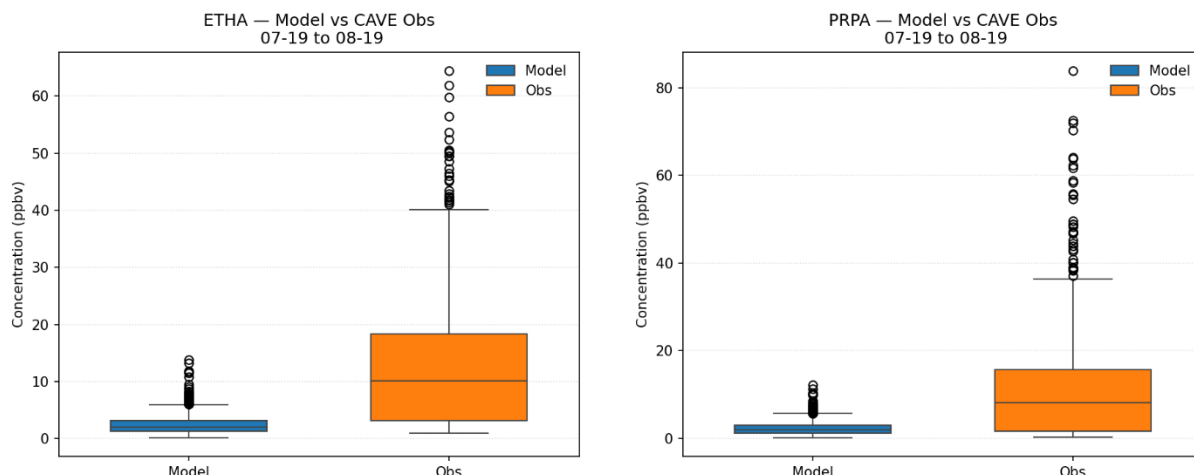


Figure ES-6. Box and Whisker Plots of the predicted and observed distributions of hourly Ethane (left) and Propane (right) concentrations at Carlsbad Caverns from the CarCavAQS July 19 – August 19, 2021 field study and CAMx 2022v2 4 km July 17 – August 19, 2022 base case simulation.

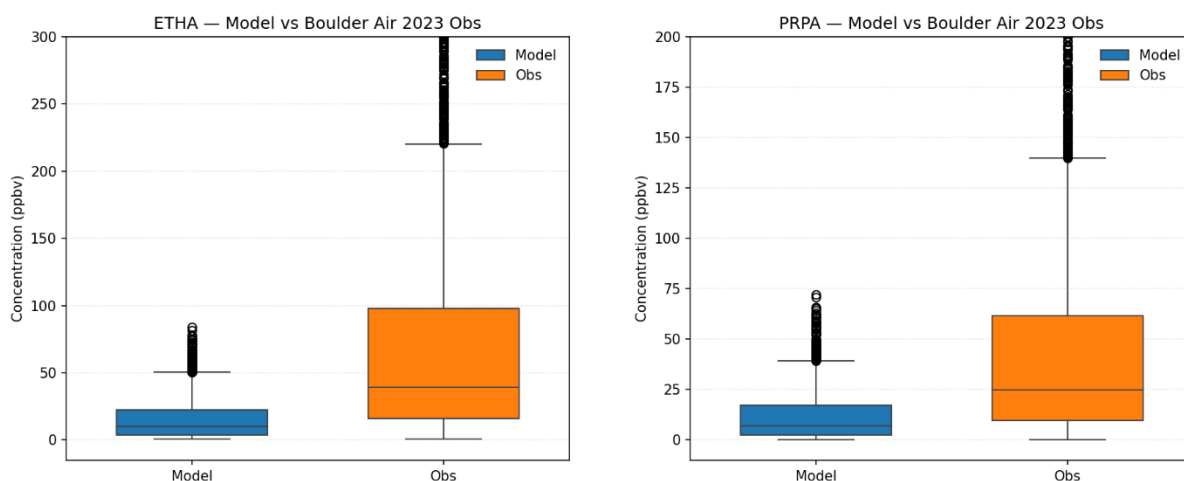


Figure ES-7. Box and Whisker Plots of predicted and observed distributions of hourly Ethane (left) and Propane (right) concentrations at Loving, New Mexico from the HEI Study Boulder Air May – October 2023 field study and CAMx 2022v2 4 km May – October 2022 base case simulation.

Figure ES-8 compares predicted and observed benzene concentrations from the CarCavAQS and HEI LNM field studies with results from the CAMx 2022v2 4 km base case. At the Carlsbad Caverns site, observed benzene concentrations are higher than modeled values, which may be partially attributable to the monitor's proximity to the visitor center and nearby roadways, whereas the model represents concentrations averaged over a 4 km grid cell. At the LNM site, where roadways are more widely distributed within the 4 km grid cell, predicted and observed benzene concentrations show good agreement on average, although the observed data exhibit a greater number of higher outliers.

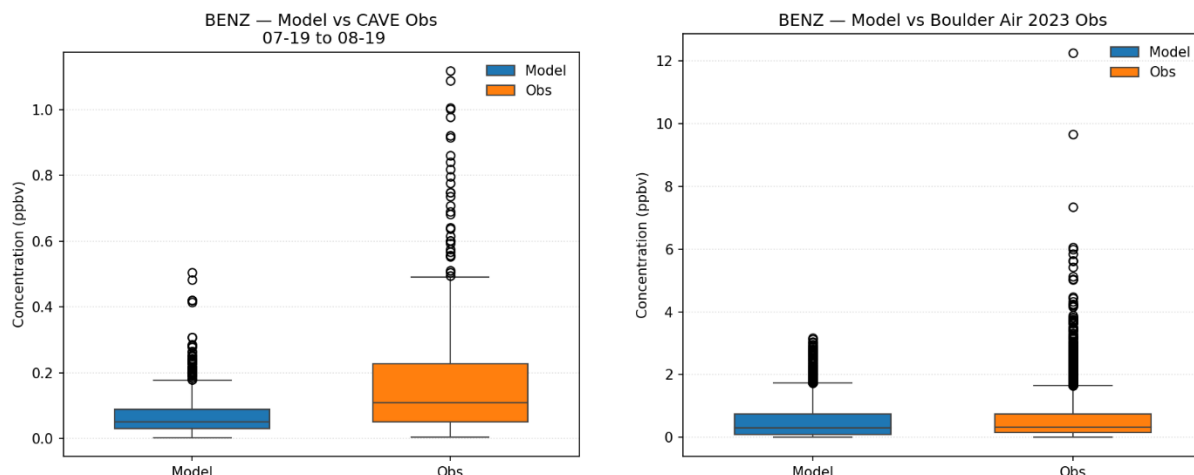


Figure ES-8. Box and Whisker Plots of predicted and observed distributions of hourly Benzene concentrations at Carlsbad Caverns (left) and Loving, New Mexico (right) from the 2021 CarCavAQS and 2023 HEI Boulder Air studies and the CAMx 2022v2 4 km base case simulation.

Table ES-1 summarizes differences between mean and median ethane, propane, and benzene concentrations at the two sites, comparing modeled and observed values. As expected, both observed and modeled concentrations are substantially higher, by factors of approximately 3 to 7, at the LNM site than at the Carlsbad Caverns site. At both sites, observed ethane and propane concentrations are approximately five times higher than modeled values. In contrast, benzene concentrations show good agreement at LNM, within approximately 10–20%. At Carlsbad Caverns, observed benzene concentrations are approximately a factor of two higher than modeled values on average, which is likely attributable to grid-cell averaging in the model compared with the point measurement located near roadways.

Table ES-1. Comparison of the Mean and Median Observed and Modeled Ethane, Propane and Benzene concentrations (ppb) and their ratios (Observed/Modeled) from the CarCavAQS and HEI Loving, NM field studies and the CAMx 2022v2 4 km base case simulation.

CarCavAQS Species	N	Model		Observed		Obs/Mod Ratio	
		Mean	Median	Mean	Median	Mean	Median
ETHA	563	2.5	1.9	13.0	10.1	5.2	5.2
PRPA	562	2.3	1.9	11.6	8.2	5.2	4.4
BENZ	561	0.07	0.05	0.17	0.11	2.4	2.2
Loving, NM Species	N	Model		Observed		Obs/Mod Ratio	
		Mean	Median	Mean	Median	Mean	Median
ETHA	3385	14.6	9.9	79.3	39.1	5.4	3.9
PRPA	3385	11.3	7.2	50.2	25.0	4.4	3.5
BENZ	3385	0.49	0.29	0.58	0.32	1.2	1.1

Evaluation Of CAMx 2022v2 4 km Base Case Against Satellite Data

The CAMx 2022v2 4 km vertical column density (VCD) predictions for formaldehyde (HCHO) and nitrogen dioxide (NO₂) were evaluated against measurements from the Tropospheric Monitoring Instrument (TROPOMI) satellite. TROPOMI provides measurements over New Mexico once per day in the afternoon, and retrievals can be affected by measurement interferences such as cloud cover. As a result, longer-term averaging periods are used for comparison, although additional uncertainty still remains in satellite observations.

Figure ES-9 compares satellite-derived and CAMx-predicted VCD HCHO, along with their differences, over the Permian Basin for the period from May 14 through September 30, 2022. Despite the nearly five-month averaging period, the TROPOMI HCHO spatial distribution remains pixelated, illustrating the uncertainty in the satellite measurements and their interpretation. Both the satellite-derived and modeled HCHO VCD show elevated concentrations in oil and gas (O&G) regions of southern Eddy and Lea Counties, as well as across the border in Texas. The TROPOMI spatial patterns suggest that the CAMx model may be overstating HCHO concentrations in these areas.

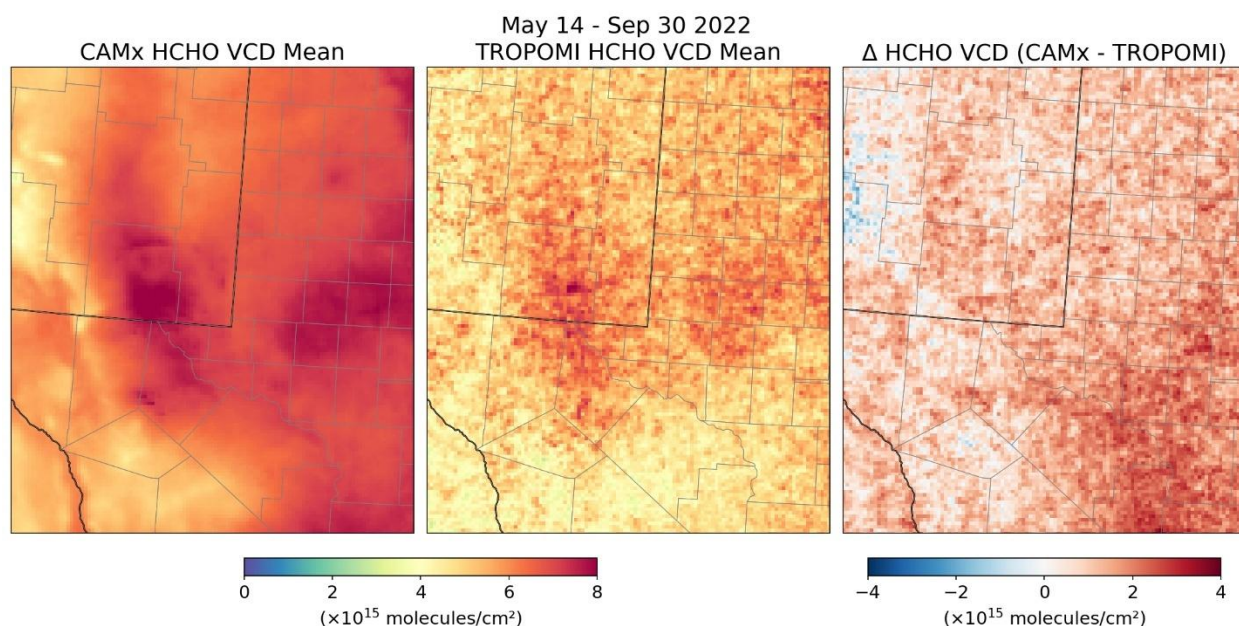


Figure ES-9. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) VCD HCHO concentrations and their differences (right) over the Permian Basin for May 14 – September 30, 2022.

Figure ES-10 presents an analysis analogous to Figure ES-9, but for NO₂ vertical column density (VCD). Elevated NO₂ levels associated with areas of intensive oil and gas (O&G) development in southern Eddy and Lea Counties are evident in both the CAMx model results and the TROPOMI satellite observations. In contrast, TROPOMI reports higher NO₂ VCD than the model across the border in the Texas portion of the Permian Basin. This difference is illustrated in the right panel of Figure ES-10, where blue shading indicates locations in which modeled NO₂ VCD are lower than those reported by TROPOMI in the Texas region adjacent to Eddy and Lea Counties. These results suggest that O&G NO_x emissions may be understated in the Texas portion of the Permian Basin.

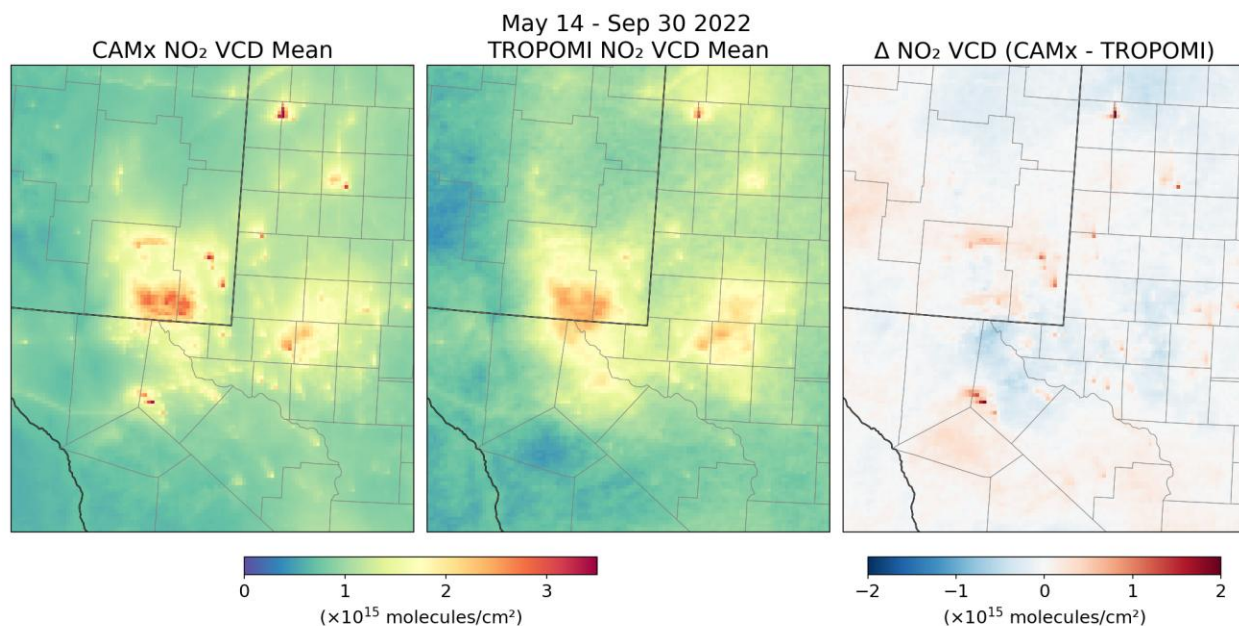


Figure ES-10. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) VCD NO₂ concentrations and their differences (right) over the Permian Basin for May 14 – September 30, 2022.

Several studies have proposed using the formaldehyde-to-NO₂ ratio (FNR) to indicate whether ozone formation is more sensitive to NO_x emissions (i.e., NO_x reductions more effectively reduce ozone concentrations than VOC reductions) or more sensitive to VOC emissions (i.e., VOC reductions are more effective, and NO_x reductions may increase ozone concentrations). Ozone formation is rarely exclusively NO_x-sensitive or VOC-sensitive, as sensitivity can vary by day and within a given day, with conditions typically being more VOC-sensitive in the morning and becoming more NO_x-sensitive later in the afternoon. Based on FNR threshold ranges reported in the peer-reviewed literature, the following shading scheme was developed for plotting FNR values in this report:

- Black (0.0 < FNR < 1.0): clearly VOC-sensitive
- Dark blue (1.0 < FNR < 2.1): likely VOC-sensitive but possibly transitional
- Purple (2.1 < FNR < 3.2): likely transitional but possibly VOC-sensitive
- Light blue (3.2 < FNR < 4.1): transitional
- Yellow (4.1 < FNR < 5.0): likely NO_x-sensitive
- Orange and red (FNR > 5.0): clearly NO_x-sensitive

Figure ES-11 compares FNR values derived from CAMx and TROPOMI, as well as their differences, across the Permian Basin. TROPOMI indicates a larger area of potentially VOC-sensitive and transitional ozone formation regimes within the oil and gas portions of the Permian Basin than indicated by the model. This suggests that the model may understate the potential benefits of VOC emission reductions for decreasing ozone concentrations in the Permian Basin.

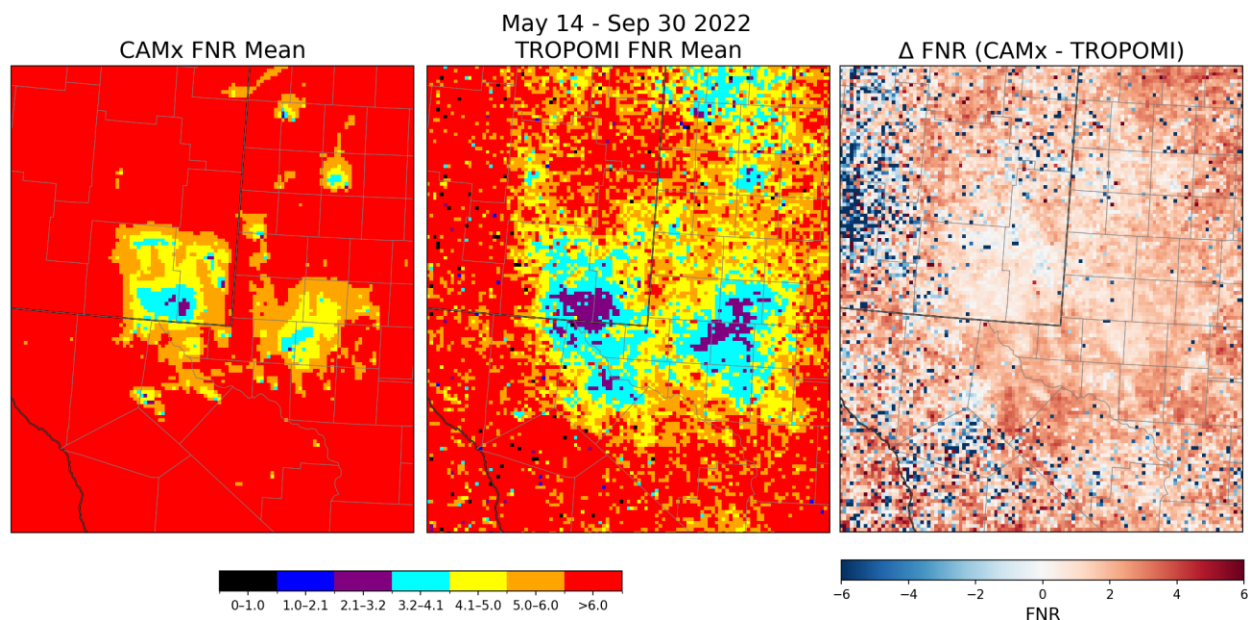


Figure ES-11. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) formaldehyde to NO₂ ratios (FNR) and their differences (right) over the Permian Basin for May 14 – September 30, 2022 period.

The TROPOMI five-month average VCD HCHO and NO₂ were gridded to the New Mexico 4 km modeling domain, and a statistical comparison was performed between the CAMx and TROPOMI VCD HCHO and NO₂ results. As noted previously, TROPOMI VCD HCHO tended to be higher than the modeled-derived values, a pattern that was also evident in the statistical comparison. In contrast, comparison of VCD NO₂ was confounded by the higher spatial resolution of the CAMx 4 km model, which produced higher VCD NO₂ values in grid cells containing major NO_x point sources compared to the lower-resolution TROPOMI measurements.

Figure ES-12 compares CAMx and TROPOMI VCD NO₂ within the New Mexico and Texas portions of the Permian Basin for 4 km grid cells that include oil and gas (O&G) NO_x emissions greater than 0.02 tons per day (TPD). In the New Mexico portion of the Permian Basin, there is generally good agreement between the modeled and TROPOMI VCD NO₂ at locations associated with O&G NO_x emissions (Figure ES-12, left panel). Several 4 km grid cell locations show higher CAMx VCD NO₂ values, which are likely associated with NO_x point sources (e.g., midstream O&G facilities) and reflect the finer spatial resolution of the CAMx model relative to TROPOMI. In contrast, within the Texas portion of the Permian Basin, the model generally underestimates TROPOMI VCD NO₂ at locations with O&G emissions, except for a small number of grid cells where CAMx values are higher due to the finer horizontal resolution. These results suggest that O&G NO_x emissions may be understated in the Texas portion of the Permian Basin.

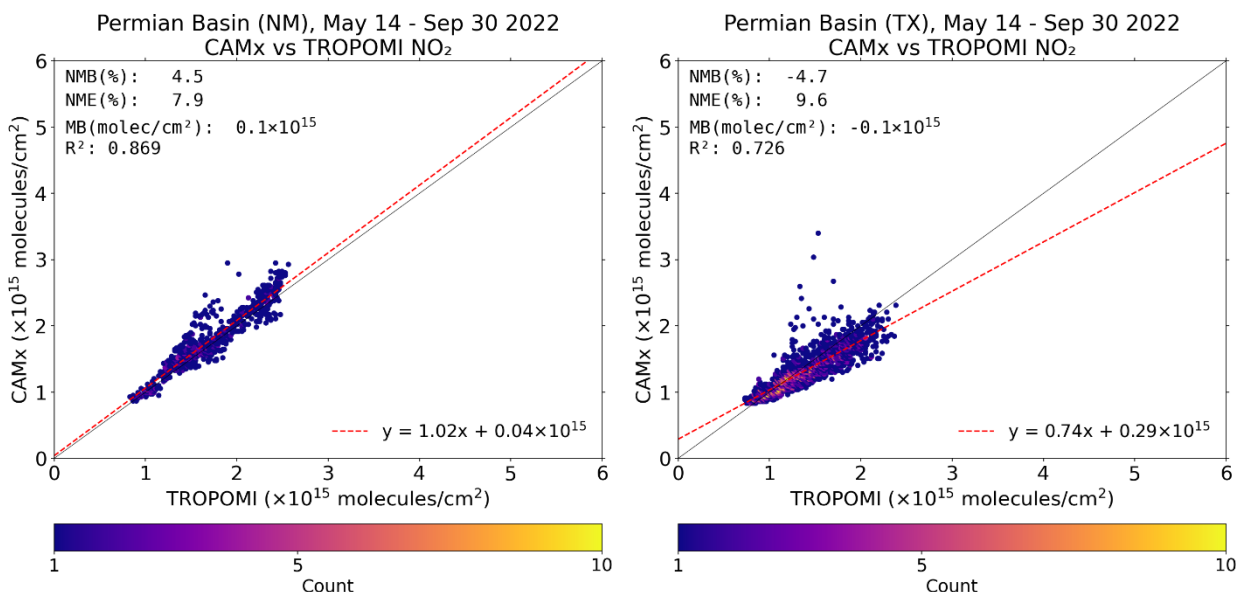


Figure ES-12. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD NO₂ concentrations for the New Mexico (left) and Texas (right) portions of the Permian Basin in 4 km grid cells with O&G NO_x emissions greater than 0.02 TPD.

CAMx Sensitivity Test Modeling

Seven CAMx 2022v2 12/4 km sensitivity tests (Sens1 – Sens7) were conducted to investigate potential causes of the afternoon underestimation of ozone and NO₂ on select days. Both meteorological and emissions sensitivity tests were performed, with a focus on model performance in the Permian Basin. While results were generated for the full New Mexico 4 km modeling domain, Permian Basin monitoring sites exhibited some of the highest observed ozone concentrations and the largest ozone underestimation bias. The sensitivity analyses focused on a 20-day episode from June 28 through July 17, 2022, during which approximately 40% of the observed ozone exceedances occurred at the Carlsbad City monitoring site.

Three meteorological sensitivity tests were performed. The first two tests (Sens1 and Sens2) evaluated alternative approaches for representing vertical mixing in CAMx, as excessive vertical mixing could dilute near-surface concentrations and result in overly low modeled afternoon NO₂ concentrations, thereby limiting ozone photolysis and subsequent ozone formation. These vertical mixing sensitivity tests did not produce appreciable changes in ozone or NO₂ model performance. The third meteorological test (Sens6) removed cloud cover in the New Mexico 4 km domain. Because excessive cloud cover can attenuate solar radiation and reduce photolysis rates, this test examined whether cloud representation limited ozone formation. The no-cloud-cover sensitivity test also had little effect on modeled ozone and NO₂ concentrations.

Four emissions sensitivity tests were conducted to evaluate the effects of increased O&G emissions in the Permian Basin on ozone, VOC, and NO_x performance. Three tests increased O&G emissions in the New Mexico portion of the Permian Basin (NM PB) and one increased O&G emission in the Texas portion of the Permian Basin (TX PB):

- Sens3: three times O&G NO_x emissions in NM PB.
- Sens4: three times O&G VOC emissions in NM PB.

- Sens5: three times O&G NO_x and VOC emissions in NM PB.
- Sens7: three times O&G NO_x and VOC emissions in TX PB.

Figure ES-13 shows time series of hourly ozone and NO₂ concentrations at the Carlsbad City site for the New Mexico Permian Basin O&G emissions sensitivity tests during July 8–11, 2022. Increasing New Mexico Permian Basin O&G NO_x emissions, with or without concurrent VOC increases (Sens3 and Sens5), resulted in improved hourly ozone performance. However, nighttime NO₂ concentrations were overestimated in both Sens3 and Sens5, and modeled afternoon NO₂ concentrations remained lower than observed, although higher than in the 2022v2 base case. Increasing New Mexico Permian Basin O&G VOC emissions alone (Sens4) had a smaller effect on hourly ozone and NO₂ concentrations but produced a noticeable increase in ozone when combined with increased O&G NO_x emissions (Sens5).

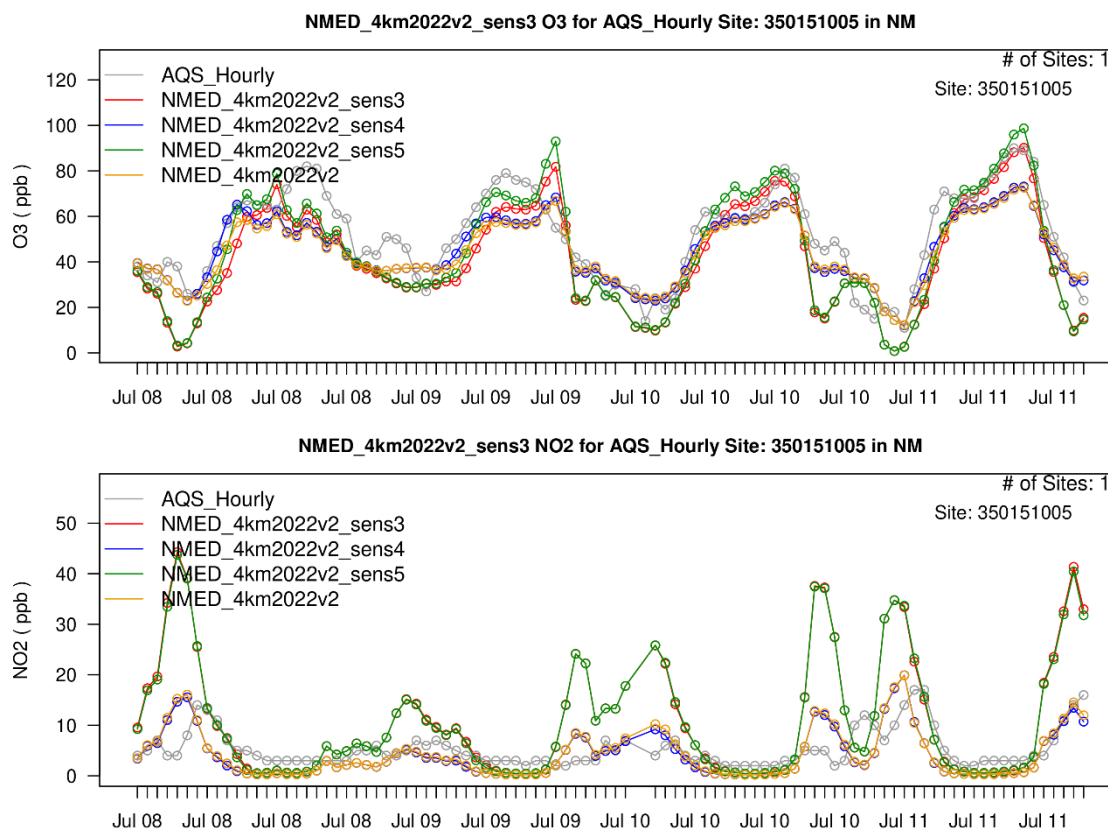


Figure ES-13. Time series of predicted and observed hourly ozone (top) and NO₂ (bottom) concentrations at Carlsbad City monitoring site, June 30 – July 3, 2022, and the New Mexico Permian Basin O&G emissions sensitivity tests: Base Case (orange); Sens3 (3 x NM PB O&G NO_x; red); Sens4 (3 x NM PB O&G VOC; blue), and Sens5 (3 x NM PB O&G NO_x and VOC; green).

Scatter plots and performance statistics for MDA8 ozone concentrations at the Carlsbad City site for the New Mexico Permian Basin oil and gas (O&G) emissions sensitivity tests are presented in Figure ES-14. For the CAMx 2022v2 12/4 km base case and the Sens4 simulation (NM PB O&G VOC increases only), MDA8 ozone values for all days fall below the 1:1 line of perfect agreement. When New Mexico Permian Basin O&G NO_x emissions are increased by a factor of three, improved MDA8 ozone performance is observed, with some points above the 1:1 line. The best MDA8 ozone performance occurs when both O&G NO_x and VOC emissions are increased (Sens5).

The MDA8 ozone normalized mean bias (NMB) at Carlsbad City for the CAMx 2022v2 4 km base case is -14% , which marginally meets the bias performance criterion and MDA8 ozone NMB remains at approximately -14% when the NM PB O&G VOC emissions are increased alone (Sens4). The NMB improves to -9% when just NM PB O&G NO_x emissions are increased (Sens3). When both New Mexico Permian Basin O&G NO_x and VOC emissions are increased by a factor of three, the NMB is reduced to -3% , achieving the bias performance goal, and the MDA8 ozone scatter plots span the 1:1 line of perfect agreement (Figure ES-14, lower right panel).

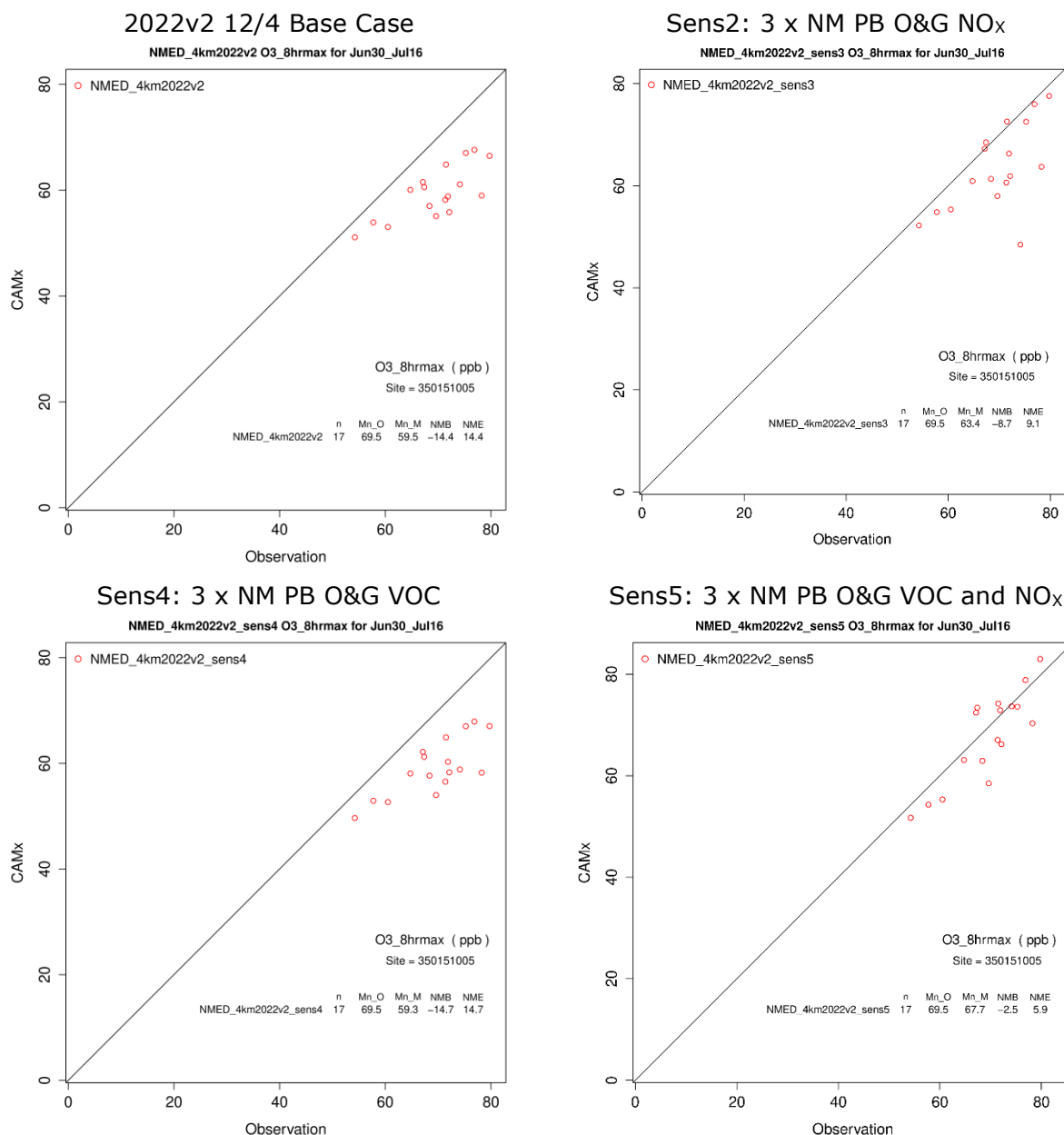


Figure ES-14. Scatter plots of predicted and observed MDA8 ozone concentrations and performance statistics at the Carlsbad City site for the CAMx 2022v2 12/4 km base case and the three New Mexico Permian Basin O&G emissions sensitivity tests.

The observed and predicted frequency distributions of hourly ethane and propane concentrations at Loving, New Mexico (LNM) are compared in Figure ES-15 for the CAMx 2022v2 base case and the Sens5 sensitivity test (3 x NM PB O&G NO_x and VOC emissions). The CAMx 2022v2 base case underestimates observed ethane and propane concentrations during the 20-day sensitivity test modeling period by approximately a factor of four and three, respectively. When NM PB O&G NO_x and VOC emissions are increased by a factor of three, agreement with the observations improves substantially, with ethane and propane concentrations underestimated by approximately a factor of 1.5 and 1.2, corresponding to an underestimation of about 50% and 20%, respectively.

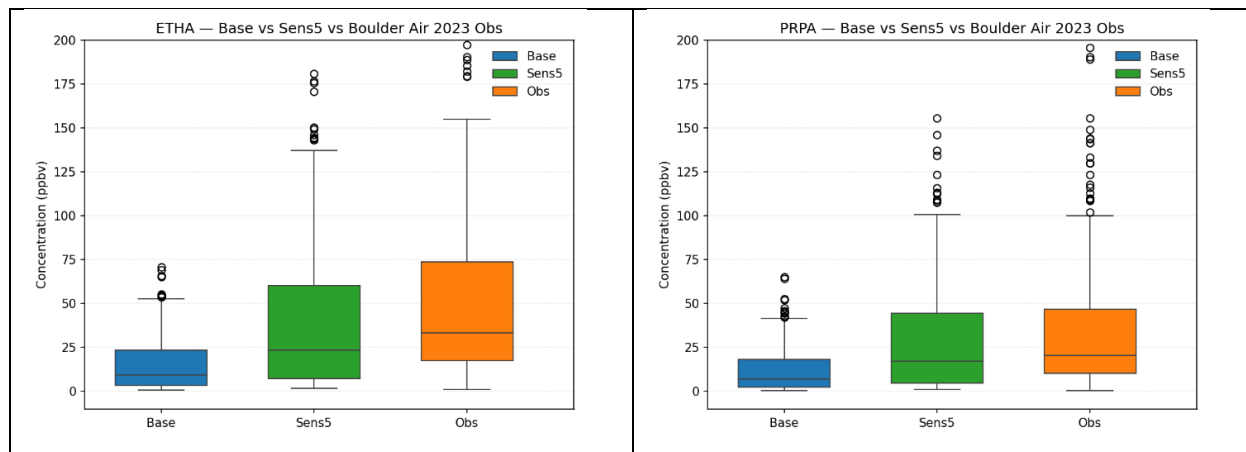


Figure ES-15. Comparison of the frequency distribution of the predicted and observed (orange) hourly Ethane (left) and Propane (right) concentrations at Lovin, New Mexico site for the CAMx 2022v2 base case (blue) and 3 times NM PB O&G NO_x and VOC emissions Sens5 sensitivity test.

In contrast, increasing NM PB O&G VOC emissions by a factor of three results in overestimation of benzene and ethene concentrations at LNM (Figure ES-16). This suggests that the understated O&G VOC emissions in the Permian Basin is likely not associated with gasoline combustion-related sources but may instead reflect other O&G VOC sources, such as emissions from venting, flashing and leakage. Increasing NM PB O&G NO_x emissions by a factor of three also leads to overestimation of observed NO and NO₂ concentrations at LNM, indicating that NM PB O&G NO_x emissions are not understated to the same degree as VOC emissions.

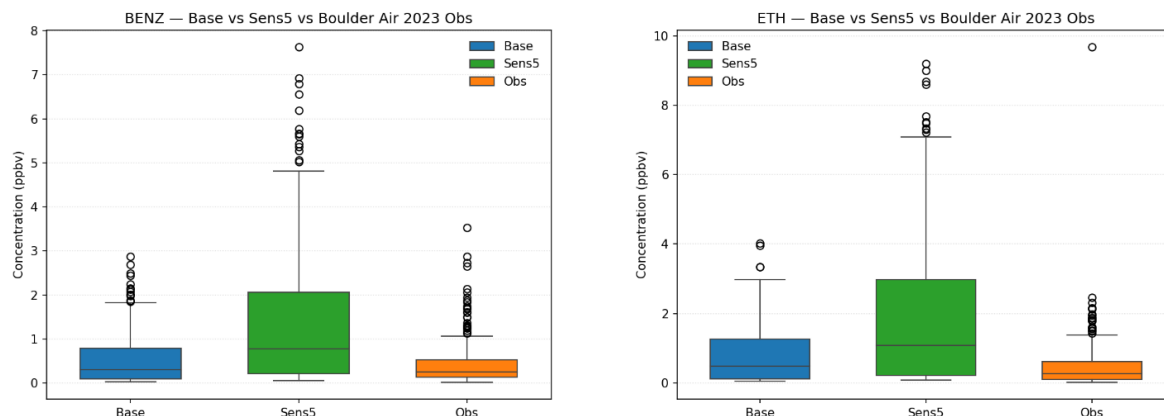


Figure ES-16. Comparison of the frequency distribution of the predicted and observed (orange) hourly Benzene (left) and Ethene (right) concentrations at Lovin, New Mexico site for the CAMx 2022v2 base case (blue) and 3 times NM PB O&G NO_x and VOC emissions Sens5 sensitivity test.

Scatter plots comparing predicted and observed MDA8 ozone concentrations for the 2022v2 4 km base case and the Sens7 sensitivity (3 x TX PB O&G NO_x and VOC emissions) are shown in Figure ES-17 for the Carlsbad City and Hobbs monitoring sites. Increasing Texas O&G emissions improves MDA8 ozone performance at both sites located within New Mexico. At Carlsbad City, the MDA8 ozone NMB underestimation is reduced from -14.4% to -8.5% , and the NME decreases from 14.4% to 8.7% . At Hobbs, the MDA8 ozone NMB is reduced from -13.9% to -7.3% , and the NME is reduced from 13.9% to 8.6% . Similar improvements in model performance are observed for hourly ozone concentrations at both sites, with lower NMB and NME values when Texas O&G emissions are increased.

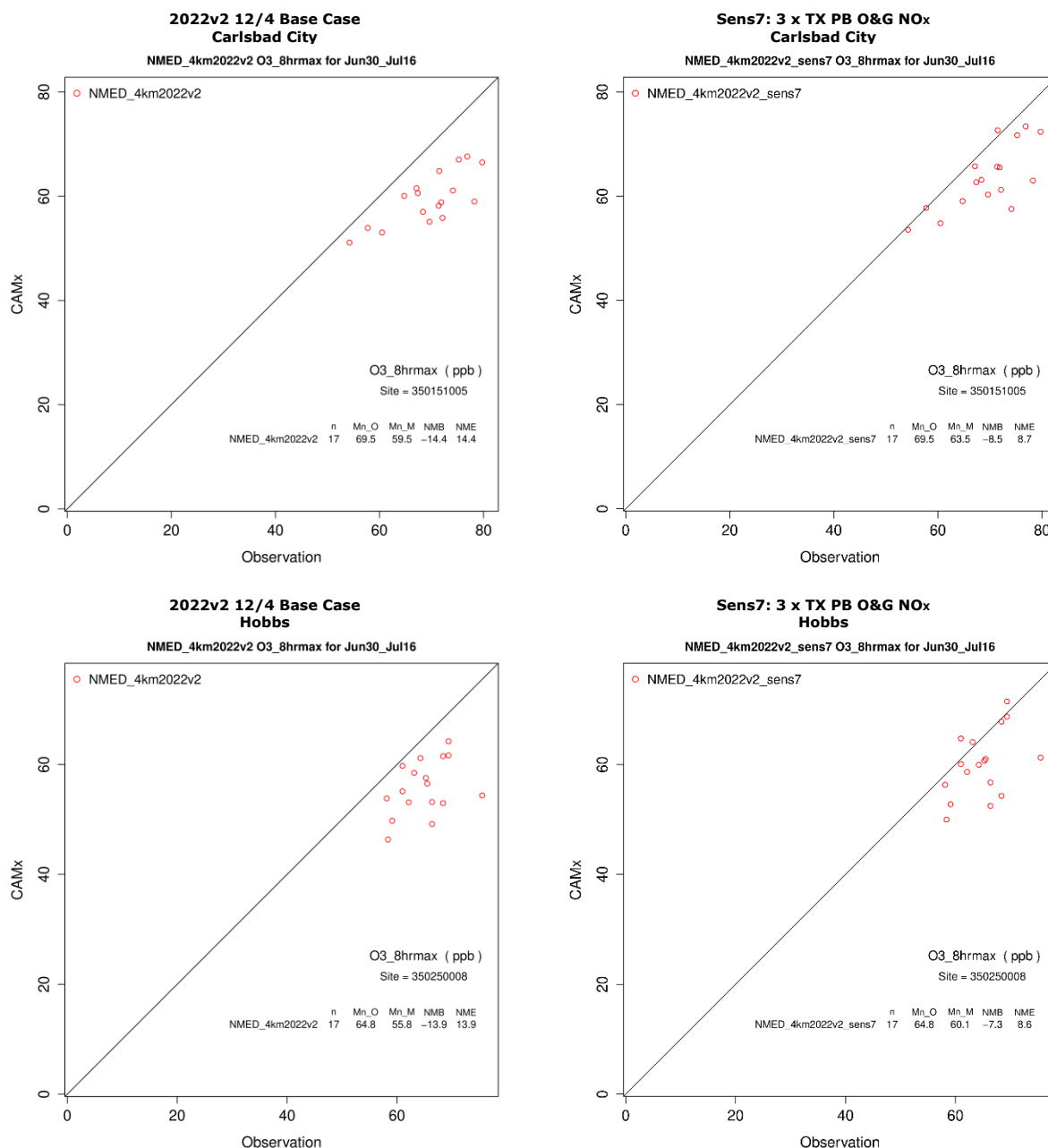


Figure ES-17. Scatter plots of predicted and observed MDA8 ozone concentrations and performance statistics at Carlsbad City (top) and Hobbs for the CAMx 2022v2 4 km base case (left) and Sens7 3 times Texas Permian Basin O&G NO_x and VOC emissions (right).

Figure ES-18 compares the frequency distributions of predicted and observed hourly ethane and propane concentrations at LNM, based on the 2023 HEI Boulder AIR monitoring data and the CAMx 2022v2 4 km base case and Sens7 sensitivity. Increasing TX PB O&G emissions reduces the CAMx underestimation of ethane concentrations at LNM from approximately a factor of four to a factor of three and reduces the underestimation of propane from approximately a factor of three to a factor of two during the 20-day sensitivity test period. These results indicate that missing Texas O&G VOC emissions in the Permian Basin likely contribute to the substantial CAMx ethane and propane underestimation bias at New Mexico Permian Basin ozone sites but are not the sole cause. Missing O&G VOC

emissions from the New Mexico portion of the Permian Basin in the 2022v2 emissions inventory are also likely contributing to the modeled underestimation of the observed ethane and propane concentrations.

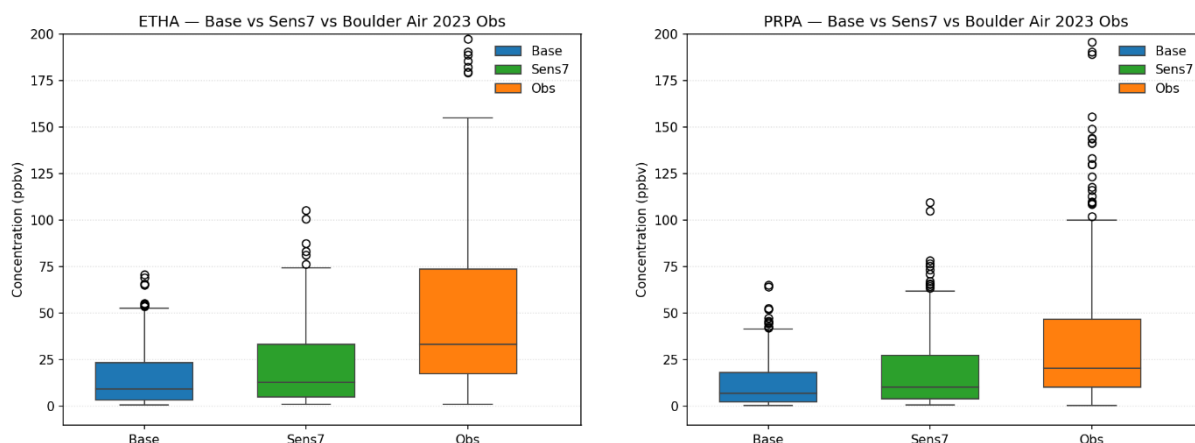


Figure ES-18. Comparison of the frequency distribution of the predicted and observed (orange) hourly Ethane (left) and Propane (right) concentrations at Loving, New Mexico site for the CAMx 2022v2 4 km base case (blue) and 3 times Texas Permian Basin O&G NO_x and VOC emissions Sens7 sensitivity test.

Summary and Conclusions of NMED CAMx 2022v2 12/4 km Base Case and Sensitivity Modeling

The Phase II New Mexico Environment Department (NMED) regional ozone source apportionment study developed a high resolution CAMx 2022v2 12/4 km modeling platform that when evaluated with available observations, resulted in slightly degraded ozone model performance compared with the Phase I CAMx 2022v1 12 km simulation. The Phase II base case modeling showed larger ozone underestimation bias compared to the Phase I modeling. The increase in underestimation bias was attributable to erroneously too high NO_x emissions from O&G drilling and fracking engines in the 2022v1 emissions inventory, which were corrected in the 2022v2 emissions platform.

The CAMx 2022v2 12/4 km base case simulation achieved the ozone bias performance criterion at nearly all monitoring sites in New Mexico and achieved the bias performance goal at numerous sites. On many days, the increase in modeled hourly ozone concentrations closely matched observed ozone in the morning and early afternoon but leveled off later in the afternoon, while observed ozone continued to increase. This behavior resulted in underestimation of observed afternoon highest hourly ozone concentrations. During these periods, modeled afternoon NO₂ concentrations frequently approached zero, whereas measured NO₂ concentrations were higher. This discrepancy may explain the continued observed hourly ozone rise in the afternoon when modeled ozone levels plateau. Several factors may contribute to the stalled modeled afternoon ozone increase associated with low modeled NO₂ concentrations, including excessive vertical mixing, understated NO_x and/or VOC emissions, insufficient ozone aloft available for entrainment as afternoon mixing heights increase (e.g., from upwind sources such as Mexico and boundary conditions), or other processes. Additionally, lower modeled NO₂ concentrations relative to observations may reflect measurement interference from other reactive nitrogen species (e.g., PAN, PNA, HONO, HNO₃) or observations near instrument detection limits.

The CAMx 2022v2 12/4 km base case results were evaluated against ozone precursor (VOC and NO_x) observations at two sites near Carlsbad City: Carlsbad Caverns and Loving, New Mexico (LNM). Observed ethane and propane concentrations, which primarily originate from O&G production in the Permian Basin, were underestimated by approximately a factor of five. Acetone, a solvent also used in O&G operations, was similarly underestimated. Other VOC species were underestimated to a lesser degree, and some showed reasonable agreement, such as benzene at LNM, which is a marker for gasoline combustion. These findings indicate that O&G VOC emissions in the Permian Basin are likely understated in the 2022v2 emissions inventory, consistent with reports of excess emissions from O&G sources in the region.

Meteorological sensitivity tests examining vertical mixing and cloud cover did not result in appreciable changes in ozone or NO₂ model performance. Emissions sensitivity tests that increased NO_x and/or VOC O&G emissions in either the New Mexico or Texas portions of the Permian Basin led to substantial improvements in ozone model performance at Permian Basin monitoring sites, with the best ozone performance achieved when both NO_x and VOC O&G emissions were increased. There are documented excess emissions from O&G sources in the Permian Basin that are not included in the 2022v2 emissions inventory, and likely additional unreported excess emissions are also likely present.

Overall, the CAMx 2022v2 12/4 km base case simulation demonstrates some skill in reproducing observed ozone concentrations in New Mexico, achieving peer-reviewed ozone bias and error performance criteria at most sites and performance goals at many sites, despite an underestimation bias that is most pronounced in the Permian Basin. It is recommended that the 2022 and 2032 ozone source apportionment modeling proceed using the CAMx 2022v2 12/4 km modeling platform, considering the likelihood that O&G emissions in the Permian Basin are understated in the 2022v2 emissions inventory when interpreting the modeling results.

1.0 INTRODUCTION

In 2015, EPA promulgated a new 70 ppb ozone National Ambient Air Quality Standard (NAAQS). The new ozone NAAQS uses an ozone Design Value (DV), defined as the three-year average of the fourth highest Maximum Daily Average 8-hour (MDA8) ozone concentration, as the metric for comparison with the 70 ppb threshold. EPA designated ozone nonattainment areas (NAA) under the 2015 ozone NAAQS using the 2014-2016 ozone DVs on August 3, 2018.

1.1 Ozone Concentrations in the Permian Basin

The Permian Basin is currently the most active producing oil and gas (O&G) basin in the U.S. The Permian Basin covers areas that include southeast New Mexico (NM) and western Texas (TX). In New Mexico, most of the Permian Basin O&G production is within Eddy and Lea Counties. In 2022, three ozone monitoring sites were operating in Eddy and Lea Counties:

- Carlsbad Caverns (35-015-0010), 727 Carlsbad Caverns Highway, Eddy County.
- Carlsbad City (35-015-1005), 2811 Holland St., Carlsbad, Eddy County.
- Hobbs (35-25-0008), 2320 N. Jefferson St., Hobbs, Lea County.

Figure 1-1 displays the ozone DV trends at the three monitoring sites in Eddy and Lea Counties for the period of 2005 to 2024. The currently active Carlsbad Caverns monitor has been in operation since 2019 and did not report a 2014-2016 ozone DV when NAAs were designated. The Carlsbad City and Hobbs 2014-2016 ozone DVs were, respectively, 67 and 66 ppb, which were below the 70 ppb NAAQS resulting in Eddy and Lea Counties being designated as attainment areas under the 2015 ozone NAAQS. However, since then there has been increases in ozone at the two sites such that by 2023 the Carlsbad City and Hobbs monitoring sites had ozone DVs of, respectively, 78 and 71 ppb that violate the 2015 ozone NAAQS. In fact, the Carlsbad City site in Eddy County has been violating the 70 ppb 2015 ozone NAAQS since 2018 and has been violating the 75 ppb 2008 ozone NAAQS since 2019. Although the Eddy County Carlsbad Caverns monitor only has three valid years of ozone DVs, it confirms the high ozone trends showed at the nearby Carlsbad City site as both had nearly identical ozone DVs for 2022-2024.

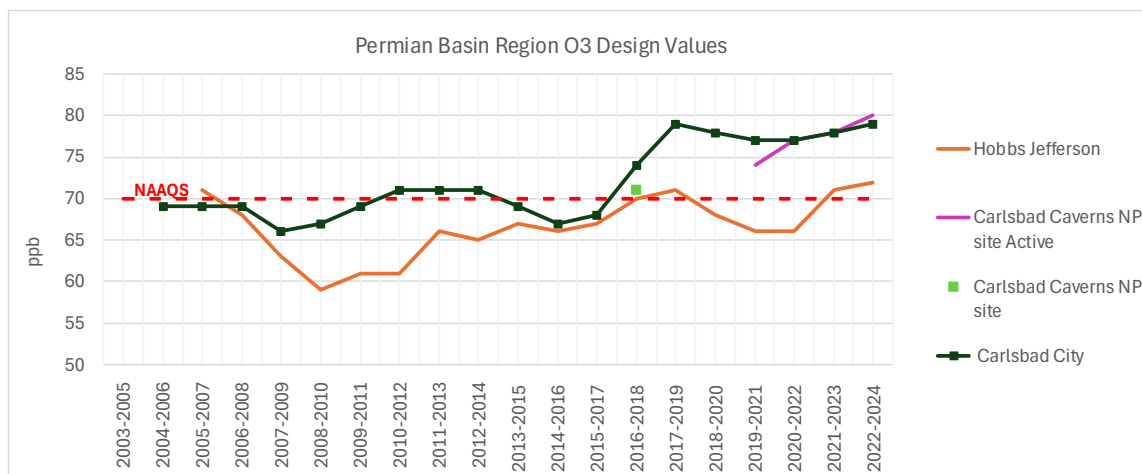


Figure 1-1. Ozone Design Value trends for 2005-2024 at the Carlsbad Caverns (350150010) and Carlsbad City (350151005) monitors in Eddy County and the Hobbs (350250008) monitor in Lea County.

1.2 Purpose

The New Mexico Environment Department (NMED), Air Quality Bureau (AQB), seeks to understand the causes of, and potential mitigation strategies for, elevated ozone concentrations within the New Mexico portion of the Permian Basin. To support this effort, NMED/AQB contracted Ramboll to conduct ozone source apportionment modeling to estimate the contributions of emissions from New Mexico and other regions to ozone concentrations in New Mexico, with a particular focus on the contribution of oil and gas emissions to ozone levels in the New Mexico portion of the Permian Basin. This work is organized into two phases:

- Phase I (FY2025):** The first phase was conducted between mid-April and June 30, 2025 and used the Comprehensive Air-quality Model with extensions (CAMx) photochemical grid model (PGM) with the existing EPA CAMx 2022v1 12 km modeling platform. CAMx 12 km simulations were conducted for a 2022v1 base case and a 2026v1 future year, the latter invoking ozone source apportionment. Phase I also conducted summer 2022 4 km high resolution WRF meteorological modeling that was used to develop a higher resolution CAMx 2022 4 km modeling platform for use in Phase II. Phase I produced several Excel Dashboards that display the contributions of emissions from Source Categories and Source Regions to MDA8 ozone concentrations at monitoring sites in New Mexico and adjacent regions and three main reports:
 - 2026 Ozone Source Apportionment Modeling for the Permian Basin using the 2022v1 Modeling Platform – 2022v1 Model Evaluation and 2026v1 Source Apportionment Results (Ramboll, 2025b).
 - WRF 2022 4 km Modeling for New Mexico and Model Performance Evaluation (Ramboll, 2025c).
 - Preliminary CAMx 2022 4 km Ozone Model Performance Evaluation Using New WRF 2022 4 km Meteorological Inputs (Ramboll, 2025d).

- **Phase II (FY2026):** Phase II started in July 2025 and ends in June 2026 and developed an enhanced CAMx summer 2022 12/4 km modeling platform with a higher resolution 4 km grid covering New Mexico and adjacent areas. Emissions for the CAMx 2022v2 12/4 km platform were based on EPA's 2022v2 emissions inventory. CAMx 2022v2 12/4 km modeling platform ozone source apportionment modeling will be conducted using the 2022 and 2032 emission years and documented in future reports and dashboards. To date, Phase II has produced two reports:
 - Conceptual Model of Ozone Formation in New Mexico with a Focus on the Permian Basin (Ramboll, 2026a).
 - Ozone Source Apportionment Modeling for the New Mexico Environmental Department -- CAMx 2022v2 4 km Base Case Model Performance Evaluation (this report).

1.3 Conceptual Model of Ozone Formation in New Mexico

At the outset of the NMED Phase II ozone source apportionment modeling study, Ramboll prepared a report dated January 2026 describing the Conceptual Model of ozone formation in New Mexico, with particular emphasis on the Permian Basin. Key findings from the Conceptual Model report are summarized below, with additional detail provided in Ramboll (2026a).

Development of the Conceptual Model included analyses of ozone and precursor trends based on surface ambient measurements and satellite observations, emissions trends, relationships between elevated ozone and meteorology, weekend ozone behavior as an indicator of NO_x/VOC sensitivity, climate anomalies, impacts of wildfire smoke on ozone, prior ozone modeling studies, special field study measurements conducted in the Permian Basin, and other supporting analyses.

Factors influencing ozone pollution vary geographically across New Mexico. Analyses of ambient ozone trends and satellite-based trends in ozone precursors show distinct regional patterns. Accordingly, the Conceptual Model was organized by region, with a focus on the Permian Basin. In the New Mexico portion of the Permian Basin, observed ozone concentrations have increased by at least five ppb over the past two decades. This increase has led to a substantial rise in ozone exceedance days at the Carlsbad City monitor, from fewer than six days per year during 2007–2016 to more than seventeen days per year during 2018–2024 (excluding 2020). Ambient surface NO₂ concentrations at Carlsbad City, an important ozone precursor, have increased rapidly since 2017, a trend that is supported by satellite NO₂ observations.

Figure 1-2 presents trends in Carlsbad City ozone design values alongside Permian Basin oil and gas production¹ and New Mexico oil and gas ozone precursor emissions (NO_x and VOC)². Production estimates and precursor emissions are normalized to 2017 values, such that 2017 corresponds to 100%, earlier years are generally lower, and subsequent years are generally higher. The year 2017 represents a pivotal point in the rapid increase of oil and gas production in the Permian Basin, and Figure 1-2 illustrates the corresponding increases

¹ From U.S. Energy Information Administration: Crude Oil Production: Permian million barrels per day and Marketed (Wet) Natural Gas Production: Permian billion cubic feet per day

² 2009 through 2020 estimates from EPA Trends, 2022 estimate from EMP OG emissions, 2021 interpolated between 2020 and 2022.

in New Mexico ozone precursor emissions and ozone design values at the Carlsbad City monitor, which is located near major oil and gas development areas. Taken together, these trends provide circumstantial evidence that increasing ozone concentrations in the New Mexico portion of the Permian Basin are associated with increased oil and gas production.

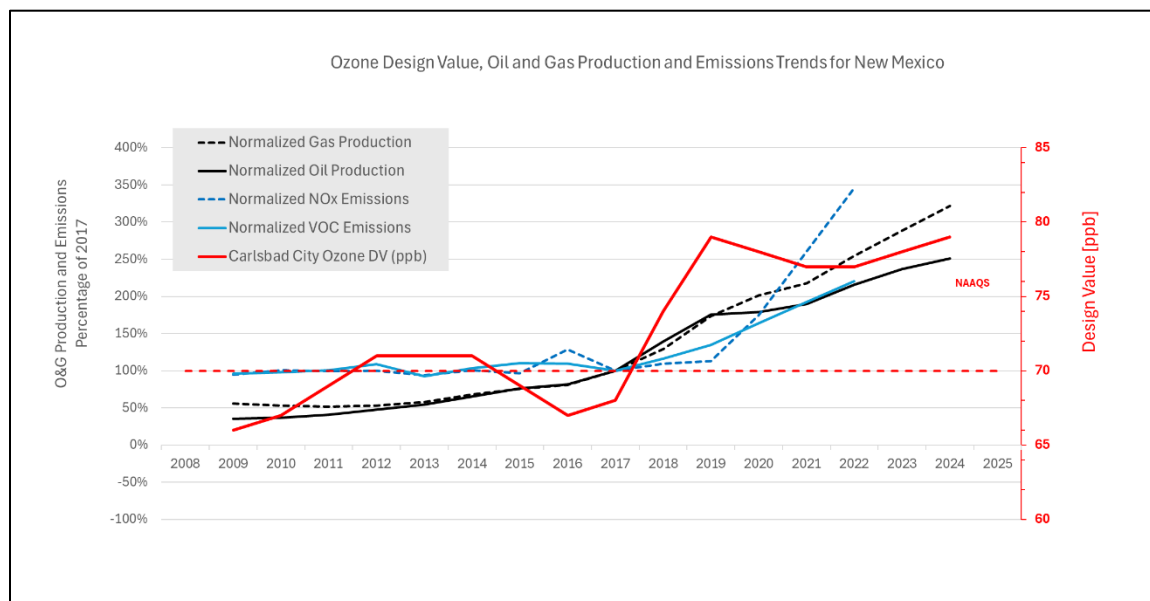


Figure 1-2. Trends in Carlsbad City ozone Design Value (red scaled by right y-axis) and Permian Basin O&G production and New Mexico O&G ozone precursor emissions (left axis normalized to 100% in 2017).

Per the Bureau of Land Management Carlsbad Field Office oil and gas emissions projections are expected to remain elevated through 2032 across all evaluated scenarios (BLM, 2024). Previous photochemical grid modeling studies for the Permian Basin region have underestimated peak ozone concentrations. While the specific causes of this underestimation are not fully understood, they are likely attributable in part to understated oil and gas (O&G) emissions. In recent years, air quality measurement field campaigns in the region have collected additional VOC and NO_x observations, which were used to support more detailed model performance evaluations for the NMED Phase II modeling effort.

Across New Mexico, all ozone monitoring sites share the common characteristic that transported ozone from outside New Mexico contributes substantially to observed concentrations on most days. The highest local ozone formation typically occurs during hot summer conditions associated with high-pressure systems or ridge that suppress synoptic westerly winds without excessive precipitation from the summer monsoon. In southern New Mexico, including Doña Ana County and surrounding areas, peak ozone concentrations commonly occur during transport from the south, with contributions from El Paso, Texas; Ciudad Juárez, Mexico; and other international sources. In southeastern New Mexico, including Eddy and Lea Counties, ozone concentrations reflect contributions from Permian Basin O&G emissions superimposed on substantial background transport. In northwestern New Mexico, ozone levels are influenced by O&G emissions from the San Juan Basin, local electric generating unit emissions, and transported ozone. Ozone concentrations at sites in Bernalillo County and adjacent areas are affected by emissions from Albuquerque, the state's largest metropolitan area, in addition to transported contributions.

1.4 Approach Overview

Below we provide a summary of the Phase II CAMx 12/4 km modeling approach.

1.4.1 Episode Selection

The summer 2022 was selected for the NMED ozone source apportionment modeling due to the availability of 2022 emissions and EPA's 2022 modeling platform, and presence of elevated ozone concentrations in the Permian Basin.

Table 1-1 lists the observed MDA8 ozone concentrations during 2022 that exceed the 70 ppb 2015 ozone NAAQS at the three New Mexico sites in the Permian Basin. The MDA8 ozone concentrations in Table 1-1 are colored red if they exceed the 75 ppb 2008 ozone NAAQS, yellow if they are between 70 and 75 ppb, and green if they are between 68 ppb and 70 ppb. In 2022, there were 28 days that exceed the 70 ppb 2015 ozone NAAQS and 11 days that exceed the 75 ppb 2015 ozone NAAQS for at least one of the three monitoring sites in the New Mexico portion of the Permian Basin. 2022 was a high wildfire year in New Mexico; New Mexico had the largest wildfire in the contiguous U.S. in 2022. The last column in Table 1-1 lists the density of smoke in the Permian Basin on each 2022 ozone exceedance days based on the NOAA Hazard Mapping System ([HMS](#)) Fire and Smoke Product.

The CAMx 2022v2 12/4 base case simulations were run for the period of May 1 through October 15, 2022, that encompasses almost all the 2022 ozone exceedance days in the Permian Basin. May 1-10, 2022 was used as a model spin-up period.

1.4.2 Domain Selection

The NMED CAMx ozone source apportionment modeling used a 12/4 km two-way nested domain structure with the 12 km domain being the same 12US2 continental U.S. domain as used in EPA's modeling platforms and in the Phase I CAMx 2022v1 12 km modeling. The 4 km grid resolution domain covered all of New Mexico and portions of adjacent states stretching far enough into northwest Texas to include all the Permian Basin O&G activity. Figure 1-3 displays the CAMx 12/4 km domains.

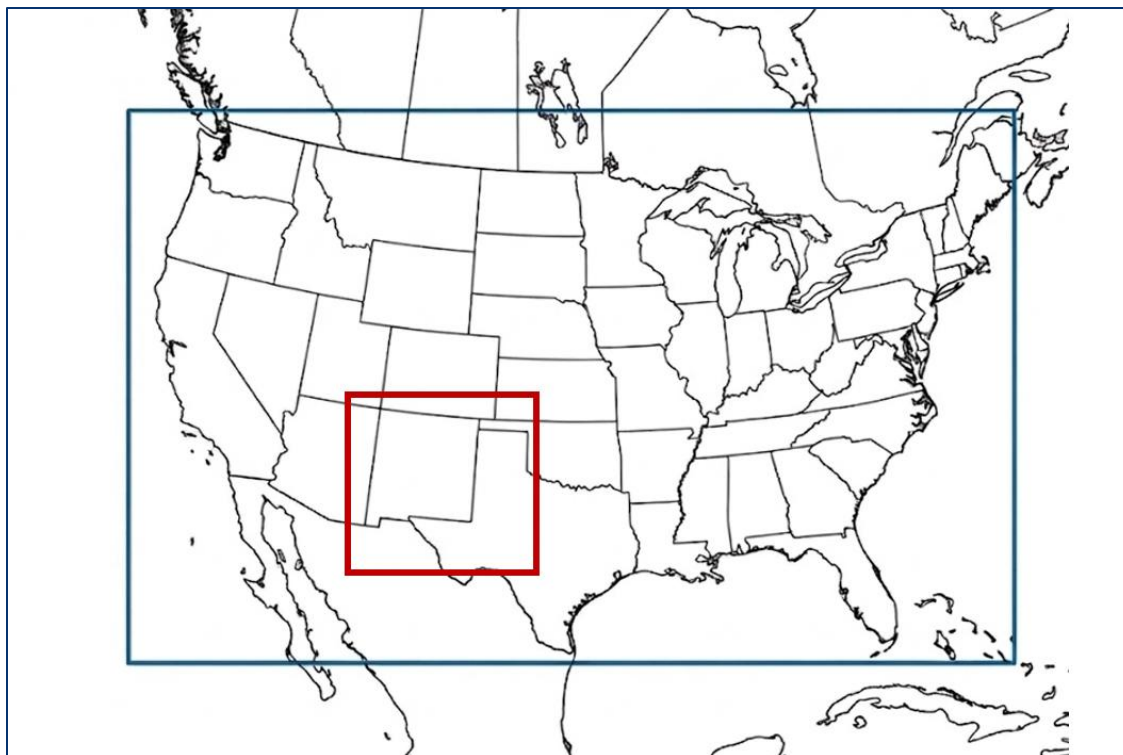


Figure 1-3. CAMx 12 km CONUS (blue) and 4 km New Mexico (red) modeling domains used in the CAMx 2022v2 12/4 km modeling platform.

1.4.3 EMISSIONS Inputs and the EMP 2022v2 Modeling Platform

The CAMx 2022v2 12/4 km modeling platform base case emissions were based on the National Emissions Collaborative ([NEC](#)) [2022v2 Emissions Modeling Platform](#) (EMP). The 2022v2 EMP is documented in the 2022v2 emissions inventory technical support document (TSD; [EPA, 2025](#)). EPA processed the 2022v2 inventories to generate CAMx and CMAQ model-ready emission inputs for the 36 km North American (not shown) and 12 km Continental United States (CONUS) domains (Figure 1-3). The EMP 2022v2 model-ready emissions for the 36/12 km domains were downloaded via [EPA's Open Data Program site](#) and used in the Phase II CAMx 12/4 km modeling.

The 2022v2 emissions were processed using SMOKE to generate 4 km domain 2022 hourly gridded speciated CAMx emissions inputs for the 4 km New Mexico domain. Chapter 3 provides details on the SMOKE emissions modeling to generate CAMx 2022v2 emission inputs for the New Mexico 4 km domain.

Table 1-1. 2022 observed MDA8 ozone at the three New Mexico monitoring sites in the Permian Basin on days when any one of the sites measures an exceedance of the 70 ppb 2015 ozone NAAQS. The HMS smoke density over the Permian Basin is also indicated in the last column.

Local Name:	Carlsbad Caverns	Carlsbad City	Hobbs	HMS
County:	Eddy	Eddy	Lea	Smoke
Site ID:	35-015-0010	35-015-1005	35-025-0008	Density
4/30/2022	70	73	53	Light-Medium
5/3/2022	71	72	56	None
5/14/2022	64	71	63	Light
5/15/2022	68	71	50	Light-Medium
5/16/2022	71	79	55	Light-Medium
5/26/2022	71	73	70	Light-Medium
5/27/2022	60	74	59	Medium-Heavy
5/30/2022	72	72	72	Light
6/4/2022	51	59	74	Light
6/9/2022	72	71	52	Light
6/10/2022	71	69	54	Light
6/15/2022	68	69	50	Light
6/29/2022	81	77	75	Light
6/30/2022	69	71	69	Light
7/1/2022	78	76	69	Light
7/2/2022	72	75	68	Light
7/8/2022	85	72	66	None
7/9/2022	71	71	62	Light
7/10/2022	71	67	61	Light
7/11/2022	83	79	65	Light
7/13/2022	71	74	66	Light
7/14/2022	71	71	68	Light
7/15/2022	76	78	75	Light
8/12/2022	86	84	70	Light
8/13/2022	84	83	67	Light
8/14/2022	78	80	62	Light
8/24/2022	71	66	56	None
9/8/2022	83	NA	68	Light
10/13/2022	65	76	64	None
#Exceedances	21	23	4	

1.4.4 2022 12/4 km Meteorological Inputs

The WRF meteorological model was run for the summer of 2022 using 36/12/4 km nested domains. The WRF 2022 12/4 km output was processed to generate CAMx 12/4 km meteorological inputs. Chapter 2 summarizes the WRF 2022 meteorological modeling with details provided in the WRF 2022 application/evaluation report (Ramboll, 2025c).

1.4.5 CAMx 2022v2 12/4 km Base Case Modeling

A CAMx 2022v2 12/4 km base case simulation was performed for the period of May 1 through October 15, 2022. A preliminary ozone model performance evaluation was conducted and found that the Phase II CAMx 2022v2 12/4 km ozone performance was degraded compared to the Phase I CAMx 2022v1 12 km simulation. The CAMx 2022v2 12/4 km simulation had a larger ozone underestimation bias than CAMx 2022v1 12 km simulation, especially at sites in the Permian Basin portion of New Mexico. The cause of the degradation of the ozone underestimation bias in the CAMx 2022v2 12/4 km simulation was mainly due to a decrease in the New Mexico 2022v2 Non-Point O&G NO_x emissions by 40% between the 2022v1 and 2022v2 emission inventories. The 2022v2 EITSD (EPA, 2025) notes that an error was corrected in the O&G drill rig and fracking engine emissions that reduced their NO_x emissions by 74% between the 2022v1 and 2022v2 emission inventories, which is believed to be the cause of the larger ozone underestimation bias in the Phase II CAMx 2022v2 12/4 km simulation compared to the Phase I CAMx 2022v1 12 km simulation.

1.4.6 CAMx 2022v2 12/4 km Model Performance Evaluation

The CAMx 2022v2 12/4 km base case simulation results were evaluated against concurrent surface ozone and NO_x observations. The ozone and NO_x model performance evaluation is presented in Chapter 4. The CAMx 2022v2 12/4 km base case modeling results were also compared against special field study ozone precursor (VOC and NO_x) measurements collected at Carlsbad Cavern National Park in 2021 and Loving, New Mexico in 2023. The VOC evaluation is presented in Chapter 5. The CAMx 2022v2 12/4 km base case was also compared against satellite data that is presented in Chapter 6.

1.4.7 CAMx 2022v2 12/4 km Sensitivity Modeling

CAMx 2022v2 12/4 km sensitivity tests were performed for meteorology (i.e., vertical mixing and cloud cover) and O&G emissions in the Permian Basin that is discussed in Chapter 7.

2.0 DEVELOPMENT OF 4 KM METEOROLOGICAL INPUTS FOR THE CAMX 2022V2 12/4 KM MODELING PLATFORM

During Phase I of the NMED ozone source apportionment modeling study, Ramboll conducted meteorological modeling for the 2022 summer period using the Weather Research and Forecasting (WRF) meteorological model, Advanced Research WRF (ARW) core. WRF was used to provide the 2022 12/4 km meteorological inputs required by CAMx. WRF is a mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs (Skamarock et al., 2019). Details on the WRF 2022 12/4 km application and model performance evaluation are provided in the Phase I WRF modeling report (Ramboll, 2025c) with a summary presented below.

2.1 WRF 2022 12/4 km Model Configuration

Meteorological inputs for the New Mexico CAMx application were developed from a summer 2022 WRF simulation on a 4 km grid covering New Mexico, west Texas, small portions of surrounding states including Colorado, Oklahoma, Kansas, Arizona and Utah and small portion of Mexico (Figure 2-1). The 4 km WRF grid was nested within a 12 km grid resolution domain covering the continental U.S. (CONUS) equivalent to that used by EPA to develop meteorological inputs for the 2022 12US2 modeling platform (MP). The 4 km grid aligns with the 12US2 grid with sufficient extent to fully include the 4 km CAMx modeling grid while maintaining the 5-grid point buffer recommended in EPA's photochemical modeling guidance (EPA, 2018). The WRF vertical grid structure used 35 vertical layers that was identical to the EPA 2022 MP (Table 2-1). Ramboll applied most of the same science configuration, inputs, and application methodology as in the NMED Ozone Assessment Initiative (OAI) modeling (Ramboll and WESTAR, 2021a,b). We changed the source of boundary conditions and analyses fields for data assimilation to the European Center for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) as in more recent years we have found superior WRF performance using this dataset in other western U.S. applications, especially for atmospheric moisture. We also used the WRF default MODIS-based landcover datasets to define terrestrial surface conditions. Details on the WRF configuration are listed in Table 2-2.

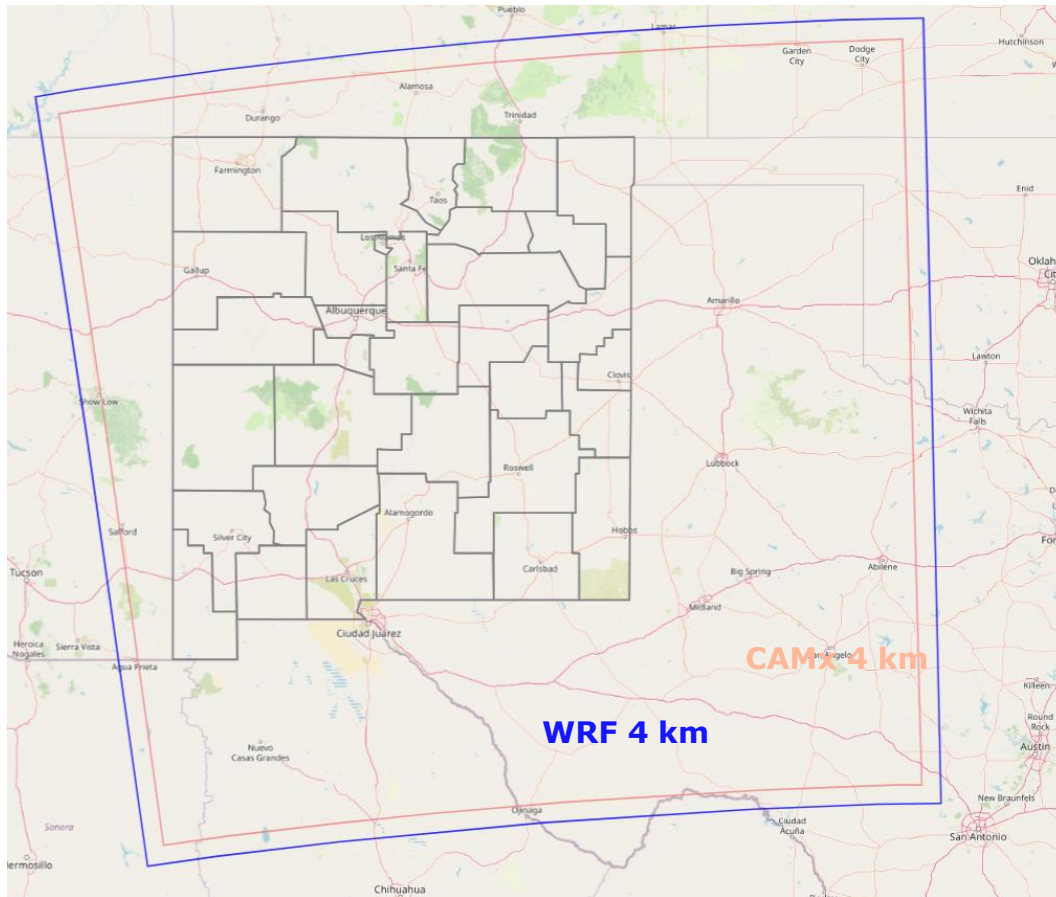


Figure 2-1. Extent of the 4 km WRF domain covering New Mexico, Western Texas and portions of the surrounding states. The domain meshes with the 2022 EMP 12US2 grid.

Table 2-1. WRF vertical grid structure for the EPA 2022 MP and the current NMED CAMx 2022v2 12/4 km model application.

Layer	eta	Pressure (mb)	Height (m)
35	0.00	50	20576
34	0.05	98	16297
33	0.10	146	13766
32	0.15	194	11961
31	0.20	243	10555
30	0.25	291	9372
29	0.30	339	8337
28	0.35	387	7416
27	0.40	435	6583
26	0.45	483	5822
25	0.50	532	5120
24	0.55	580	4467
23	0.60	628	3857
22	0.65	676	3284
21	0.70	724	2743
20	0.74	763	2331
19	0.77	792	2033
18	0.80	821	1744
17	0.82	840	1555
16	0.84	859	1370
15	0.86	878	1188
14	0.88	898	1010
13	0.90	917	835
12	0.91	927	748
11	0.92	936	662
10	0.93	946	577
9	0.94	955	493
8	0.95	965	409
7	0.96	975	326
6	0.97	984	243
5	0.98	994	162
4	0.985	999	121
3	0.990	1004	81
2	0.995	1008	40
1	0.9975	1011	20
0	1.0000	1013	0

Table 2-2. WRF configuration for the NMED WRF 2022 12/4 km meteorological modeling.

Model Component	Specifications and Datasets
Model Code	WRF v4.6.1
Modeling Period	May 1 – October 16, 2022
Application	Chain of 5-day segments
<u>Horizontal Grid</u>	
Map Projection	Lambert Conic Conformal
Projection Center	-97°N / 40°W
True Latitudes	33°N and 45°N
Grid Points	255 x 237
SW Corner coordinate	-1212, -1140
NE Corner coordinate	-192, -192
<u>Vertical Grid</u>	
Layers	35, up to 50 hPa (~20 km AGL)
Coordinate	Default hybrid eta coordinate
Initial/Boundary Conditions	ECMWF Reanalysis v5 (ERA5)
Nudging Analyses	ECMWF Reanalysis v5 (ERA5)
Landcover	Moderate Resolution Imaging Spectroradiometer-International Geosphere-Biosphere Programme (MODIS-IGBP)
Sea Surface Temperature	Fleet Numerical Meteorology and Oceanography Center Sea Surface Temperatures (FNMOC SST)
Lightning Data	None
<u>Physics</u>	
Short/Longwave Radiation	Rapid Radiation Transfer Model - Global (RRTMG)
Resolved Clouds	Thompson microphysics
Surface Model	Noah
Surface Layer	MM5 Similarity
Boundary Layer	Yonsei University (YSU)
Sub-grid Clouds	Multiscale Kain-Fritsch
<u>Data Assimilation/Nudging</u>	
3-D Wind	$3 \times 10^{-4} \text{ s}^{-1}$ (all layers) 12-km grid only
3-D Temperature	$3 \times 10^{-4} \text{ s}^{-1}$ (above PBL) 12-km grid only
3-D Moisture	$1 \times 10^{-5} \text{ s}^{-1}$ (above PBL) 12-km grid only
Surface Analysis Nudging	None
Observation Nudging	None
Soil Nudging	None
Lightning Assimilation	None

Performance statistics of bias and error were calculated and compared against Simple and Complex performance benchmarks that are routinely used to help assess meteorological model performance. Soccer Plots that display bias versus error statistics against the Simple and Complex performance benchmarks are used to assess WRF monthly performance for surface meteorological variables. Below we present the WRF Soccer Plots performance across all sites in the 4 km domain and across the 5 sites in the New Mexico portion of the Permian Basin (green symbols in Figure 2-2) with the other subregional WRF performance evaluations available in Ramboll (2025c).

Figure 2-3 shows excellent performance for wind speeds in all 6 months across the 4 km modeling domain, with near zero bias well within Simple benchmark ($\leq \pm 0.5$ m/s) and error (RMSE) within Simple benchmark (≤ 2.0 m/s) for three months (Aug-Oct) and within Complex benchmarks (≤ 2.5 m/s) for all months (May-Oct), with May being exactly at the Complex benchmark of 2.5 m/s. Wind direction performance shows that all 6 months also meet the Simple/Complex benchmark for bias ($\leq \pm 10$ degrees), and all months are within the Complex error benchmark (≤ 55 degrees). Temperature bias is quite good, ranging within ± 1.1 K, with slight over predictions in most months and minimal under prediction in May. Temperature error is outstanding, remaining within the Simple benchmark (≤ 2.0 K) in all 6 months. Water vapor mixing ratio (humidity) performance shows a negative bias for the first 3 months and positive bias for the last 3 months, and all 6 months meet the Simple benchmark for bias ($\leq \pm 0.8$ g/kg). All months are within the Simple/Complex benchmark for error (≤ 2.0 g/kg).

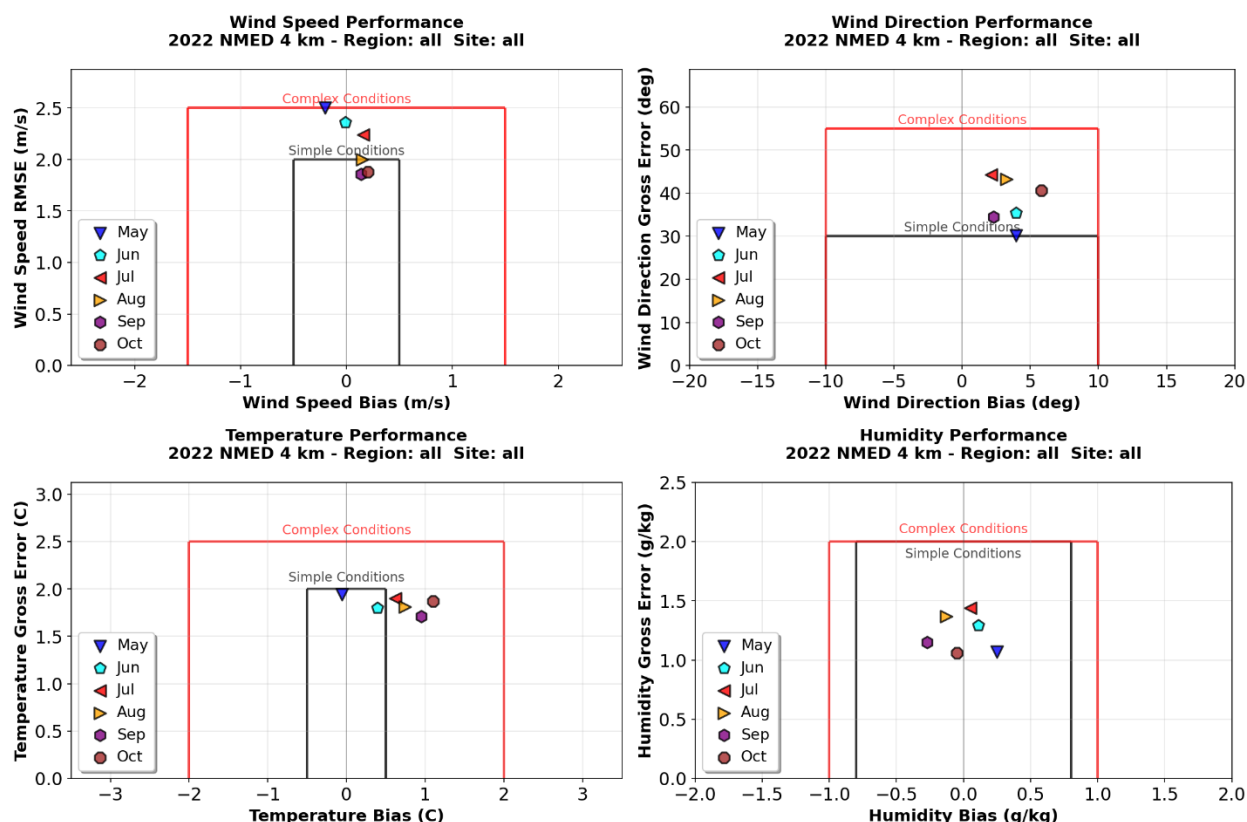


Figure 2-3. Soccer plots comparing WRF model performance statistical metrics against simple and complex benchmarks averaged over all 75 sites within the CAMx New Mexico 4 km modeling domain: 10-m wind speed (top left), 10-m wind direction (top right), 2-m temperature (bottom left) and 2-m water vapor mixing ratio (bottom right). Symbols refer to each of the six simulation months in 2022.

Figure 2-4 displays Soccer Plots model performance for the New Mexico portion of the Permian Basin and shows excellent performance for wind speeds across all 6 months, with bias near zero, well within the Simple benchmark ($\leq \pm 0.5$ m/s) and RMSE within the Simple benchmark (≤ 2.0 m/s) for three months (Aug-Oct) and between the Simple and Complex benchmarks (≤ 2.5 m/s) for the other three months (May-Jul). Wind direction performance shows a positive bias, with 5 months meeting the Simple/Complex benchmark ($\leq \pm 10$ degrees) and October slightly exceeding it at 11.6 degrees, Wind direction error is within the complex benchmark (≤ 55 degrees) for all months. Temperature bias is within ± 1.0 K, with three months meeting the Simple benchmark ($\leq \pm 0.5$ K), being positive in three months and negative in the other three. Temperature error is within the Simple benchmark (≤ 2.0 K) for all months except for May, when it falls within the Complex benchmark (≤ 2.5 K). Water vapor mixing ratio performance shows a negative bias for all 6 months with 4 months meeting the Simple benchmark ($\leq \pm 0.8$ g/kg), one meeting the Complex benchmark ($\leq \pm 1.0$ g/kg), and one outside the Complex benchmark. All months are within the Simple/Complex benchmark for error (≤ 2.0 g/kg).

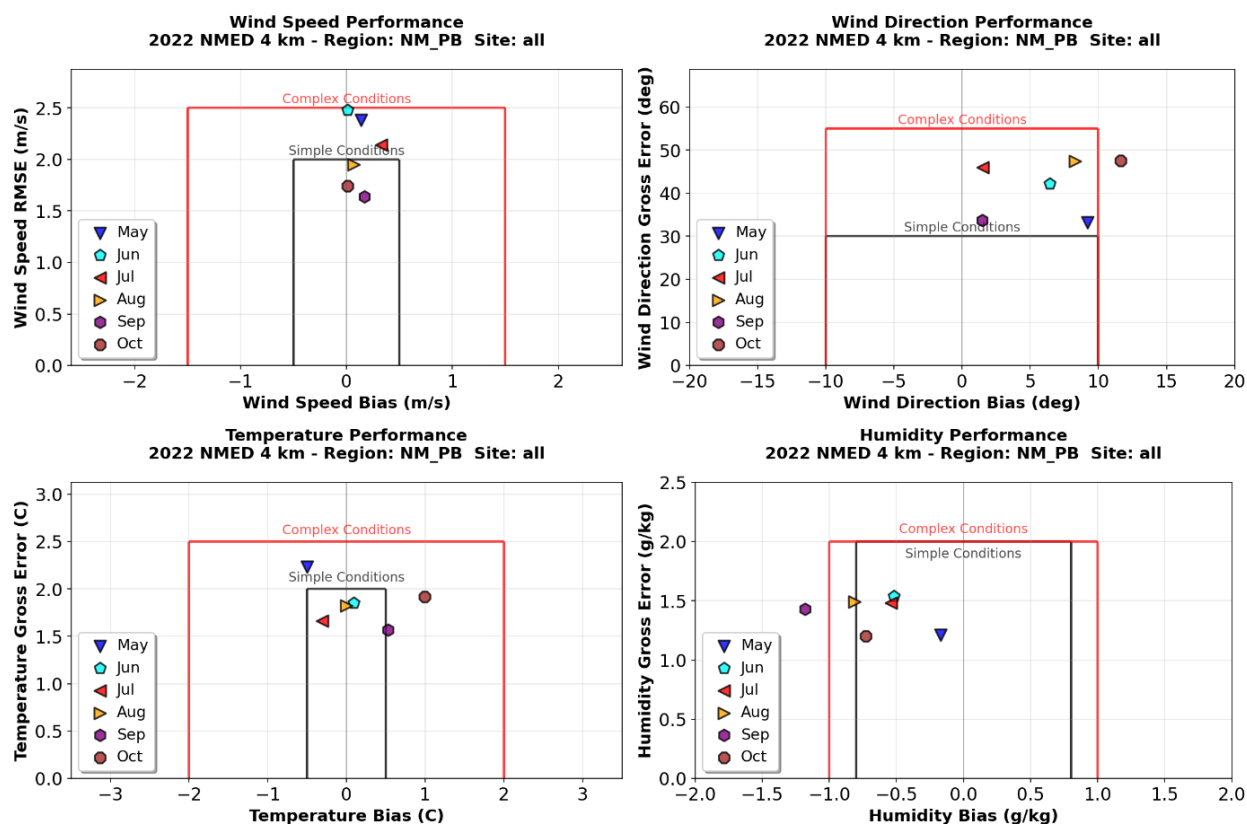


Figure 2-4. Soccer plots comparing WRF model performance statistical metrics against simple and complex benchmarks averaged over the 5 NM_PB sites: 10-m wind speed (top left), 10-m wind direction (top right), 2-m temperature (bottom left) and 2-m water vapor mixing ratio (bottom right). Symbols refer to each of the six simulation months in 2022.

2.2.2 Qualitative Precipitation Model Performance

WRF estimated monthly precipitation patterns in the New Mexico 4 km domain were compared against [PRISM](#) analyses, as well as daily precipitation patterns on ozone exceedance days when either WRF or observations reported significant precipitation in the region. The PRISM precipitation interpolation scheme works better for organized synoptic weather systems than for the stochastic summer convective showers, which tend to be spotty and intermittent, especially in areas with sparse rain gauge data. This is the primary reason why the analysis of precipitation performance remains a qualitative comparison of spatial patterns and magnitudes.

Figure 2-5 to Figure 2-7 compare PRISM (left) and simulated (right) total precipitation patterns during June, July and August 2022. WRF generally simulated the precipitation patterns well on the monthly scale across the domain, although in various places the PRISM rain exceeded the WRF total and extent, such as far western Texas during all months except August. On many of the high ozone days, WRF succeeded in replicating the overall patterns but fell short in the totals or had regions lacking any simulated rain. Neither PRISM nor WRF can be expected to replicate the stochastic nature of actual summer convective rainfall in time and space, as illustrated by the different patterns of the heaviest areas of precipitation in each month. It is therefore perhaps more desirable for the meteorological simulation to tend toward a drier environment, as spurious convective precipitation events can drive large

local errors in wind and temperature patterns. Such meteorological errors often lead to poor replication of ozone patterns during those times.

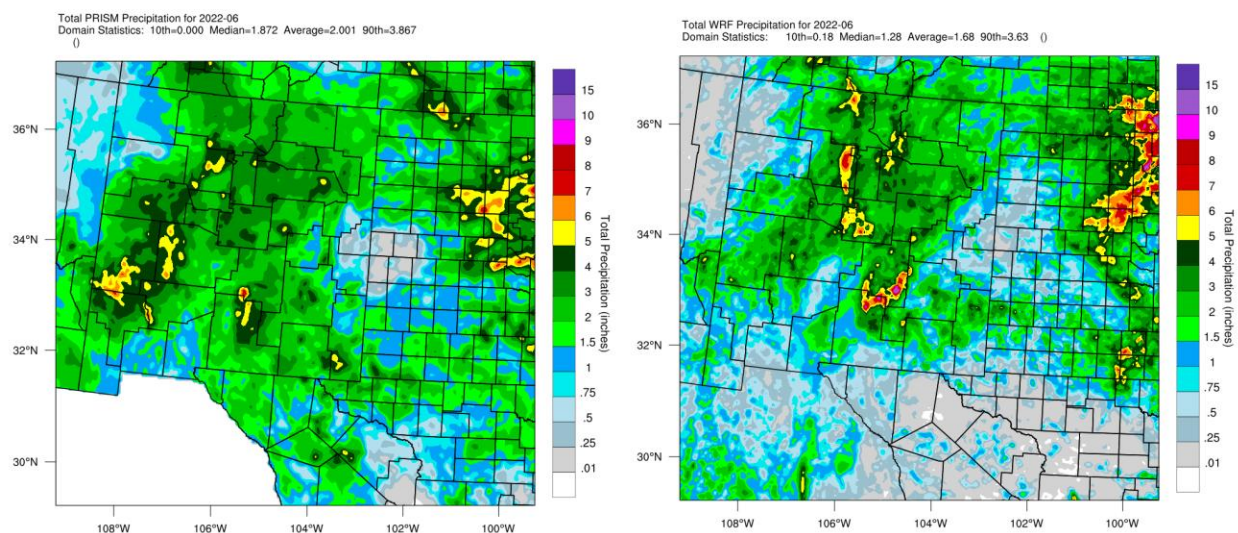


Figure 2-5. June total precipitation patterns from PRISM based on observations (left) and modeled by WRF (right).

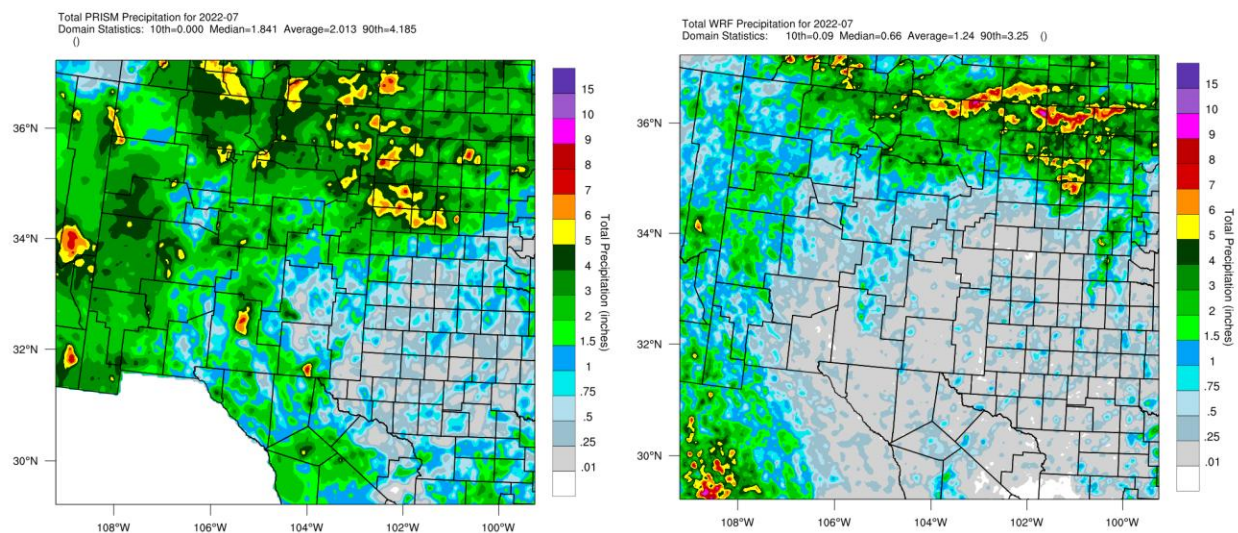


Figure 2-6. July total precipitation patterns from PRISM based on observations (left) and modeled by WRF (right).

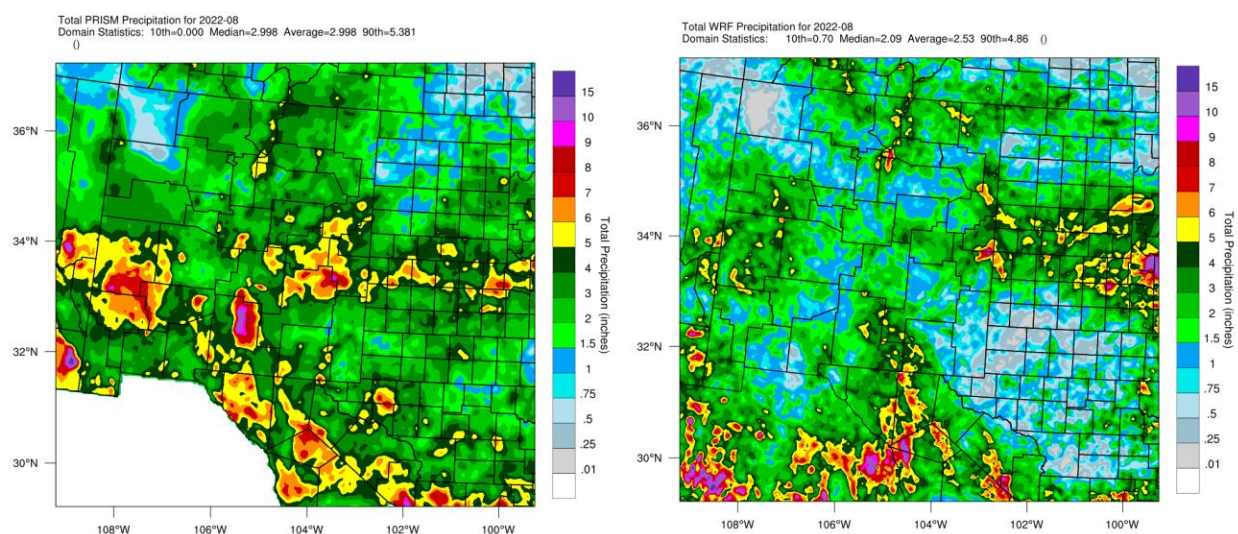


Figure 2-7. August total precipitation patterns from PRISM based on observations (left) and modeled by WRF (right).

2.3 WRF Model Performance Summary

The WRF summer 2022 4 km simulation demonstrated strong performance during the May–October 2022 modeling period. Statistical benchmarks were met at airport monitoring sites across the Permian Basin region, encompassing all of New Mexico, most of western Texas, the Oklahoma panhandle, and the southernmost ~50 miles of Colorado. Performance was notably improved compared to prior WRF 2016 modeling supporting the NMED Ozone Assessment Initiative (OAI). The analyses confirm that the WRF run is suitable for CAMx photochemical modeling over the May–October 2022 ozone modeling period for the following reasons:

- Surface temperature and wind fields were replicated with high accuracy at both local and regional scales, meeting statistical benchmarks and outperforming other recent WRF modeling efforts in the western U.S.
- The model accurately captured observed wind speed and direction shifts, particularly during periods of stronger winds, while exhibiting appropriate hour-by-hour stochastic variability during weaker winds. Some missing wind direction observations were noted due to calm conditions during high ozone periods.
- Surface humidity was generally simulated well across all six months, with the model capturing day-to-day variability associated with synoptic-scale weather systems. Errors in water vapor have less impact on ozone compared to similar errors in temperature.
- On ozone exceedance days with rainfall within the CAMx domain, WRF generally tracked observed spatial patterns but tended to simulate lower precipitation totals than PRISM.

Temperature accuracy is crucial for ozone modelling, as it influences diurnal mixing depth, temperature-sensitive emissions, and chemical rates affecting ozone formation. The use of ERA5 analysis fields alongside the multi-scale Kain-Fritsch sub-grid convection

parameterization resulted in less convective activity and overall precipitation than observed but maintained excellent performance for temperature and winds. No substantial or widespread errors in wind or temperature were observed in the current modeling.

WRF produced spottier, convection-oriented rainfall patterns, whereas PRISM indicated broader areas of precipitation. The WRF pattern may be more reasonable, though not necessarily accurate in time or space, as PRISM interpolates between rain gauge data, which are sparse in rural areas and may overstate rainfall extent. The PRISM interpolation scheme performs better for organized synoptic weather systems than for stochastic summer convective showers, which are intermittent and localized. As a result, precipitation performance is assessed qualitatively by comparing spatial patterns and magnitudes.

Neither PRISM nor WRF can fully replicate the stochastic nature of summer convective rainfall in time and space. A drier meteorological simulation is often preferable, as spurious convective precipitation events can introduce large local errors in wind and temperature, which may lead to poor replication of ozone patterns during those periods.

3.0 DEVELOPMENT OF 2022 EMISSION INPUTS FOR THE CAMX 2022V2 12/4 KM MODELING PLATFORM

This chapter describes how the 2022v2 12/4 km base case emissions were developed for the CAMx Photochemical Grid Model (PGM). These emissions were built on EPA's 2022v2 Emissions Modeling Platform (EMP)³ developed by the National Emissions Collaborative (NEC). The 2022v2 platform is based on the 2020 National Emissions Inventory (NEI) and incorporates updates from EPA and individual states to better reflect 2022 conditions (EPA, 2023; EPA 2025). It includes emissions inventories for 2022, along with spatial surrogates, temporal profiles, and other supporting files.

EPA processed the 2022v2 inventories to produce model-ready emissions for the Continental U.S. (CONUS) 12 km domain; these 2022v2 12 km model-ready emission inputs were downloaded and used directly in the NMED modeling. For the finer-resolution 4 km domain, the 2022v2 inventories were downloaded separately by source sector and processed for input into CAMx.

3.1 2022v2 CONUS 12 km Anthropogenic Emissions

The 2022v2 platform provides model-ready emissions for a 12 km grid covering the CONUS (12US2), which were used directly in the NMED modeling. These CMAQ-ready, pre-merged gridded emission files were downloaded from EPA's Open Data Program and converted to CAMx format using the CMAQ2CAMx processor.

3.2 2022v2 4 km Anthropogenic Emissions

The 2022v2 4 km anthropogenic emissions are primarily based on the 2022v2 emission inventories. Table 3-1 summarizes the inventory data sources used for the NMED 4 km domain. The Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system v5.0 was used to develop emissions for the 4 km domain, leveraging spatial surrogates, temporal profiles, and other ancillary inputs from the 2022v2 EMP to generate CAMx-ready emission inputs.

Point source emissions (EGU, Non-EGU and Point O&G) are not grid-specific and were used directly from the 2022v2 platform for both domains. On-road mobile source emissions for the 4 km domain were generated using the SMOKE-MOVES processor with vehicle miles traveled (VMT) and population data from the 2022v2 platform. This processing also incorporated 2022 MOVES5 emissions factors from the 2022v2 EMP and hourly 4 km meteorology from WRF (see Chapter 2). Unlike most other emission inputs, agricultural fertilizer emissions were not processed through SMOKE; instead, they are computed inline during a CMAQ bi-directional model run and output directly from the CMAQ model. They were therefore spatially disaggregated from the 12 km grid to the NMED 4 km domain for the CAMx 2022v2 12/4 km modeling.

³ <https://www.epa.gov/air-emissions-modeling/2022v2-emissions-modeling-platform>

Table 3-1. 2022 emissions data sources for the 4 km and 12 km domains used in NMED Phase II CAMx 2022v2 12/4 km modeling.

Source Category	NMED 4km Domain (4km grid)	12US2 Continental U.S. (12km grid)
Area: <i>afdust, rwc, nonpt, solvents, openburn, livestock</i>	EPA 2022v2 inventory	EPA 2022v2 model-ready emissions files
Agricultural fertilizer: <i>Fertilizer</i>	EPA 2022v2 12US1 windowed and regridded to NMED 4 km domain	EPA 2022v2 model-ready emissions files
Oil & Gas: <i>np_oilgas, pt_oilgas</i>	EPA 2022v2 inventory	EPA 2022v2 model-ready emissions files
On-road Mobile: <i>onroad</i>	SMOKE-MOVES and MOVES5 lookup tables with 4 km met data from NMED modeling	EPA 2022v2 model-ready emissions files
Nonroad: <i>nonroad</i>	EPA 2022v2 inventory	EPA 2022v2 model-ready emissions files
Airports: <i>airports</i>	EPA 2022v2 inventory	EPA 2022v2 model-ready emissions files
CMV: <i>cmv_c1c2, cmv_c3</i>	N/A	EPA 2022v2 model-ready emissions files
Locomotives: <i>rail</i>	EPA 2022v2 inventory	EPA 2022v2 model-ready emissions files
EGU Point: <i>ptegu</i>	EPA 2022v2 model-ready emissions files. EPA 2022v2 inventory with hourly CAMD data.	EPA 2022v2 model-ready emissions files
Point: <i>ptnonipm</i>	EPA 2022v2 model-ready emissions files	EPA 2022v2 model-ready emissions files
Non-US: <i>Canada/Mexico</i>	EPA 2022v2 inventory	EPA 2022v2 model-ready emissions files
Fires	EPA 2022v2 CAMx-ready emissions files	EPA 2022v2 model-ready emissions files
Biogenic	2022 BEIS4/BELD6	EPA 2022v2 model-ready emissions files
LNOx	EPA 2022v2 data and processor to create 4km emissions data	EPA 2022v2 model-ready emissions files

3.3 2022 Natural Source Emission Inputs

Biogenic emissions for the 12/4 km domains were generated using the Biogenic Emission Inventory System version 4 (BEIS4), which relies on the Biogenic Emissions Landcover Database version 6 (BELD6) as input. BEIS4/BELD6 was run with hourly WRF meteorology for each domain (Chapter 2).

Open land fire (e.g., wildfires) emissions were based on the 2022v2 inventory which was developed using Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation version 2 (SMARTFIRE2) and the BlueSky Framework for U.S. fires. Canadian fires were estimated using a similar methodology, with tools comparable to those used for the U.S. fire inventory. Mexican fire emissions were estimated using the Fire INventory from NCAR (FINN). The 2022v2 platform provided three-dimensional (3D) layered fire emissions with plume rise calculated by SMOKE, which were then converted to CAMx point binary files using virtual stacks placed at the center of each horizontal and vertical grid cell.

Lightning NOx (LNOx) emissions were generated using the EPA LNOx processor. EPA provided both the processor and 2022 lightning detection observation data to generate

three-dimensional NetCDF LNOx emissions for the 4 km grid. These inputs were developed using study-specific WRF meteorological data for the NMED 4 km domain as described in Chapter 2. Oceanic emissions, including sea salt and dimethyl sulfide (DMS), were generated using a CAMx preprocessor and the 12 km WRF meteorological data.

3.4 Summary of 2022 Emissions by Source Sector

Table 3-2 and Figure 3-1 show episode-average 2022v2 NO_x and VOC anthropogenic emissions by source sectors in New Mexico, expressed in tons per day (TPD). In 2022, the largest New Mexico NO_x source sector was oil and gas (O&G), contributing 60% of the total, followed by on-road mobile sources at 18%; all other source sectors contributed 10% or less individually. For anthropogenic VOC emissions, the O&G sector dominated accounting for 85% of the total, followed by nonpoint sources at 10%, with the remaining sectors contributing 3% or less individually.

Biogenic VOC emissions are not shown in these tables and figures. The episode average biogenic VOC emissions (~1,568 TPD) are almost 40% higher than the total anthropogenic VOC emissions in New Mexico. Because biogenic VOC emissions are temperature-sensitive, they tend to be higher on days with elevated ozone levels.

Table 3-2. New Mexico 2022v2 anthropogenic NO_x and VOC emissions by source sector.

	New Mexico	
Tons per Day (TPD)	2022v2	2022v2
Source Sector	NO _x	VOC
EGU Point	19.1	0.6
Non-EGU Point	7.1	5.5
O&G	265.9	963.7
Rail	44.2	1.8
Non-Point	11.5	110.2
Non-Road	11.9	13.9
On-Road	78.7	35.4
Airports	1.7	1.0
Anthro Total	440.1	1132.0

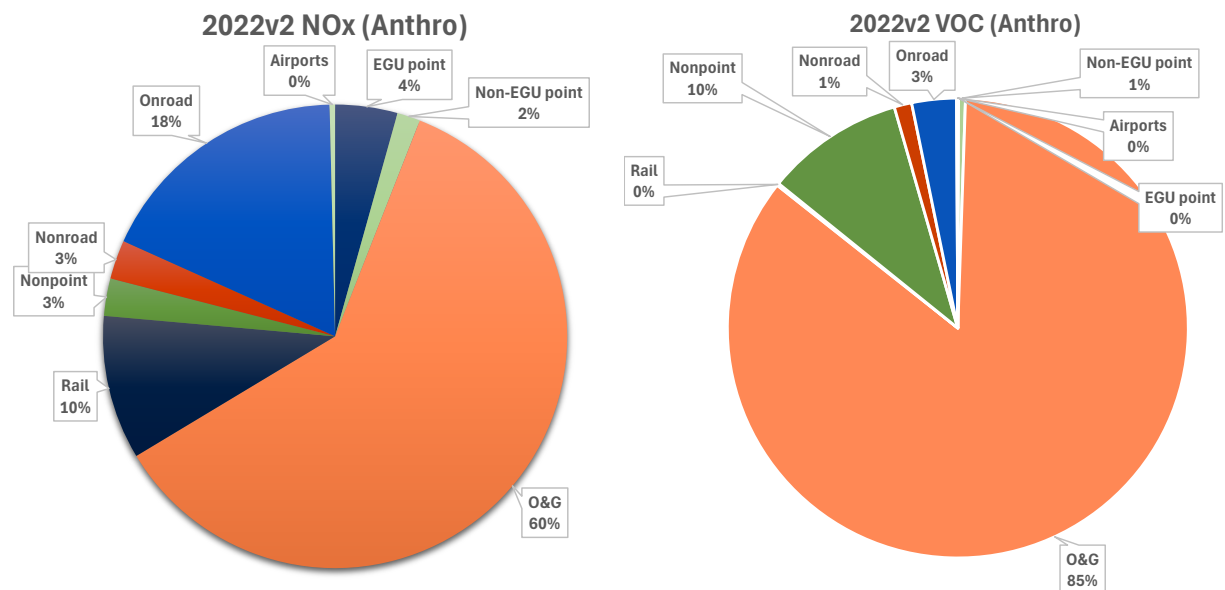


Figure 3-1. Pie Charts showing the percent contributions of 2022v2 anthropogenic emission source sectors to total anthropogenic NO_x and VOC emissions in New Mexico.

Figure 3-2 through Figure 3-6 display the spatial distribution of episode-average 2022v2 NO_x and VOC emissions within the 4 km domain for the following anthropogenic sectors: non-point O&G, point O&G, on-road mobile, non-road mobile, and non-point. Urban areas, roadways, and O&G development areas are clearly identifiable in the emission maps.

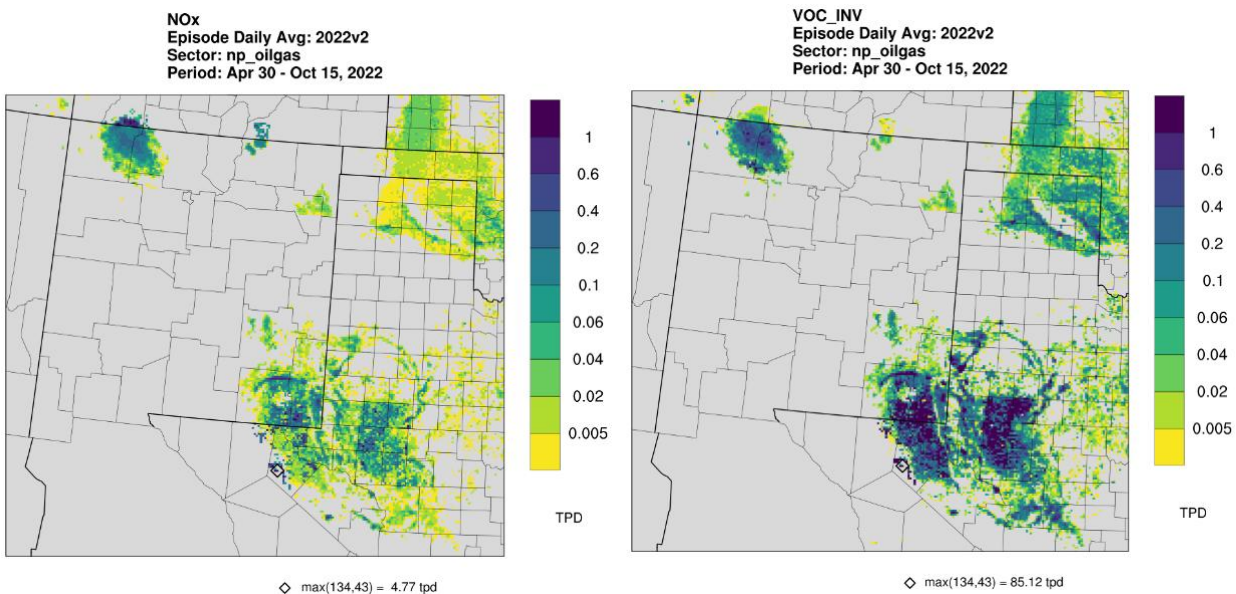


Figure 3-2. Episode-average total 2022v2 Non-Point O&G NO_x (left) and VOC (right) emissions in the NMED 4 km domain [tons per day (TPD)].

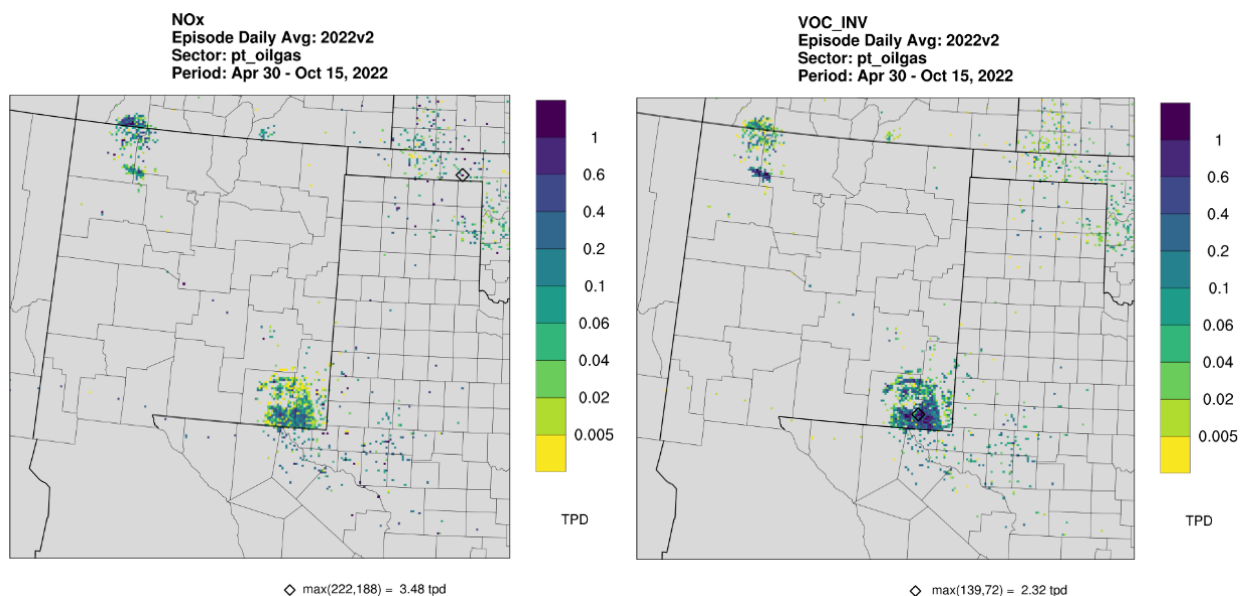


Figure 3-3. Episode-average total 2022v2 Point O&G NO_x (left) and VOC (right) emissions in the NMED 4 km domain [tons per day (TPD)].

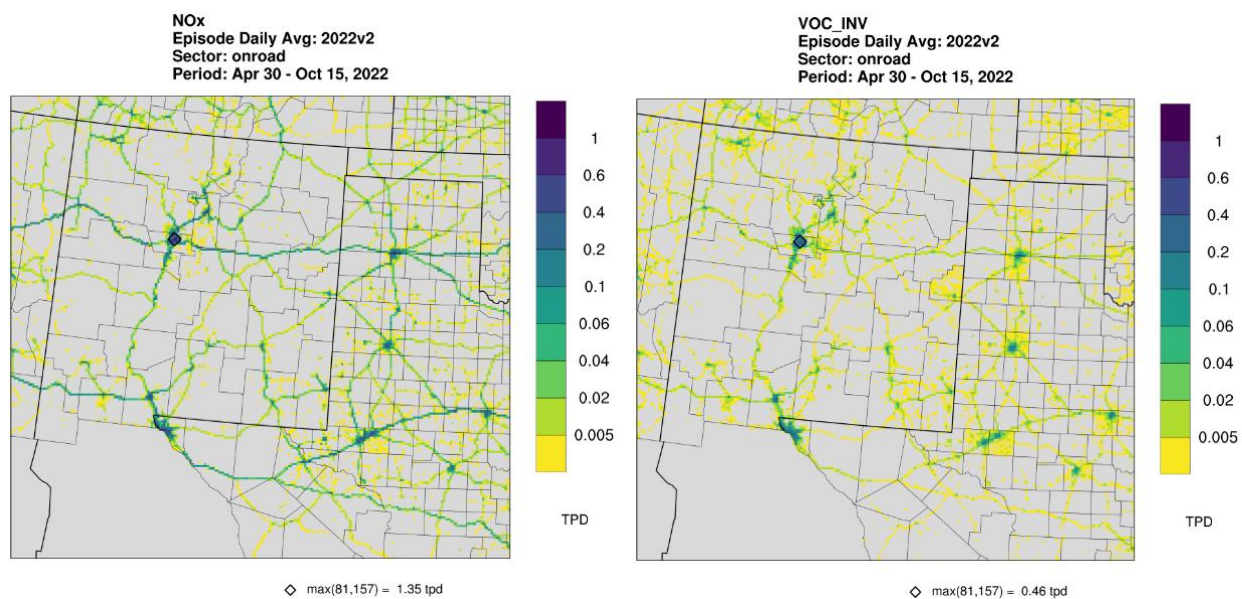


Figure 3-4. Episode-average total 2022v2 On-Road Mobile NO_x (left) and VOC (right) emissions in the NMED 4 km domain [tons per day (TPD)].

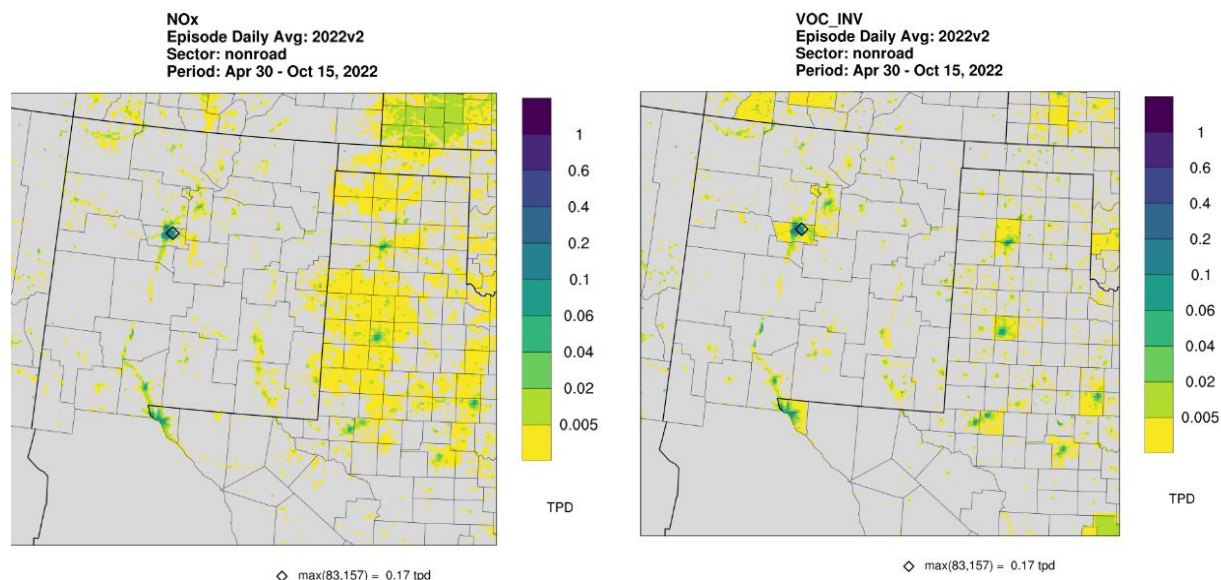


Figure 3-5. Episode-average total 2022v2 Non-Road Mobile NO_x (left) and VOC (right) emissions in the NMED 4 km domain [tons per day (TPD)].

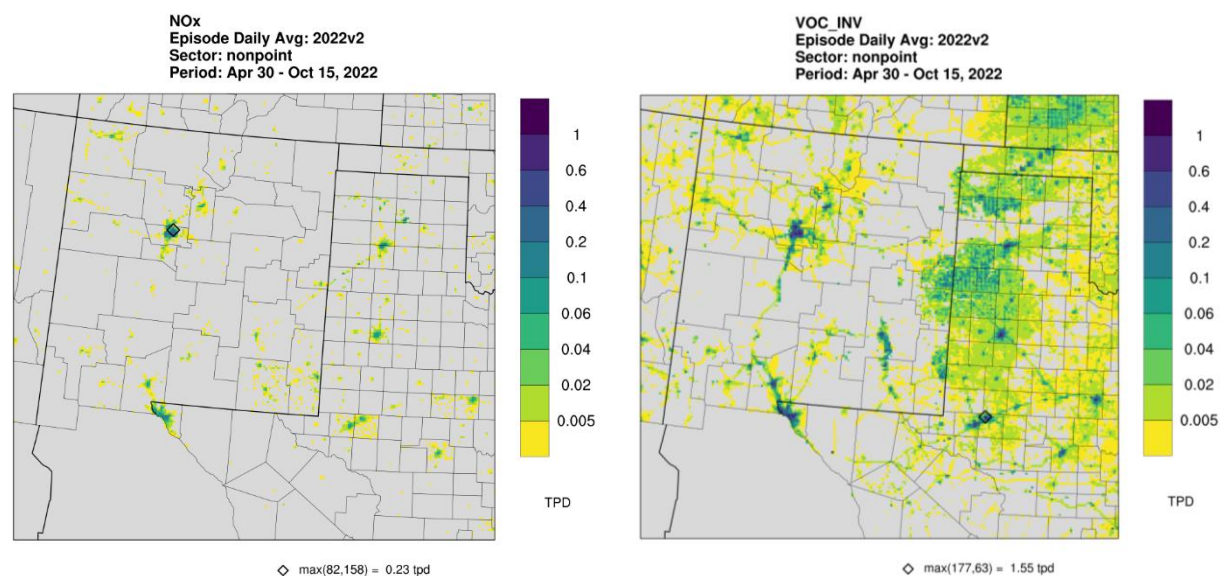


Figure 3-6. Episode-average total 2022 Non-Point NO_x (left) and VOC (right) emissions in the NMED 4 km domain [tons per day (TPD)].

3.5 Comparison of NMED Phase I 2022v1 and Phase II 2022v2 Emissions

This section compares emissions between 2022v1 emissions used in Phase I and 2022v2 emissions used in Phase II of the NMED ozone source apportionment modeling study. Table 3-3 and Table 3-4 provide a side-by-side comparison of May-October episode average emissions (TPD) from Phase I, which was based on the EPA 2022v1 platform, and Phase II, which is based on the 2022v2 platform, for New Mexico and for Lea and Eddy counties, respectively.

The total emissions in the 2022v1 and 2022v2 inventories are very similar across most source sectors in New Mexico except for on-road mobile and O&G. The on-road mobile emissions differences can be attributed to the fact that the two inventories draw from

different versions of the EPA 2022 platform that used different versions of the MOVES mobile source emissions model. NMED Phase II modeling used the 2022v2 platform with on-road mobile source emissions based on the MOVES5 model, whereas NMED Phase I modeling used 2022v1 platform emission with on-road mobile sources emissions factors derived from MOVES4. MOVES5 incorporates several updates including new regulations (such as revised light-, medium-, and heavy-duty greenhouse gas standards), updated data reflecting higher electric vehicle adoption, revised brake wear emissions, expanded vehicle age calculations to 40 years, and updated fuel and vehicle population datasets.

New Mexico 2022 O&G NO_x emissions are almost 30% lower in the 2022v2 platform used in Phase II than the 2022v1 inventory used in Phase I. Further review of the EPA inventories revealed that point O&G emissions are similar between the two platforms; however, non-point O&G emissions are substantially lower in 2022v2. This reduction is primarily due to corrections to non-road emission factors, which reduced NO_x emissions from drill rigs and hydraulic fracturing engines by approximately 74% (EPA, 2025).

Table 3-3. 2022 emissions by major source sector in New Mexico from 2022v1 and 2022v2 emission platforms.

	New Mexico					
Tons per Day (TPD)	2022v1	2022v1	2022v2	2022v2	%Diff	%Diff
Source Sector	NO _x	VOC	NO _x	VOC	NO _x	VOC
EGU point	19.1	0.6	19.1	0.6	0.0%	0.0%
Non-EGU point	7.0	5.5	7.1	5.5	1.4%	0.0%
O&G	369.1	967.5	265.9	963.7	-28.0%	-0.4%
Rail	44.2	1.8	44.2	1.8	0.0%	0.0%
Non-Point	11.5	108.9	11.5	110.2	0.0%	1.2%
Non-Road Mobile	12.0	14.1	11.9	13.9	-0.8%	-1.4%
On-Road Mobile	68.9	29.9	78.7	35.4	14.2%	18.4%
Airports	1.7	1.0	1.7	1.0	0.0%	0.0%
Anthro Total	533.5	1129.2	440.1	1132.0	-17.5%	0.2%
Fires	64.4	1874.7	64.3	1872.6	-0.2%	-0.1%
Biogenic	58.8	1567.6	58.8	1567.6	0.0%	0.0%
Natural Total	123.2	3442.2	123.1	3440.2	-0.1%	-0.1%

The differences in the 2022v1 and 2022v2 emissions in Lea and Eddy counties, the New Mexico portion of the Permian Basin (Table 3-4), show the same emissions trends as the statewide totals described above only the decrease in O&G NO_x emissions between 2022v2 and 2022v1 is even greater (almost -40%). The amount of natural emissions compared to anthropogenic emissions in Eddy and Lea Counties is also very different than the whole state of New Mexico. 2022 Fire VOC and NO_x emissions in Eddy and Lea Counties are less than 0.1% of the anthropogenic emissions, whereas across New Mexico Fire VOC emissions are 66% higher than the anthropogenic VOC emissions and Fire NO_x emissions are 12% of the New Mexico anthropogenic NO_x emissions. The Biogenic VOC emissions in Eddy and Lea Counties are 9% of the total anthropogenic VOC emissions in the two counties. While 2022 Biogenic VOC emissions across New Mexico are almost 40% (1.4 times) higher than the New Mexico anthropogenic VOC emissions.

Table 3-4. 2022 emissions by sector in Eddy and Lea counties from 2022v1 and 2022v2 platforms.

	Eddy and Lea Counties					
Tons per Day (TPD)	2022v1	2022v1	2022v2	2022v2	%Diff	%Diff
Source Sector	NOx	VOC	NOx	VOC	NOx	VOC
EGU point	3.5	0.2	3.5	0.2	0.0%	0.0%
Non-EGU point	0.9	2.9	0.9	2.9	0.0%	0.0%
O&G	263.3	763.3	160.2	759.6	-39.2%	-0.5%
Rail	0.3	0.0	0.3	0.0	0.0%	0.0%
Non-Point	1.4	9.1	1.4	9.1	0.0%	0.0%
Non-Road Mobile	1.0	0.9	1.0	0.9	0.0%	0.0%
On-Road Mobile	4.2	2.0	4.6	2.3	9.5%	15.0%
Airports	0.0	0.0	0.0	0.0	0.0%	0.0%
Anthro Total	274.6	778.5	172.0	775.0	-37.4%	-0.4%
Fires	0.1	0.7	0.0	0.5	-100.0%	-28.6%
Biogenic	3.4	69.3	3.4	69.3	0.0%	0.0%
Natural Total	3.4	70.0	3.4	69.8	0.0%	-0.3%

3.6 2022 Emissions QA/QC

An important step in developing the 2022 emission inputs for the CAMx 2022v2 12/4 km emission scenario was the implementation of Quality Assurance/Quality Control (QA/QC) activities to ensure the integrity of the emissions data throughout development and processing. QA/QC activities were conducted across the 4 km domain using 2022v2 EMP as a reference. The 2022 QA/QC activities included but were not limited to the following steps:

- Tabular comparisons of total 2022 NO_x and VOC emissions in the NMED 4 km domain by source sector.
- Spatial maps of 2022 total emissions and emissions within the 4 km domain, broken down by source sector.
- Comparisons of 2022 emissions in the NMED 4 km domain during each step of the SMOKE emissions modeling to ensure no emissions are lost or gained during processing.
- Independent QA/QC review of the 2022 emission comparisons by members of the Ramboll team not involved in the emissions development and modeling.

4.0 CAMX 2022V2 12/4 KM BASE CASE MODELING AND OZONE MODEL PERFORMANCE EVALUATION

This Chapter discusses the CAMx 2022v2 12/4 km base case simulation and model performance evaluation for ozone and NO_x using the routine Air Quality System (AQS) observation network.

4.1 CAMx 2022v2 12/4 km Base Case Simulation

A CAMx 2022v2 12/4 km base case simulation was conducted for the May through mid-October 2022 period using a 12 km 12US2 continental U.S. domain and a 4 km New Mexico domain (Figure 1-3). CAMx was run using two-way grid nesting between the 12 and 4 km domains. Three-dimensional output from a CAMx 2022 simulation of a 36 km North American domain were processed to generation BCs for the lateral boundaries of the 12 km 12US2 domain. The BCs for the CAMx 2022 36 km domain were based on output from a Hemispheric CMAQ (HCMAQ) 2022 simulation. The development of the meteorological and emission inputs for the CAMx 2022v2 12/4 km modeling platform are described in, respectively, Chapters 2 and 3.

Table 4-1 summarizes the inputs and options used in the CAMx 2022v2 12/4 km base case simulation.

Table 4-1. CAMx model options for the NMED Phase II CAMx 2022 12/4 km base case simulation.

Science Options	CAMx	Comment
Model Codes	CAMx v7.32 – August 2025	Latest version of CAMx at time of study
Horizontal Grid Mesh	12/4 km	Two-way grid nesting
12 km grid	396 x 246 cells	12 km 12US2 domain matching EPA platform
4 km grid	243 x 225 cells	New Mexico 4 km domain
Vertical Grid Mesh	35 vertical layers match WRF	Layer 1 thickness 20 m. Model top at ~19 km AGL. No layer collapsing.
Initial Conditions (ICs)	~Clean IC starting on May 1 2022	~10 days of spin-up before examining results
Boundary Conditions (BCs)	12 km BCs from CAMx 2022 36 km North American domain simulation	BCs for CAMx 2022 North American domain based on 2022 HCMAQ simulation
Emissions		
4 km NM Domain	SMOKE and SMOKE-MOVES5 processing of 2022v2 emissions and BEIS4/BELD6	Lightning NOx using CAMx processors
12 km US1 Domain	Use EPA platform model-ready 2022v2 12 km domain emissions	Oceanic emissions using CAMx processor
Sub-grid-scale Plumes	No Plume-in-Grid	4 km grid resolution
Chemistry		
Gas Phase Chemistry	CB7r1	Latest gas-phase chemistry mechanism.
Aerosol Thermodynamics	ISORROPIA	
Secondary Organic Aerosol	SOAP3	No POC evaporation
Particle Size Distribution	Coarse/Fine	
Meteorological Processor	WRFCAMx	
Horizontal Diffusion	Spatially varying	K-theory with Kh grid size dependence
Vertical Diffusion	WRFCAMx YSU-like Kv	
Diffusivity Lower Limit	Kv_min = 0.1 to 2.0 m ² /s in lowest 100 m	Depends on urban land use fraction
Deposition Schemes		
Dry Deposition	Zhang dry deposition scheme	(Zhang et. al, 2001; 2003)
Wet Deposition	CAMx -specific formulation	rain/snow/graupel
Numerics		
Gas Phase Chemistry Solver	Euler Backward Iterative (EBI)	EBI fast and accurate solver
Vertical Advection Scheme	Piecewise Parabolic Method scheme	Colella and Woodward (1984)
Horizontal Advection Scheme	Piecewise Parabolic Method scheme	Colella and Woodward (1984)
Integration Time Step	Wind speed dependent	~0.5-1 min (4 km), 1-5 min (12 km)

4.2 CAMx 2022v2 12/4 km Model Performance Evaluation Approach

The Atmospheric Model Evaluation Tool ([AMET](#)) was used to evaluate the CAMx 2022v2 12/4 km base case against observed ozone and NO_x concentrations. AMET includes standard routine AQS monitoring data. The ozone and NO_x model evaluation was conducted for sites within the 4 km New Mexico domain that includes all of New Mexico, parts of adjacent states and all the Permian Basin oil and gas production area in Texas. Figure 4-1 shows the locations of all the ozone monitoring sites in the 4 km domain and what parameters are measured at monitoring sites in New Mexico.

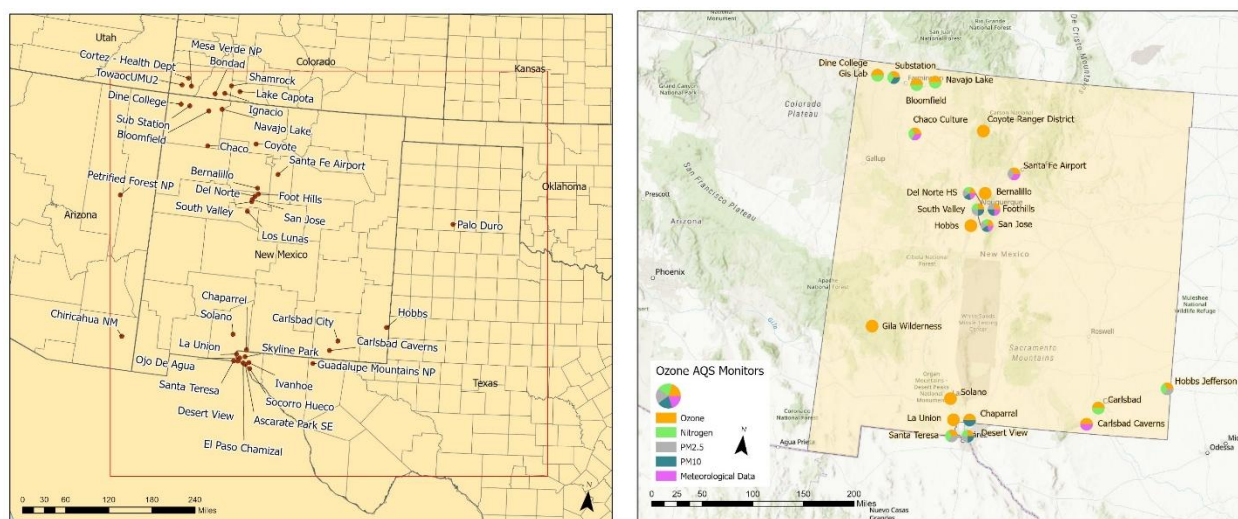


Figure 4-1. Locations of ozone monitoring sites operating in 2022 in the New Mexico 4 km modeling domain (left) and parameters that are measured at New Mexico monitoring sites (right).

AMET was used to generate numerous displays and metrics of ozone model performance as follows:

- Scatterplots of MDA8 and hourly ozone and hourly NO_x concentrations.
- Spatial plots of bias and error at monitoring sites across the New Mexico 4 km domain.
- Time series comparing predicted and observed MDA8 ozone for the months of May through September 2022.
- Time series plots of hourly ozone, NO, NO₂ and NO_x during six multiday periods during 2022:
 - May 14 – 16
 - May 25 – 30
 - June 8 – 11
 - June 30 – July 3
 - July 13 – 15
 - August 12 – 14

4.2.1 Ozone Model Performance Goals and Criteria

Model Performance Goals and Criteria allow the assessment of model performance of a PGM base case and compare it with past PGM model performance evaluations. EPA first proposed the use of model performance goals in their 1991 ozone modeling guidance (EPA, 1991) with goals for bias ($\leq \pm 15\%$) and error ($\leq 35\%$). Boylan and Russell (2006) extended the ozone performance goals to PM species and visibility. Simon, Baker and Phillips (2012) summarized the model performance statistics of 69 PGM applications from 2006 to 2012 and found significant variability but were able to isolate model performance statistical levels for the best performing models. Emery et al., (2017) built off the work of Simon, Baker and Phillips (2012) by including additional PGM model applications and came up with a set of PGM model Performance Goals and Criteria based on the variability in past PGM model applications in the peer-reviewed literature. Model performance “Goals” indicate statistical values that approximately a third of the top performing past PGM applications have met and should be viewed as the best a PGM application can be expected to achieve. “Criteria” indicates statistical values that approximately two thirds of past PGM applications have met and should be viewed as what most of the model applications have achieved. We compared the CAMx 2022 simulation ozone model performance statistics for normalized mean bias (NMB) and normalized mean error (NME) against the ozone model Performance Goals and Criteria summarized by Emery et al., (2017) given in Table 4-2 (for completeness we also include the PM performance goals and criteria).

Table 4-2. Recommended Performance Goals and Criteria benchmarks for photochemical model statistics (Source: Emery et al., 2017).

Species	NMB		NME		r	
	Goal	Criteria	Goal	Criteria	Goal	Criteria
1-hr & MDA8 Ozone	$< \pm 5\%$	$< \pm 15\%$	$< 15\%$	$< 25\%$	> 0.75	> 0.50
24-hr $PM_{2.5}$, SO_4 , NH_4	$< \pm 10\%$	$< \pm 30\%$	$< 35\%$	$< 50\%$	> 0.70	> 0.40
24-hr NO_3	$< \pm 15\%$	$< \pm 65\%$	$< 65\%$	$< 115\%$	NA	NA
24-hr OC	$< \pm 15\%$	$< \pm 50\%$	$< 45\%$	$< 65\%$	NA	NA
24-hr EC	$< \pm 20\%$	$< \pm 40\%$	$< 55\%$	$< 75\%$	NA	NA

The NMB is defined as the Mean Bias (MB; i.e., the average of the differences between the Measured (M) and Observed (O) concentrations) divided by the average Observed value:

$$\text{Normalized mean bias} = \frac{\sum_1^n (M - O)}{\sum_1^n O}$$

The NME is defined by a similar formula as the NMB only the numerator is the average of the absolute value differences between the Measured and Observed Value. We also compare the bias and error Performance Goals and Criteria against the Fractional Bias and Error (FB and FE) that are similar to the NMB and NME only instead of dividing the Mean Bias or Error by the average Observation it is divided by the average of the Observed and Measured value divided by 2. This results in the FB being bounded by -200% and +200% and FE bounded by 0% to +200%.

4.2.2 Subregional Ozone and NO_x Model Performance

The CAMx 2022 base case is evaluated across the 4 km domain (Figure 4-1) and within 7 subregions in the 4 km domain. The New Mexico model evaluation subregions roughly correspond to the New Mexico Air Quality Control Regions ([AQCR](#)):

- NM-PB: The Permian Basin portion of New Mexico includes the Carlsbad City and Carlsbad Cavern monitors in Eddy County, and the Hobbs monitor in Lea County. When examining ozone model performance in the NM-PB region we also discuss the performance at the Guadalupe Mountains National Park monitor in Culberson County in the Texas portion of the Permian Basin (TX-PB) that is right across the border from Eddy County.
- NM-S: The southern portion of New Mexico has five monitors in Doña Ana County, New Mexico that are next to El Paso, Texas.
- TX-EP: The El Paso, Texas grouping includes six monitors.
- NM-Cen: The Central New Mexico grouping includes three monitors in Bernalillo County and one monitor each in the adjacent counties of Sandoval, Santa Fe and Valencia.
- NM-SSJ: The South San Juan Basin region of New Mexico includes monitors in San Juan and Rio Arriba Counties.
- CO-NSJ: The North San Juan Basin region of Colorado includes monitors in Archuleta, La Plata and Montezuma Counties.
- AZ-Misc: There are two additional monitors at Class I areas in Arizona just west of the border of New Mexico at Chiricahua National Monument and Petrified Forest National Park. There is also a miscellaneous ozone monitor (TX-Misc) in Randall County in the Texas Panhandle east of the border with New Mexico.

4.3 Ozone Model Performance Across the New Mexico Analysis Domain

Figure 4-2 displays the spatial distribution of MDA8 ozone NMB and NME performance statistics at sites across the New Mexico 4 km domain for the entire May 10 through October 15, 2022 analysis period. When the NMB at a site achieves the Performance Goal ($\leq \pm 5\%$) the symbol is colored grey, and when a site's NMB falls between the bias Performance Goal and Criterion it is colored green for under-predictions or yellow for over-predictions.

Table 4-3 is a tabular summary of the site-specific NMB and NME MDA8 ozone performance statistics which also include the Fractional Bias and Error (FB and FE) and correlation (COR or r) statistics. Cells in Table 4-3 are colored green if the performance statistics achieves the Performance Goal, yellow if it falls between Performance Goal and Criterion, and red if it fails to achieve the Performance Criteria.

For MDA8 ozone NMB, almost all sites achieve the bias Performance Criterion and over 40% of the sites achieve the bias Performance Goal. Two sites have NMB that fails to achieve the bias Performance Criterion, Palo Duro (-20.6%) on the Texas Panhandle and Carlsbad Caverns (-15.7%) whose NMB is barely outside the ozone bias Performance Criterion ($\leq \pm 15\%$). Over 80% of the sites achieve the error Performance Goal ($\leq 15\%$). The correlation for MDA8 ozone for over 90% of the sites falls between the Performance Goal and Criterion (i.e., between 0.50 and 0.75) and at the 5 sites where the correlation fails to

achieve the Performance Criterion, the values are just barely below it (0.44 to 0.49). As discussed in more detail below, within the Permian Basin region, the CAMx 2022v2 base case has a MDA8 ozone underestimation bias (as indicated by the bright green and slightly duller green NMB symbols in Figure 4-2, left).

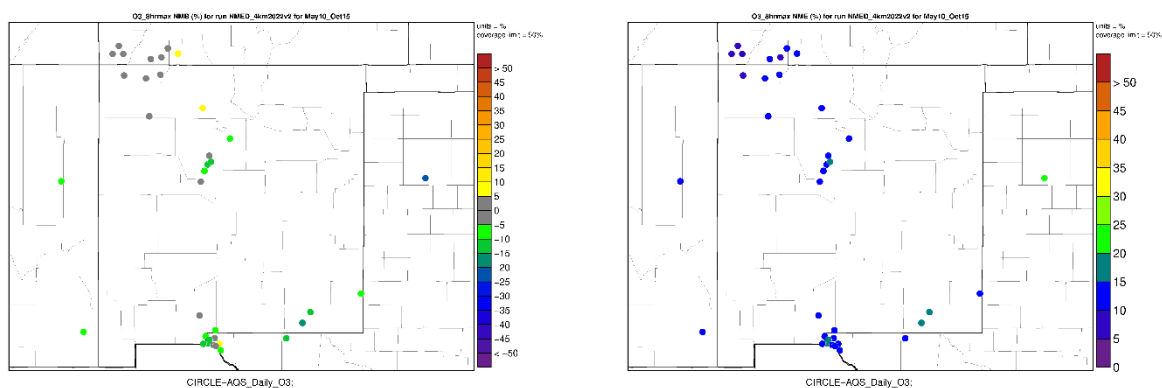


Figure 4-2. Spatial distribution of CAMx 2022v2 4 km NMB (left) and NME (right) MDA8 ozone performance statistics for the May 10 – October 15, 2022 modeling period.

Table 4-3. Bias (NMB and FB), error (NME and FE) and correlation (COR) MDA8 ozone performance statistics by site for the CAMx 2022v2 12/4 km base case simulation and May 10 – October 15, 2022 analysis period.

Region	Local Name	County	SiteID	N	NMB	FB	NME	FE	COR
NM-PB	Carlsbad Caverns	Eddy	35-015-0010	181	-15.7	-16.8	17.1	18.4	0.583
NM-PB	Carlsbad City	Eddy	35-015-1005	188	-14.6	-15.4	16.5	17.8	0.610
NM-PB	Hobbs	Lea	35-025-0008	193	-9.5	-9.3	14.8	15.4	0.595
TX_PB	Guadalupe Mtn NP	Culberson	48-109-0002	79	-11.4	-12.1	14.1	14.8	0.489
NM-S	La Union	Dona Ana	35-013-0008	192	-7.5	-7.6	12.4	12.7	0.655
NM-S	Chaparrel	Dona Ana	35-013-0020	196	-7.3	-7.3	12.3	12.5	0.652
NM-S	Desert View	Dona Ana	35-013-0021	196	-14.5	-15.5	16.3	17.5	0.652
NM-S	Santa Teresa	Dona Ana	35-013-0022	188	-10.8	-11.0	14.8	15.6	0.615
NM-S	Solano	Dona Ana	35-013-0023	194	3.8	4.0	11.4	11.3	0.649
TX_EP	Ivanhoe	El Paso	48-141-0029	193	7.2	7.5	13.4	13.2	0.700
TX_EP	El Paso Chamizal	El Paso	48-141-0044	182	-1.5	-1.1	11.6	11.9	0.710
TX_EP	Ascarate Park SE	El Paso	48-141-0055	179	0.4	1.0	12.4	12.5	0.660
TX_EP	Socorro Hueco	El Paso	48-141-0057	196	-9.3	-9.3	13.1	13.6	0.689
TX_EP	Skyline Park	El Paso	48-141-0058	194	-1.1	-0.4	14.1	14.3	0.518
TX_EP	Ojo De Agua	El Paso	48-141-1021	189	-11.7	-12.3	15.8	16.7	0.542
NM-Cen	Del Norte	Bernalillo	35-001-0023	191	-11.8	-12.5	13.9	14.8	0.640
NM-Cen	South Valley	Bernalillo	35-001-0029	181	-8.8	-9.2	11.8	12.3	0.702
NM-Cen	Foot Hills	Bernalillo	35-001-1012	191	-11.9	-12.4	15.6	16.5	0.567
NM-Cen	Bernalillo	Sandoval	35-043-1001	194	-4.7	-4.9	10.5	11.0	0.695
NM-Cen	Santa Fe	Santa Fe	35-049-0021	194	-6.3	-6.8	11.4	11.9	0.579
NM-Cen	Los Lunas	Valencia	35-061-0008	196	-2.8	-3.1	11.6	11.6	0.470
NM-SSJ	Coyote	Rio Arriba	35-039-0026	181	5.9	6.3	10.9	10.9	0.712
NM-SSJ	Bloomfield	San Juan	35-045-0009	186	-2.6	-2.8	11.4	11.5	0.436
NM-SSJ	Navajo Lake	San Juan	35-045-0018	190	-4.7	-4.8	10.3	10.6	0.618
NM-SSJ	Chaco	San Juan	35-045-0020	190	-3.5	-3.7	10.7	10.8	0.543
NM-SSJ	Sub Station	San Juan	35-045-1005	191	-3.6	-3.8	9.9	10.1	0.574
CO-NSJ	Lake Capota	Archuleta	08-007-7004	190	7.8	8.4	12.7	13.0	0.505
CO-NSJ	Shamrock	La Plata	08-067-1004	185	3.1	3.3	10.4	10.3	0.583
CO-NSJ	Ignacio	La Plata	08-067-7001	195	-3.4	-3.5	10.0	10.3	0.626
CO-NSJ	Bondad	La Plata	08-067-7003	195	-4.4	-4.6	10.2	10.7	0.645
CO-NSJ	Cortez	Montezuma	08-083-0006	194	1.3	1.4	9.7	9.7	0.565
CO-NSJ	Mesa Verde NP	Montezuma	08-083-0101	198	-1.0	-1.0	9.2	9.3	0.595
CO-NSJ	TowaocUMU2	Montezuma	08-083-8001	197	0.6	0.6	9.8	9.8	0.558
AZ-Misc	Chiricahua NM	Cochise	04-003-8001	195	-5.8	-5.4	12.8	13.1	0.613
AZ-Misc	Petrified Forest NP	Navajo	04-017-0119	192	-5.1	-5.3	10.3	10.6	0.647
TX-Misc	Palo Duro	Randall	48-381-9991	172	-20.6	-22.4	21.6	23.9	0.683

Except for the correlation coefficient, the CAMx 2022v2 12/4 km model performance for hourly ozone is generally not as good as it is for MDA8 ozone (Figure 4-3 and Table 4-4). The MDA8 ozone NMB achieved the Performance Criterion at almost all sites and Performance Goal at over 40% of the sites, for hourly ozone there are five sites with NMB that fail to meet the Performance Criterion and a comparable number of sites (a little over 40%) with hourly ozone NMB that meet the bias Performance Goal. Not surprisingly, the hourly ozone performance shows higher errors than the MDA8 ozone performance; the NME only meets the error Performance Goal at three sites (compared to MDA8 NME Performance Goal that is met at all sites but one) with 3 sites with hourly NME failing to meet the error Performance Criterion. One reason the model shows degraded performance for hourly ozone compared to MDA8 ozone at some sites is due to poorer performance during nighttime low ozone concentration hours when the point measurement may see more influence from local NO_x sources that can titrate the ozone, whereas the local NO_x sources have less influenced on the modeled nighttime hourly ozone due to the 4 km grid cell averaging.

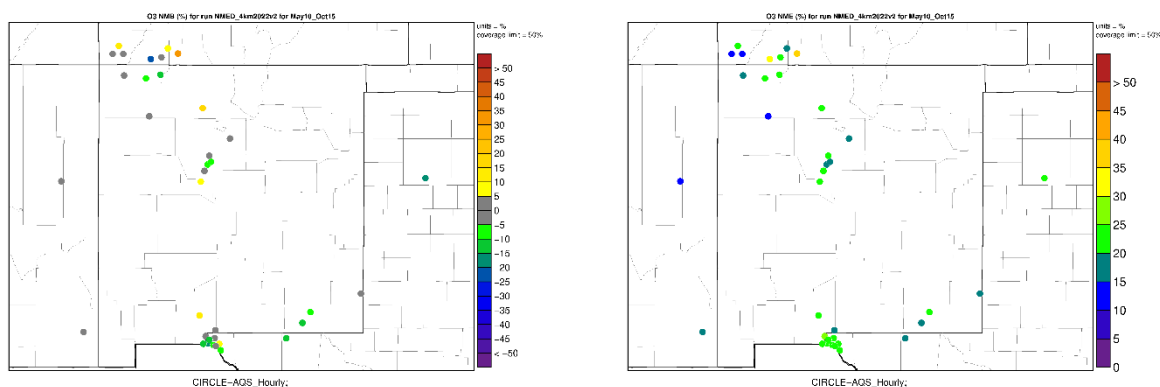


Figure 4-3. Spatial distribution of CAMx 2022v2 4 km NMB (left) and NME (right) hourly ozone performance statistics for the May 10 through October 15, 2022 modeling period.

Table 4-4. Bias (NMB and FB), error (NME and FE) and correlation (COR) hourly ozone performance statistics by site for the CAMx 2022v2 4 km base case and May 10 through October 15, 2022 modeling period.

Region	Local Name	County	SiteID	N	NMB	FB	NME	FE	COR
NM-PB	Carlsbad Caverns	Eddy	35-015-0010	3636	-14.7	19.0	-14.6	20.3	0.707
NM-PB	Carlsbad City	Eddy	35-015-1005	3634	-5.8	22.8	1.5	27.2	0.806
NM-PB	Hobbs	Lea	35-025-0008	3755	-4.9	17.3	-2.0	18.8	0.790
TX_PB	Guadalupe Mtn NP	Culberson	48-109-0002	1850	-13.1	17.3	-14.1	18.8	0.616
NM-S	La Union	Dona Ana	35-013-0008	3745	3.5	26.2	13.3	32.9	0.701
NM-S	Chaparral	Dona Ana	35-013-0020	3771	-2.0	18.3	1.4	20.3	0.718
NM-S	Desert View	Dona Ana	35-013-0021	3771	-16.6	23.4	-19.2	29.9	0.756
NM-S	Santa Teresa	Dona Ana	35-013-0022	3773	-13.8	22.3	-15.6	27.7	0.736
NM-S	Solano	Dona Ana	35-013-0023	3753	11.6	22.2	16.5	25.8	0.731
TX_EP	Ivanhoe	El Paso	48-141-0029	3713	9.3	21.6	11.7	24.6	0.723
TX_EP	El Paso Chamizal	El Paso	48-141-0044	3493	-6.2	24.6	-9.0	34.8	0.742
TX_EP	Ascarate Park SE	El Paso	48-141-0055	3672	2.4	24.9	8.0	35.7	0.770
TX_EP	Socorro Hueco	El Paso	48-141-0057	3744	-6.4	23.1	-3.6	31.6	0.725
TX_EP	Skyline Park	El Paso	48-141-0058	3664	2.0	22.4	6.0	25.3	0.647
TX_EP	Ojo De Agua	El Paso	48-141-1021	3730	-13.5	21.1	-13.5	23.2	0.638
NM-Cen	Del Norte	Bernalillo	35-001-0023	3590	-6.7	19.1	-3.4	21.9	0.744
NM-Cen	South Valley	Bernalillo	35-001-0029	3405	1.6	22.5	10.5	29.0	0.737
NM-Cen	Foot Hills	Bernalillo	35-001-1012	3649	-8.2	17.9	-6.7	19.1	0.611
NM-Cen	Bernalillo	Sandoval	35-043-1001	3764	4.2	20.4	10.5	25.2	0.773
NM-Cen	Santa Fe	Santa Fe	35-049-0021	3759	0.6	18.8	4.0	21.3	0.654
NM-Cen	Los Lunas	Valencia	35-061-0008	3772	6.2	22.2	12.2	26.7	0.715
NM-SSJ	Coyote	Rio Arriba	35-039-0026	3765	16.5	23.7	20.0	26.0	0.645
NM-SSJ	Bloomfield	San Juan	35-045-0009	3625	-6.0	22.4	-4.5	32.8	0.811
NM-SSJ	Navajo Lake	San Juan	35-045-0018	3711	-12.2	20.5	-18.6	27.9	0.801
NM-SSJ	Chaco	San Juan	35-045-0020	3679	-1.4	14.2	-0.2	15.2	0.689
NM-SSJ	Sub Station	San Juan	35-045-1005	3729	-1.6	15.5	-0.8	17.5	0.792
CO-NSJ	Lake Capota	Archuleta	08-007-7004	3577	31.7	37.2	36.4	40.3	0.702
CO-NSJ	Shamrock	La Plata	08-067-1004	3537	5.6	15.6	6.9	16.4	0.620
CO-NSJ	Ignacio	La Plata	08-067-7001	3699	2.4	21.3	4.4	25.6	0.757
CO-NSJ	Bondad	La Plata	08-067-7003	3686	-23.2	30.6	-46.3	54.2	0.793
CO-NSJ	Cortez	Montezuma	08-083-0006	3782	12.3	22.5	16.7	25.4	0.706
CO-NSJ	Mesa Verde NP	Montezuma	08-083-0101	3783	-3.9	12.1	-4.3	12.6	0.618
CO-NSJ	TowaocUMU2	Montezuma	08-083-8001	3794	3.4	14.3	4.3	14.9	0.666
AZ-Misc	Chiricahua NM	Cochise	04-003-8001	3768	1.8	19.3	4.4	20.5	0.569
AZ-Misc	Petrified Forest NP	Navajo	04-017-0119	3752	-4.1	13.2	-3.7	13.9	0.735
TX-Misc	Palo Duro	Randall	48-381-9991	3045	-16.1	22.0	-14.7	23.7	0.702

4.4 Ozone Model Performance in the Permian Basin

Four ozone monitoring sites operated in the Permian Basin during 2022: three in New Mexico and one in Texas. In the previous section (Table 4-3 and Table 4-4), the NMB at the four sites in the Permian Basin mostly fell between the Performance Goal and Criterion for MDA8 and hourly ozone concentrations with an underestimation bias (i.e., NMB between -5% and -15%) except for the Carlsbad Cavern site whose NMB underestimation bias (-15.7%) was barely outside the bias Performance Criterion benchmark. Figure 4-4 shows scatter and time series plots comparing predicted and observed MDA8 ozone concentrations at the four sites in the Permian Basin. The scatter plots indicate the model underestimates MDA8 ozone with NMB ranging from -10% to -16%.

The monthly time series comparing predicted and observed MDA8 ozone concentrations at Carlsbad City (Figure 4-5) and Hobbs (Figure 4-6) include results from the Phase I CAMx 2022v1 12/4 km flexinest and the current Phase II CAMx 2022v2 4 km base case simulations. Good agreement in both simulations occur during the first 20 days of May, which are dominated by the Boundary Conditions, a result known from the Phase I CAMx 2022v1 12 km ozone source apportionment simulation. The model tends to underestimate MDA8 ozone throughout, but this underestimation is worse in July and August than the period of May to June. The CAMx 2022v1 12/4 km flexinest simulation tends to produce higher ozone due to NO_x emissions errors in the O&G drilling and fracking for the 2022v1 inventory, as mentioned previously in Chapter 4. The incorrect emissions were four times too high compared to the 2022v2 emissions inventory.

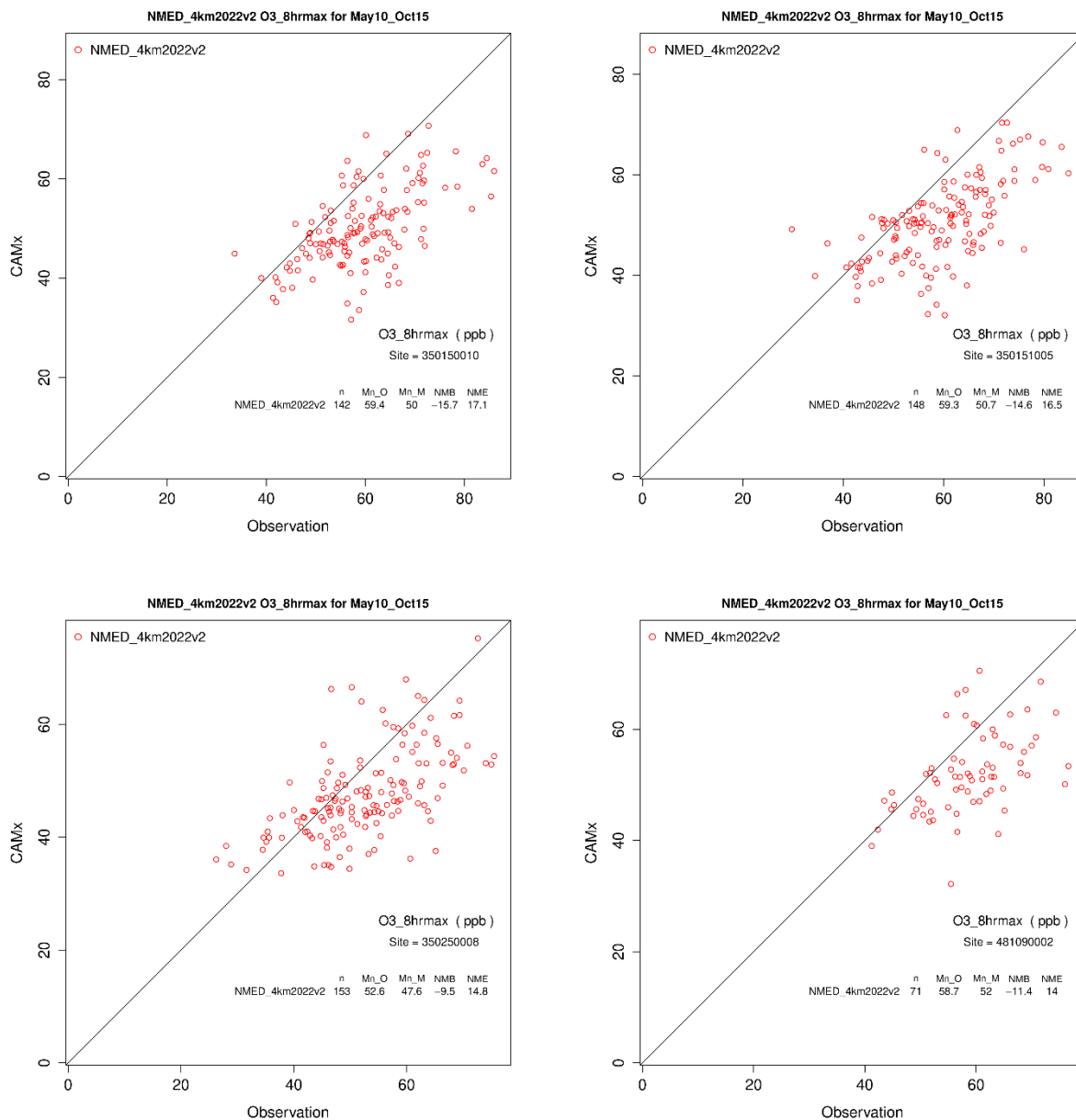


Figure 4-4. Scatter plots of predicted (CAMx 2022v2 4 km) and observed MDA8 ozone concentrations at monitoring sites in the Permian Basin: Carlsbad Cavern (350150010; top left), Carlsbad City (350151005; top right), Hobbs (350250008; bottom left) and Guadalupe Mountains NP (481090002; bottom right).

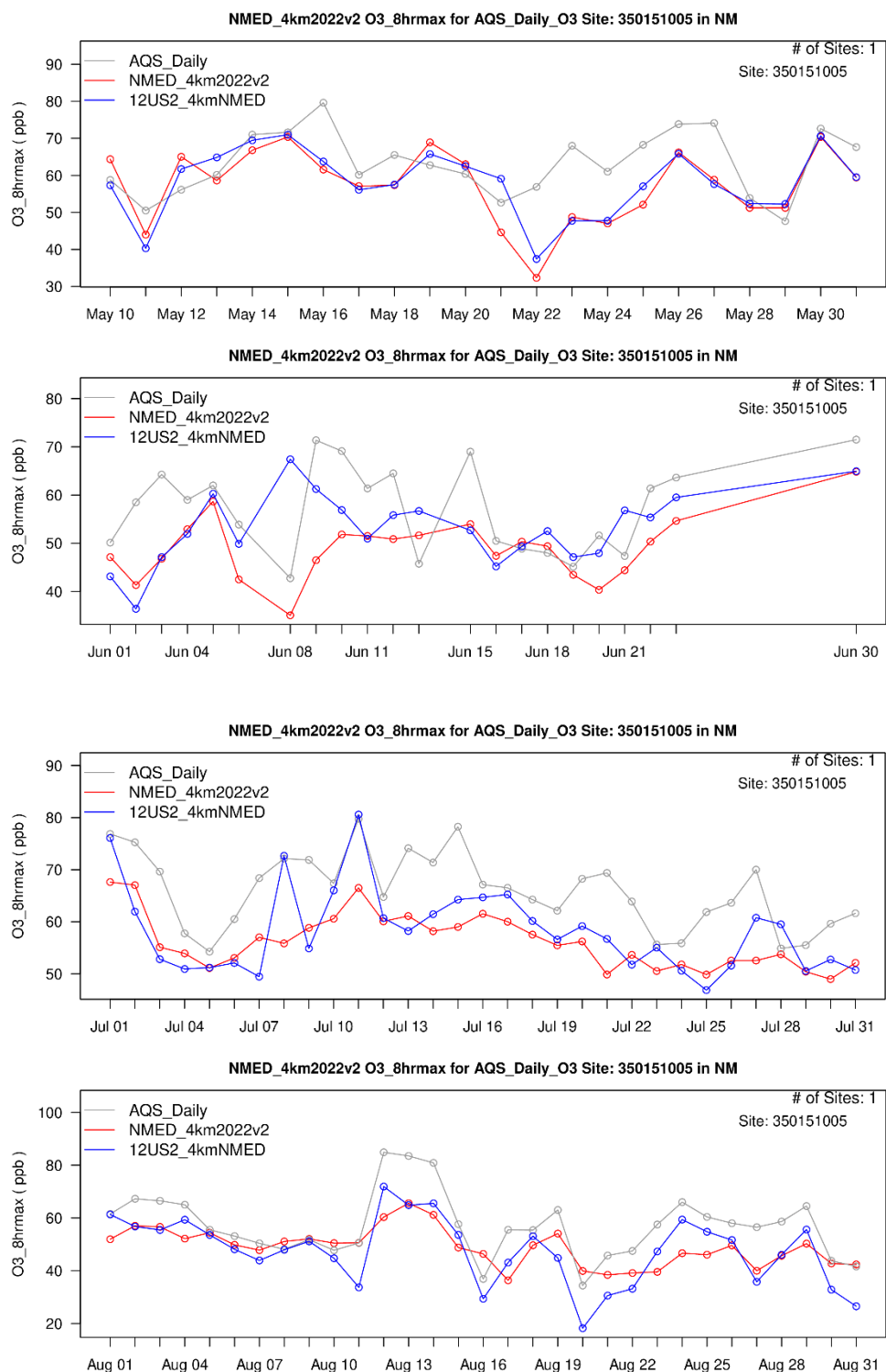


Figure 4-5. Time series plots of predicted and observed MDA8 ozone concentrations at the Carlsbad City (350151005) monitoring site, the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

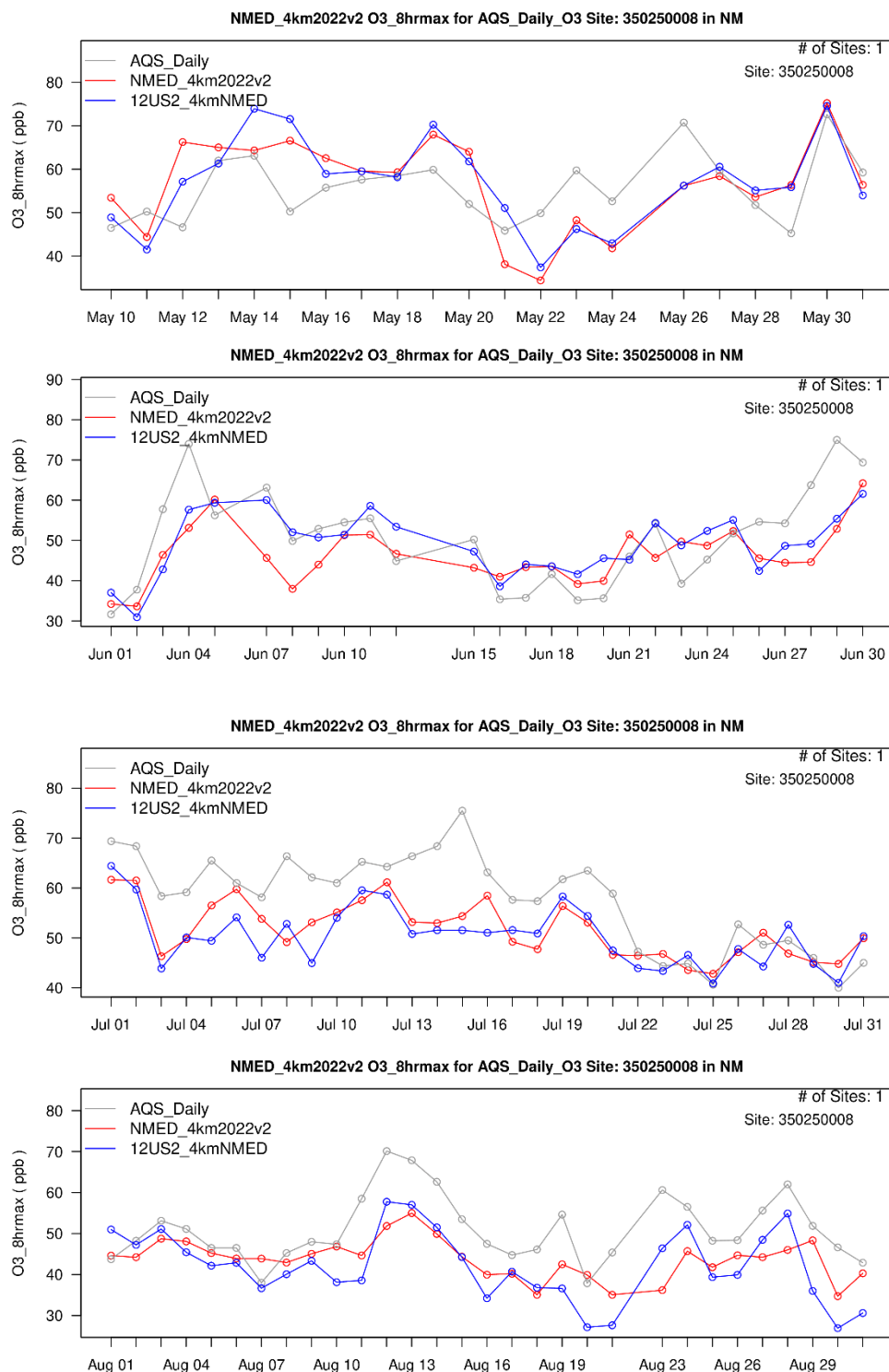


Figure 4-6. Time series plots of predicted and observed MDA8 ozone concentrations at the Hobbs (350250008) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

Figure 4-7 shows the hourly ozone scatter plots for the CAMx 2022v2 4 km base case at sites in the Permian Basin. Consistent with the MDA8 ozone results, the model underestimates hourly ozone, with an NMB of approximately –14% at the Carlsbad City and Guadalupe Mountains sites and approximately –5% at the Carlsbad Caverns and Hobbs sites. At the Carlsbad City site, both modeled and observed hourly ozone concentrations approach zero, whereas concentrations remain more elevated at the Carlsbad Caverns site, indicating a stronger influence of local NO_x emissions and nighttime ozone titration at Carlsbad City. At the Hobbs site, there are four hours during 2022 in which observed ozone concentrations reach 80 ppb or higher, and these events are reproduced extremely well by the model.

Time series of predicted and observed hourly ozone concentrations for six episodes during the May to October 2022 evaluation period at the three New Mexico Permian Basin monitoring sites are shown in Figure 4-8 and Figure 4-9. The hourly time series include results from three CAMx simulations: (1) the Phase II CAMx 2022v2 4 km base case (red); (2) the Phase I EPA 2022v1 12 km platform (green); and (3) the Phase I CAMx 2022v1 12/4 km flexi-nest scenario (blue). These comparisons provide insight into ozone model performance in the Permian Basin, showing that the CAMx 2022v1 12/4 km and 2022v2 4 km simulations frequently underestimate observed afternoon hourly ozone peaks on many days, while on other days the modeled diurnal pattern agrees well with observations. Overall, the CAMx Phase I 2022v1 simulations exhibit slightly better performance than the Phase II 2022v2 simulation, attributable to erroneously higher oil and gas NO_x emissions in the 2022v1 emissions inventory.

During the first episode, the model reproduces observed hourly ozone concentrations extremely well at both Carlsbad monitoring sites on May 14 to 15 and captures the observed morning ozone increase on May 16; however, the modeled afternoon hourly ozone peak on May 16 is lower than observed (Figure 4-8, top panels, and Figure 4-9, top left panel). For the second episode period (May 25 to 30), the model generally captures the observed diurnal ozone pattern, although afternoon peaks are underestimated on some days, while on others (e.g., May 30) the observed hourly ozone peaks are well reproduced. Ozone model performance degrades as the summer of 2022 progresses, with a systematic underestimation evident at Permian Basin sites on most days in July and August, although good hourly ozone performance is observed on July 10 to 11.

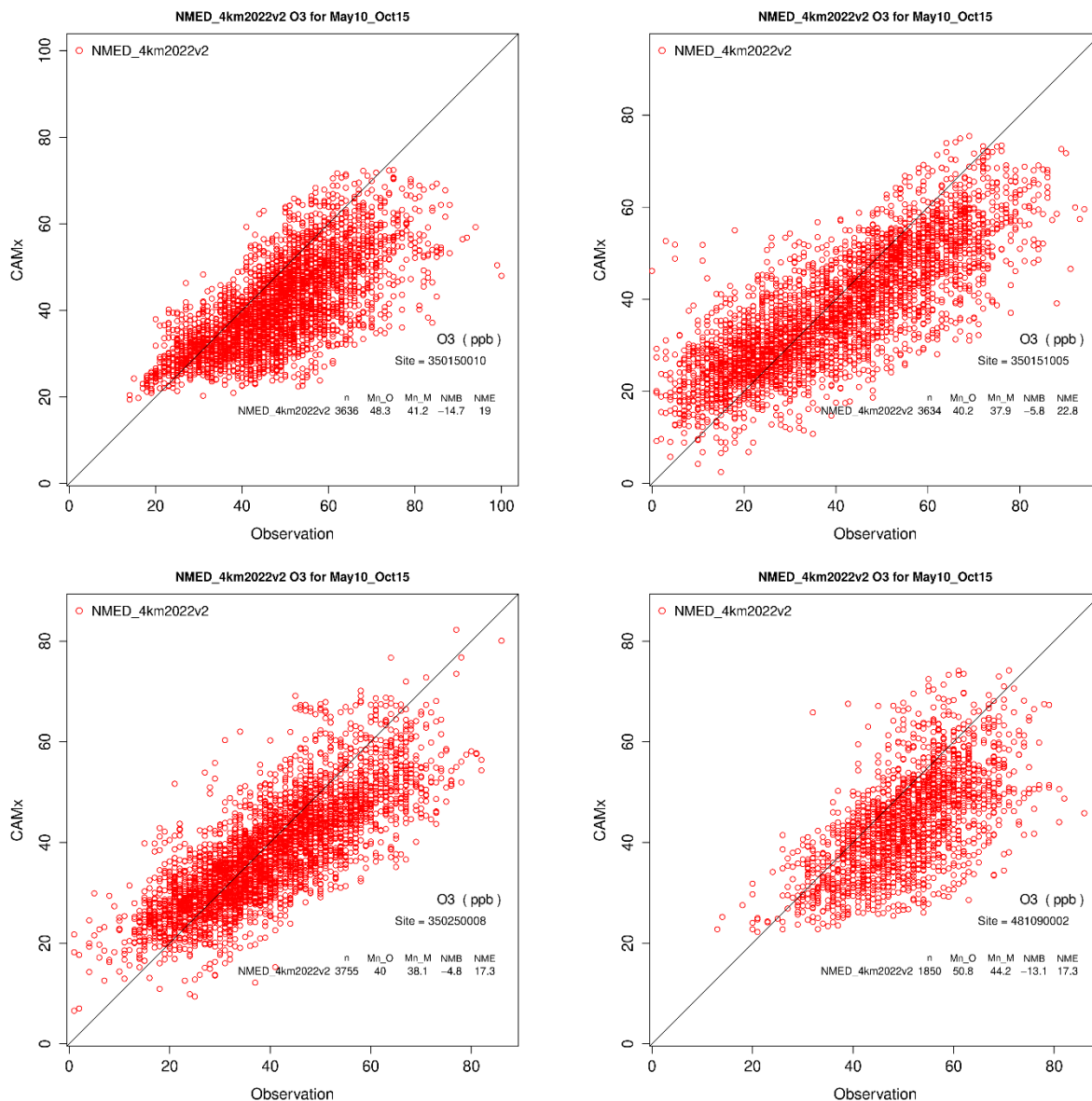


Figure 4-7. Scatter plots of predicted and observed hourly ozone concentrations at monitoring sites in the Permian Basin: Carlsbad Cavern (350150010; top left), Carlsbad City (350151005; top right), Hobbs (350250008; bottom left) and Guadalupe Mountains NP (481090002; bottom right).

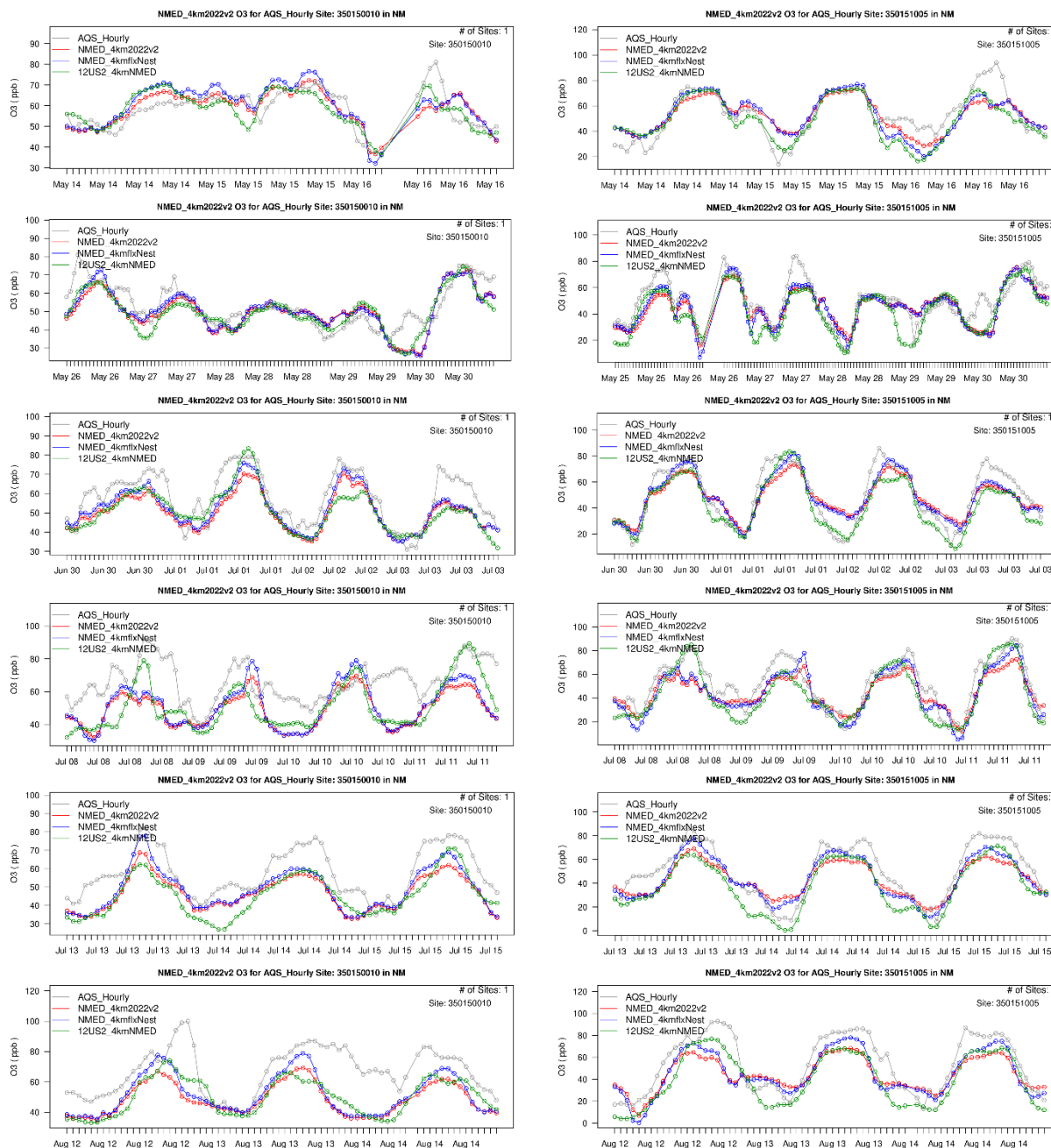


Figure 4-8. Time series of predicted and observed hourly ozone concentration at the Permian Basin Carlsbad Cavern (350150010) and Carlsbad City (350151005) monitoring sites for six episodes during the summer 2022 and the CAMx 2022v1 12 km base case simulation.

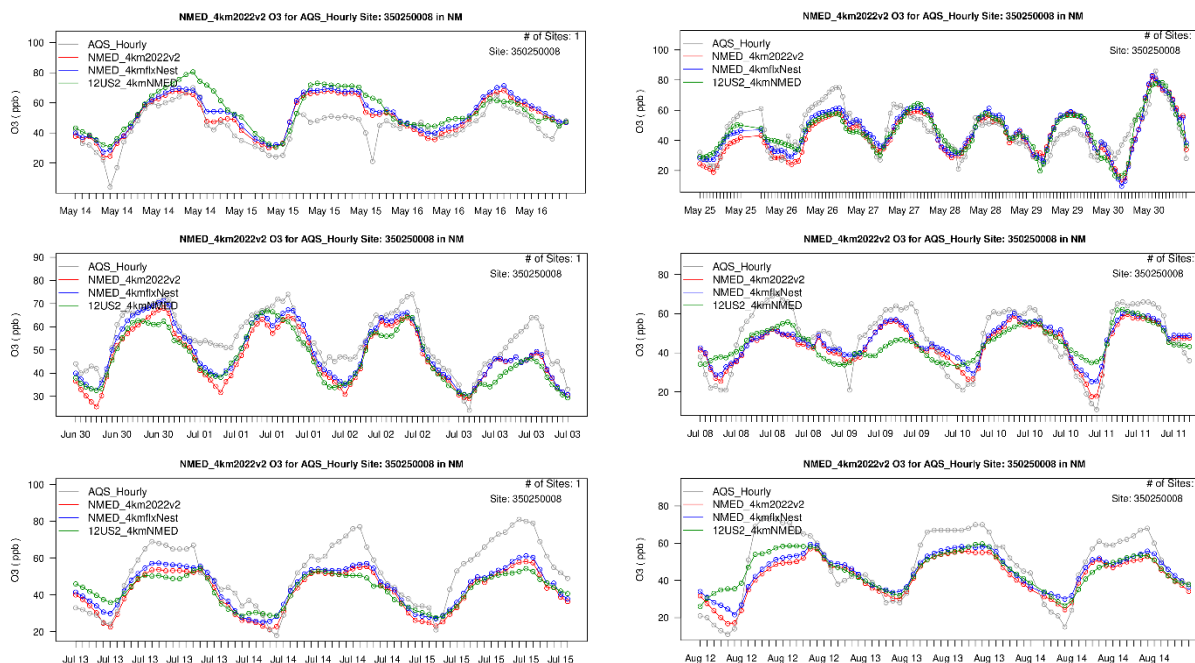


Figure 4-9. Time series of predicted and observed hourly ozone concentration at the Permian Basin Hobbs (350250008) monitoring site for six episodes during the summer 2022 and the CAMx 2022v1 12 km base case simulation.

4.5 Ozone Model Performance in Doña Ana County in Southern New Mexico

There are five monitoring sites in Doña Ana County in southern New Mexico, with most located within the El Paso–Las Cruces TX–NM ozone nonattainment area for the 2015 ozone NAAQS. Except for the Solano monitoring site, which is in central Doña Ana County outside of the nonattainment area and exhibits a low MDA8 ozone NMB (3.8%), the remaining four sites are located near El Paso, TX and show model performance similar to the nearby El Paso sites. These four sites in southern Doña Ana County exhibit MDA8 ozone underestimation biases that fall between the Performance Goal and Criterion (NMB ranging from -7.3% to -14.5% ; Table 4-3).

Scatter plots of predicted and observed MDA8 ozone concentrations at the Desert View and La Union sites, which have the highest observed ozone concentrations in Doña Ana County, are shown in Figure 4-10. The MDA8 ozone underestimation bias at Desert View (-14.5%) is greater than at La Union (-7.5%), reflecting higher observed ozone concentrations at Desert View as the modeled MDA8 ozone concentrations are very similar at the two sites.

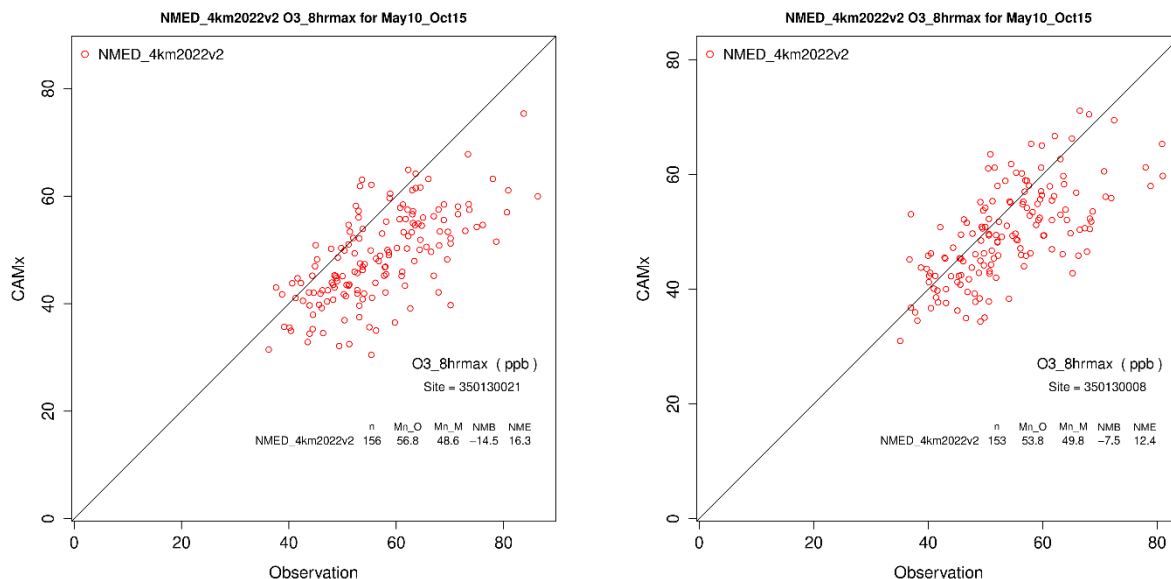


Figure 4-10. Scatter plots of predicted and observed MDA8 ozone concentrations at the Desert View (350130021; left) and La Union (350130008; right) Doña Ana County monitoring sites in southern New Mexico.

Time series of predicted and observed MDA8 ozone concentrations at the Desert View and La Union sites for the months of May, June, July, and August are shown in Figure 4-11 and Figure 4-12. The model reproduces observed MDA8 ozone concentrations reasonably well in May and most of June at these two Doña Ana County sites. Similar to the behavior observed at the Permian Basin ozone sites, the model begins to exhibit a larger and nearly systematic underestimation bias of observed MDA8 ozone concentrations toward the end of June, with this underestimation persisting through July and August.

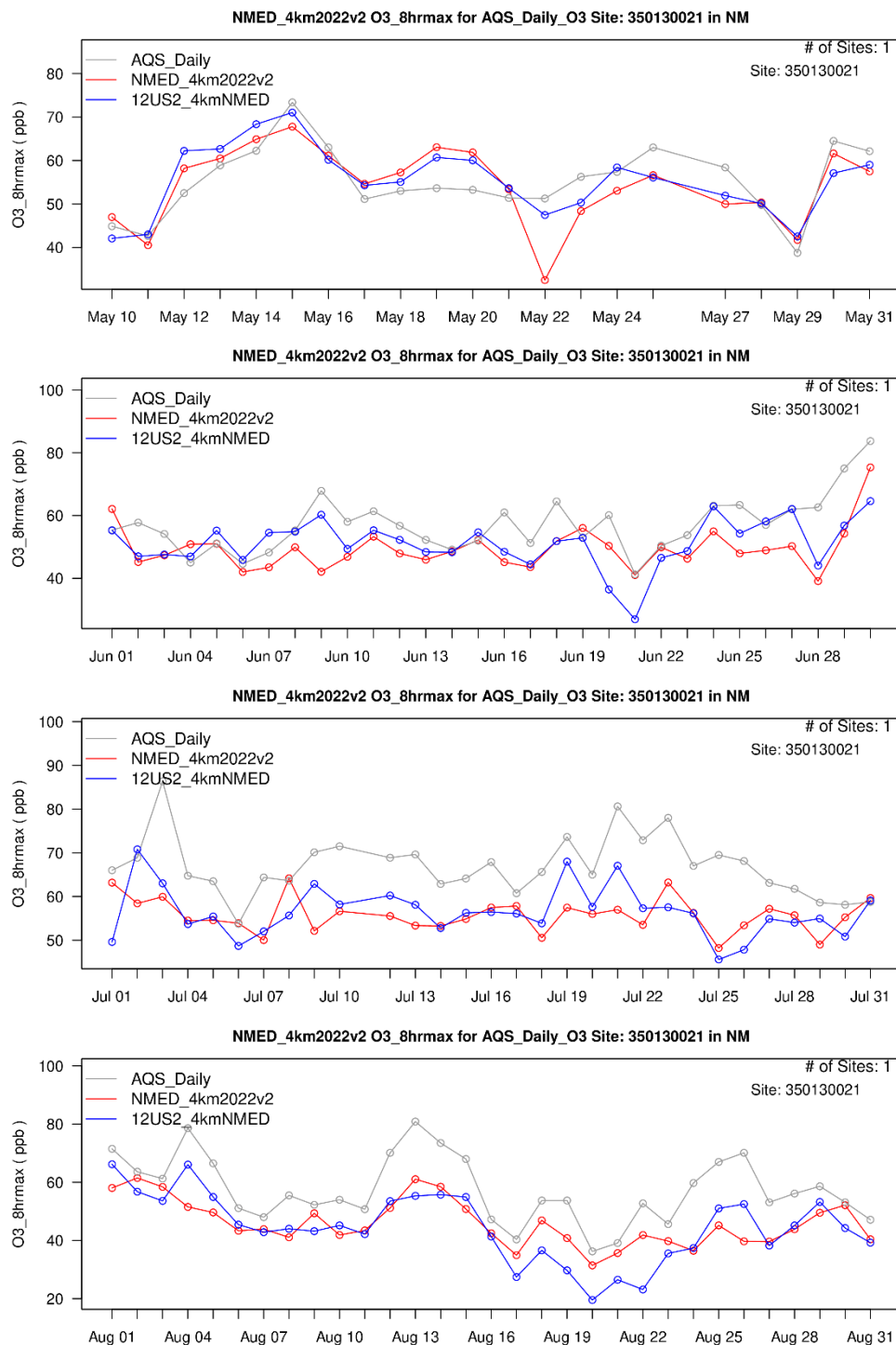


Figure 4-11. Time series plots of predicted and observed MDA8 ozone concentrations at the Desert View (350130021) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

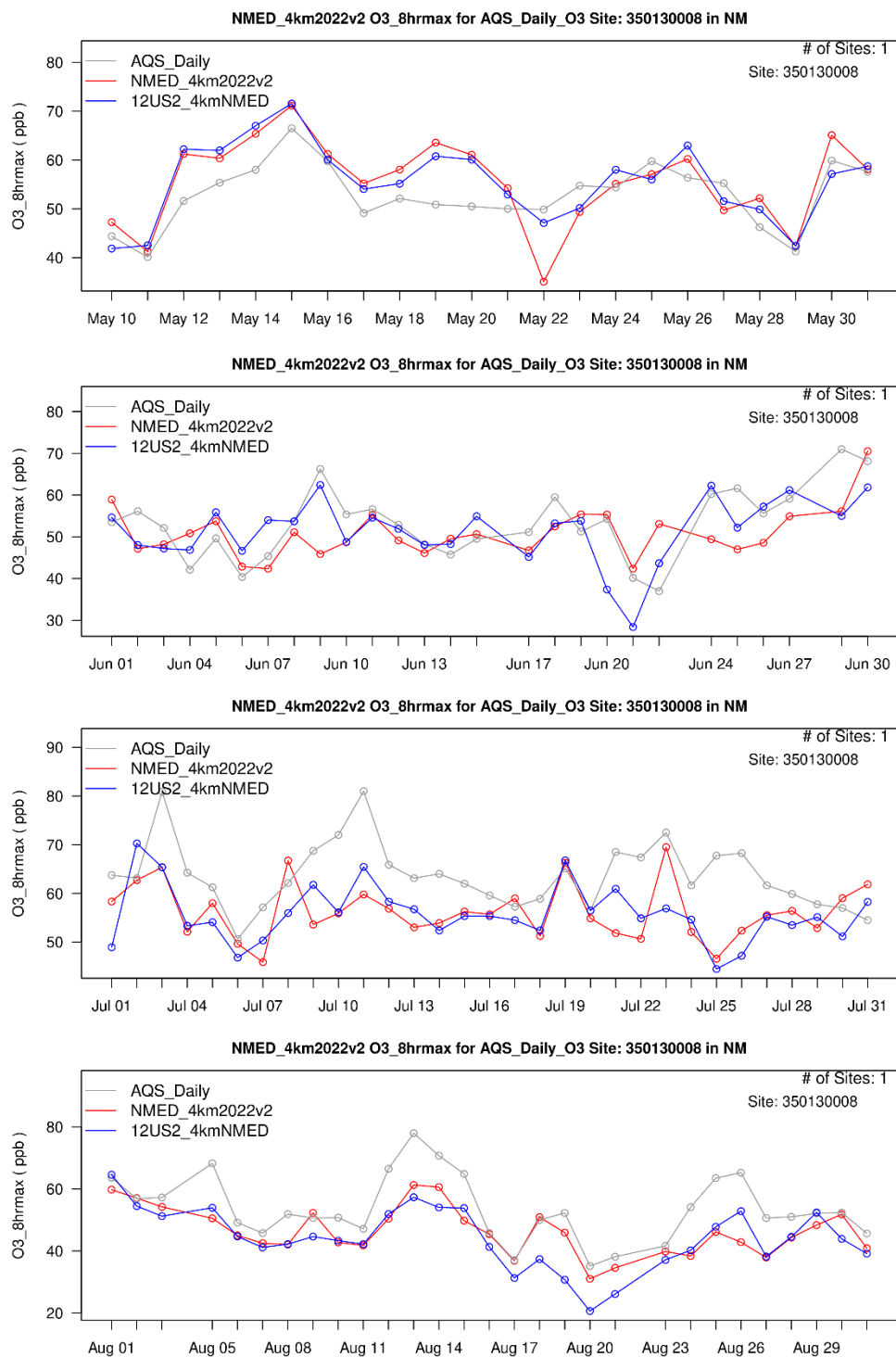


Figure 4-12. Time series plots of predicted and observed MDA8 ozone concentrations at the La Union (35013008) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

The hourly ozone scatter plots for the Desert View and La Union monitors are shown in in Figure 4-13, with Desert View exhibiting an NMB of -16.6% and La Union exhibiting an NMB of $+3.5\%$. The large negative bias at Desert View results from underestimation of both low nighttime and higher afternoon ozone concentrations. In contrast, the positive bias at La Union is driven by overestimation of low nighttime observed ozone, likely due to dilution of local NO_x emissions within the 4 km grid cell, while observed high afternoon hourly ozone concentrations are underestimated.

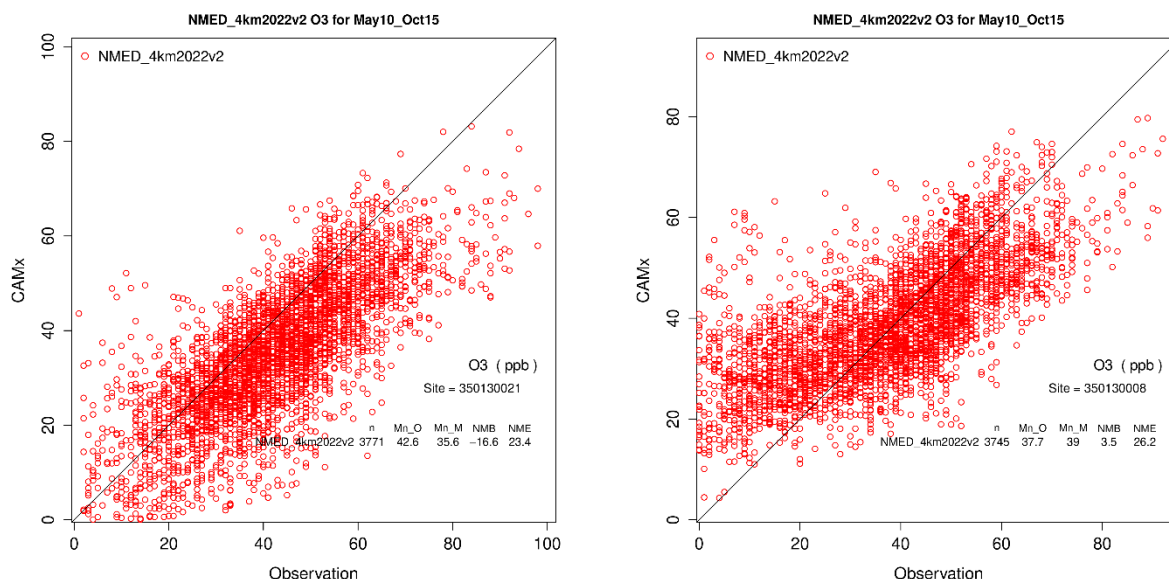


Figure 4-13. Scatter plots of predicted and observed hourly ozone concentrations at the Desert View (350130021) and La Union (35013008) Doña Ana County monitoring sites in southern New Mexico.

Time series of predicted and observed hourly ozone concentrations at the Desert View and La Union sites for the six selected episodes are shown in Figure 4-14. During the May 14–16 episode, the model does not reproduce the observed diurnal trends at both Doña Ana County sites, with higher modeled nighttime hourly ozone concentrations than observed for unknown reasons, as the model more accurately captures observed nighttime minima during other episodes. For the first four episodes occurring in May, June, and early July, the model generally reproduces observed diurnal hourly ozone concentrations on most days, although afternoon hourly ozone peaks are underestimated on some days (e.g., July 3). For the final two episodes in the second half of July and August, the model consistently underestimates observed afternoon hourly ozone concentrations, with larger underestimation at the Desert View site than at the La Union site.

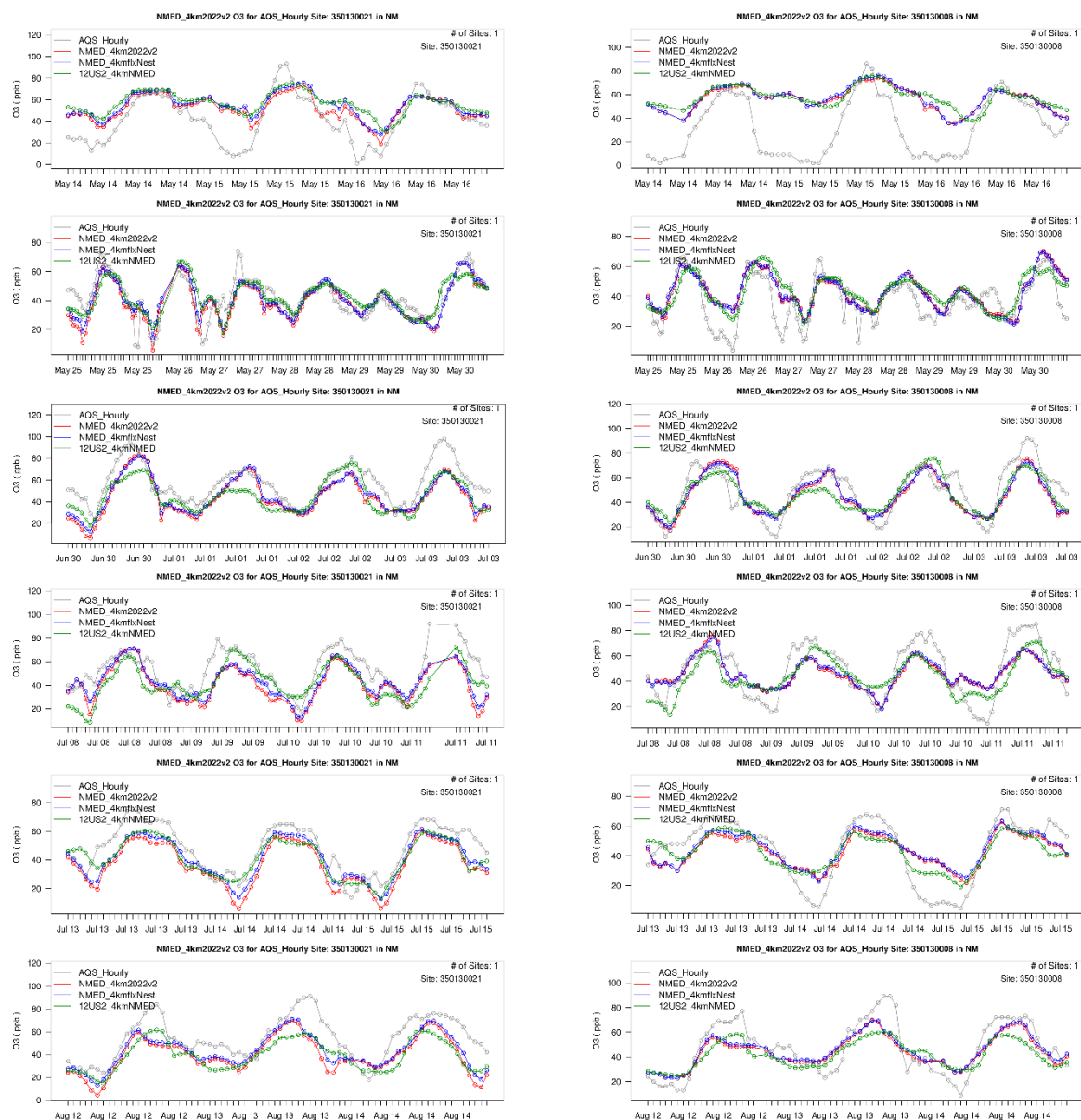


Figure 4-14. Time series of predicted and observed hourly ozone concentration at the Doña Ana County Desert View (350130021; left) and La Union (350130008; right) monitoring sites for six episodes during the summer 2022 and the CAMx 2022v2 4 km base case simulation.

4.6 Ozone Model Performance in El Paso, Texas

There are six ozone monitoring sites operating in El Paso, Texas during 2022. The MDA8 ozone NMB across these sites ranges from -11.7% to $+7.2\%$, with all sites meeting the bias Performance Criterion and three sites meeting the bias Performance Goal (Table 4-3). Example ozone model performance is presented for the Ojo De Agua (481411021) and Socorro Hueco (481410057) sites, which experience some of the highest ozone concentrations and represent the westernmost and easternmost monitoring sites in El Paso, respectively. MDA8 ozone scatter plots and time series plots for these two sites are shown in Figure 4-15 through Figure 4-17.

The MDA8 ozone performance at Ojo De Agua (-12% NMB) is similar to that at the nearby Desert View site, which is expected given their proximity (see Figure 4-1). In contrast, MDA8 ozone performance at Socorro Hueco and the other El Paso sites is notably better, with lower bias and without the pronounced degradation in model performance beginning in late June and persisting into July and August that is observed at Ojo De Agua and at sites in southern Doña Ana County.

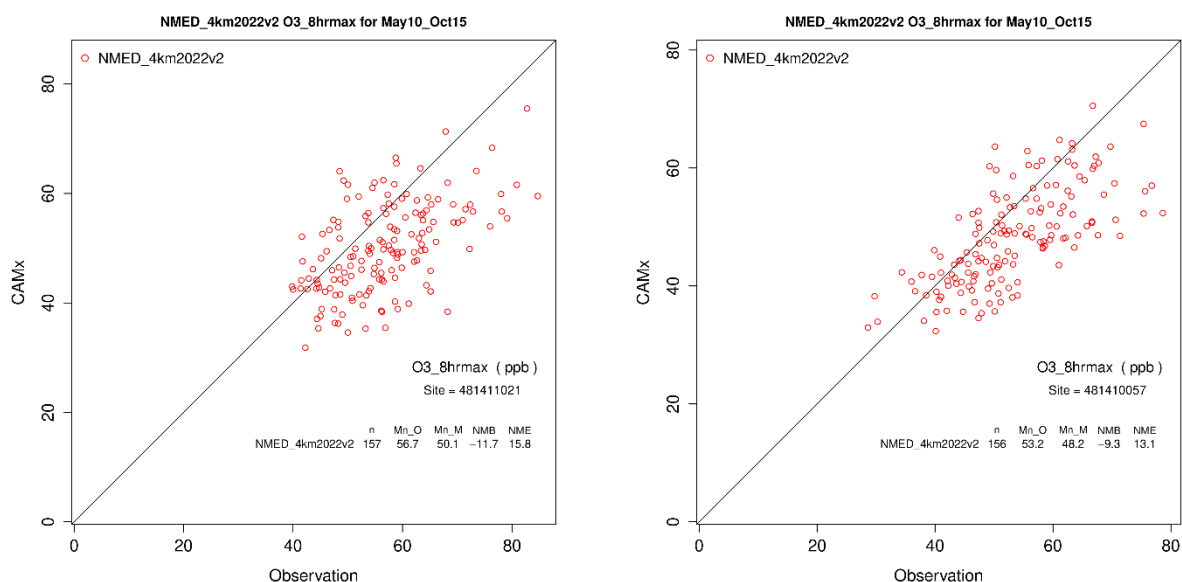


Figure 4-15. Scatter plots of predicted and observed MDA8 ozone concentrations at the Ojo De Agua (481411021) and Socorro Hueco (481410057) monitoring sites in El Paso, Texas.

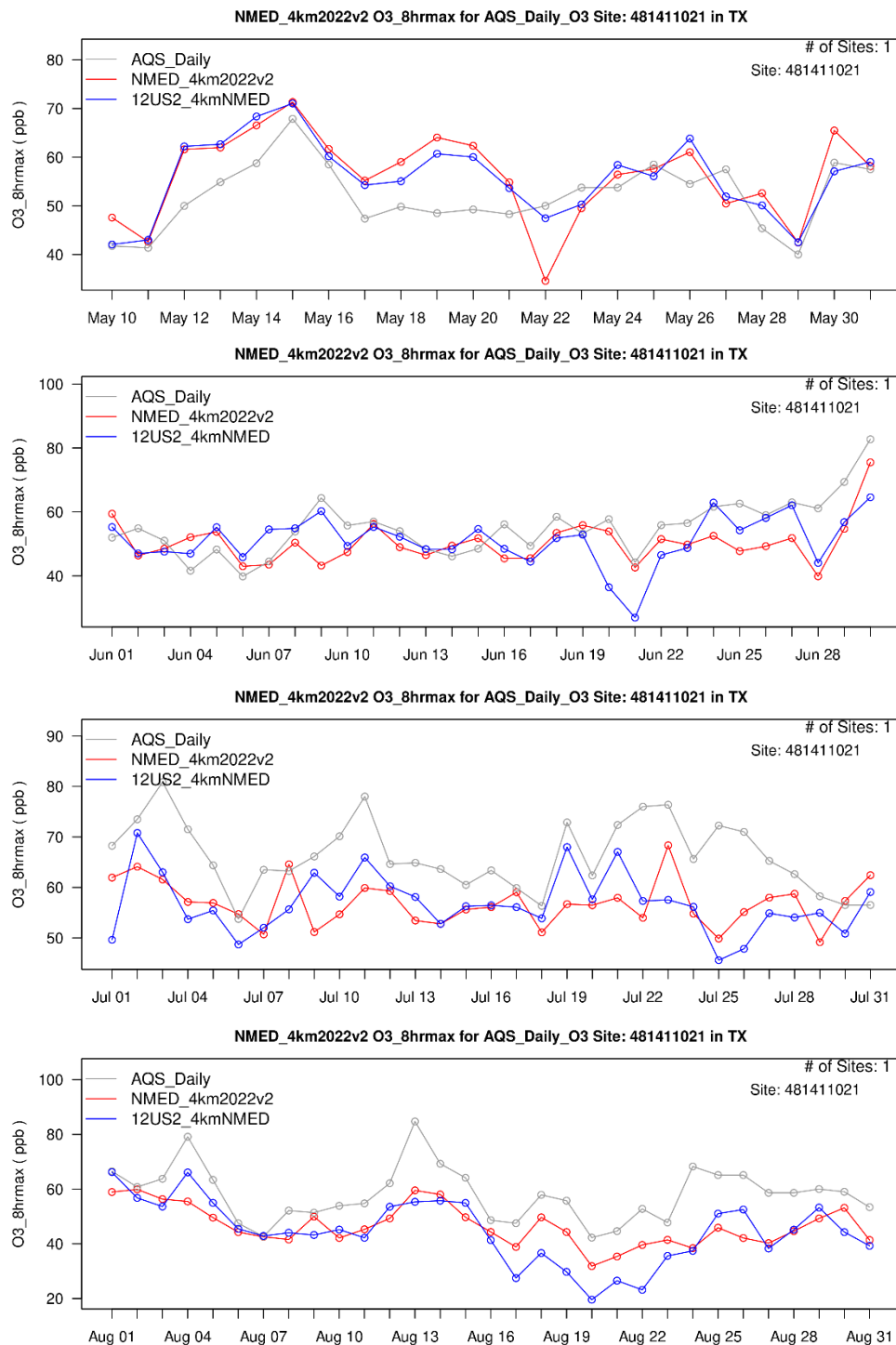


Figure 4-16. Time series plots of predicted and observed MDA8 ozone concentrations at the Ojo De Agua (481411021) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

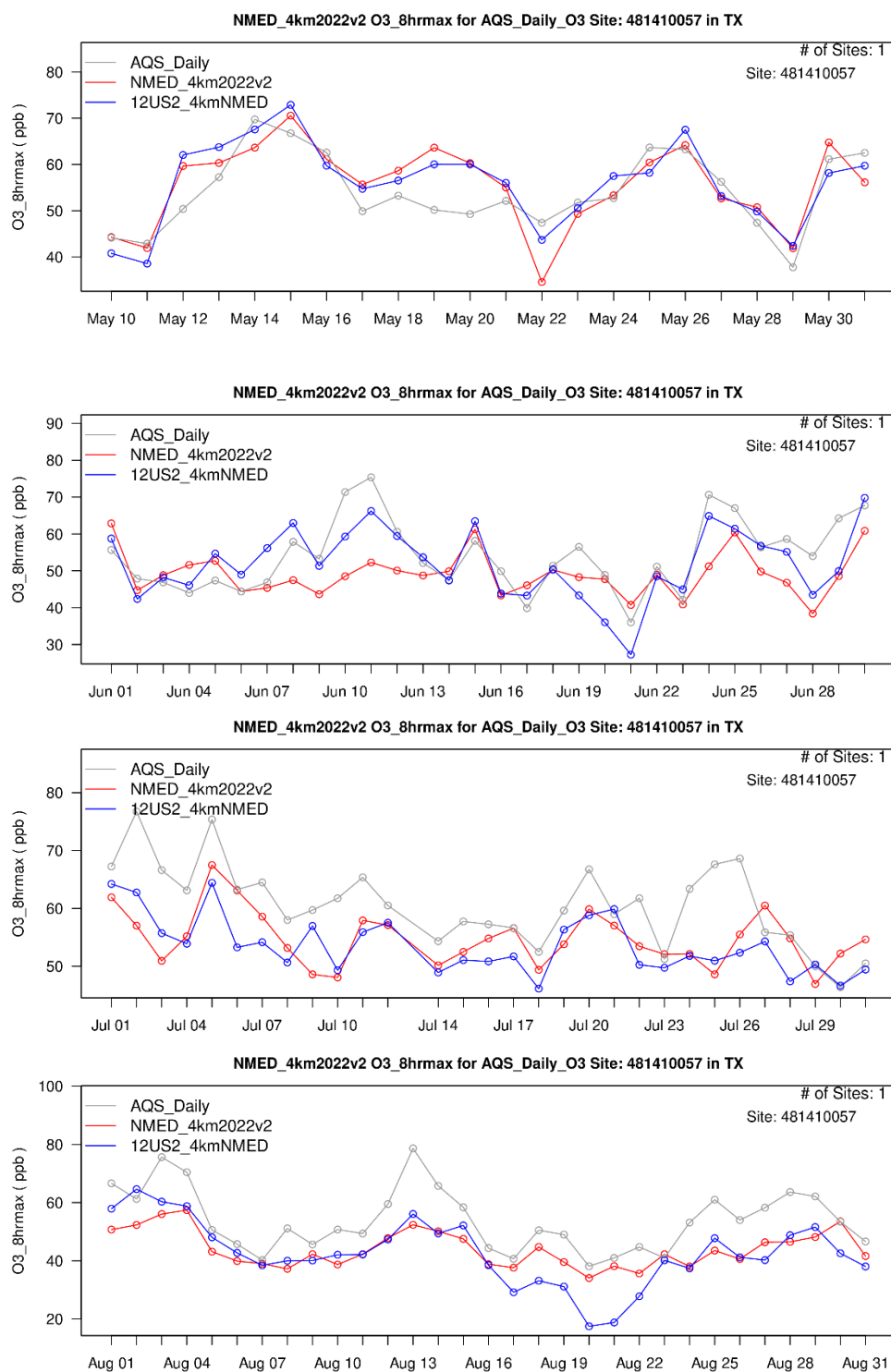


Figure 4-17. Time series plots of predicted and observed MDA8 ozone concentrations at the Socorro Hueco (481410057) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

The hourly ozone scatter plots for the two example El Paso monitoring sites are shown in Figure 4-18, with Ojo De Agua exhibiting an NMB of –14% and Socorro Hueco exhibiting an NMB of –6%. The hourly ozone underestimation at Ojo De Agua is evident in the scatter plot, with the 1:1 line passing through the upper portion of the data distribution. In contrast, the hourly ozone scatter plot at Socorro Hueco shows substantial scatter at lower observed hourly ozone concentrations (<40 ppb), suggesting that the model has difficulty estimating nighttime low hourly ozone at this site.

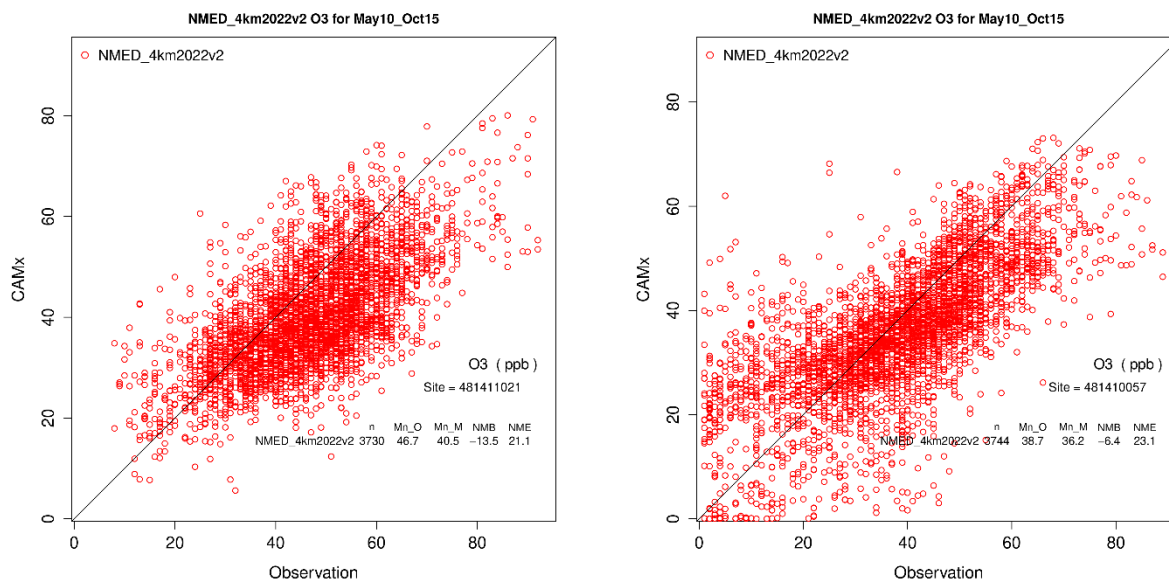


Figure 4-18. Scatter plots of predicted and observed hourly ozone concentrations at the Ojo De Agua (481411021) and Socorro Hueco (481410057) monitoring sites in El Paso, Texas.

Time series comparing predicted and observed hourly ozone concentrations at the two example El Paso sites further demonstrate improved model performance at Socorro Hueco relative to Ojo De Agua (Figure 4-19). At Ojo De Agua, a larger ozone underestimation develops and becomes nearly systematic beginning in late June and continuing through July and August, whereas at Socorro Hueco the model generally matches observed hourly ozone concentrations well through most of the evaluation period. Model performance at Socorro Hueco during the first four episodes is good, with especially strong agreement between modeled and observed hourly ozone variations during the May 25–30 episode.

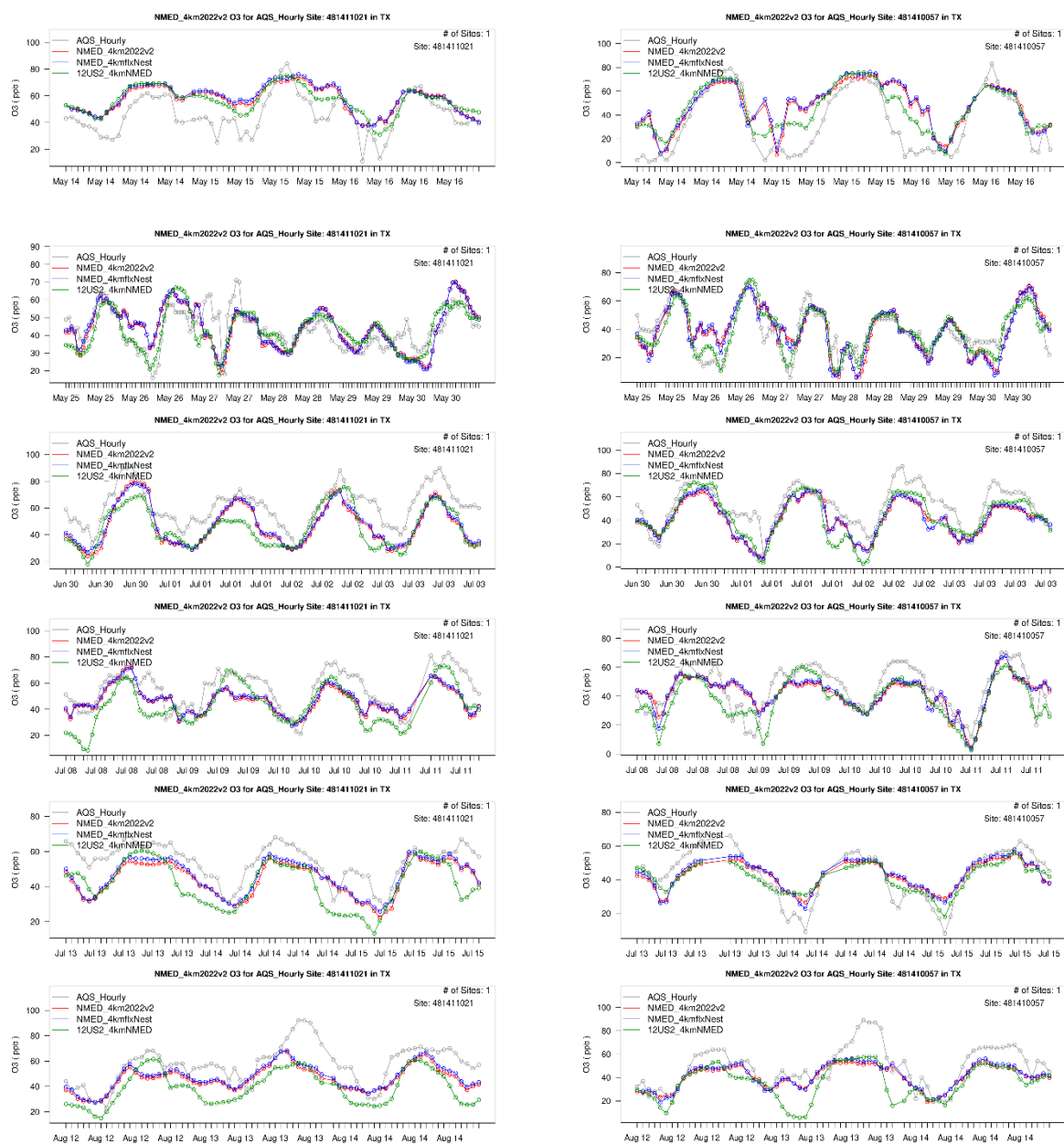


Figure 4-19. Time series of predicted and observed hourly ozone concentration at the Ojo De Agua (481411021) and Socorro Hueco (481410057) monitoring sites in El Paso, Texas for six episodes during the summer 2022 and the CAMx 2022v1 12 km base case simulation.

4.7 Ozone Model Performance in Central New Mexico

There are six monitoring sites in the Central New Mexico region, including three in Bernalillo County and one site each in Sandoval, Santa Fe, and Valencia Counties. Based on performance statistics, ozone model performance at these Central New Mexico sites is slightly better than at the southern (Doña Ana County) and southeastern (Permian Basin) New Mexico sites. The MDA8 ozone NMB ranges from -2.8% to -11.9% (Table 4-3), and the hourly ozone NMB ranges from -8.2% to $+6.2\%$ (Table 4-4), with all sites meeting the bias Performance Criterion and several sites meeting the bias Performance Goal. The Foot Hills site in Bernalillo County and the Bernalillo site in Sandoval County are used as examples of model performance for Central New Mexico because they have the highest 2021–2023 ozone design values (72 and 69 ppb, respectively) among the Central New Mexico sites.

Scatter plots comparing predicted and observed MDA8 ozone concentrations at the Foot Hills and Bernalillo sites are shown in Figure 4-20 and indicate the model shows an average underestimation bias at both locations. Although the modeled MDA8 ozone concentration ranges are similar at the two sites (approximately 40 to 70 ppb), observed MDA8 ozone concentrations are higher at Foot Hills, resulting in a larger underestimation bias (-12%) compared to the Bernalillo site (-5%).

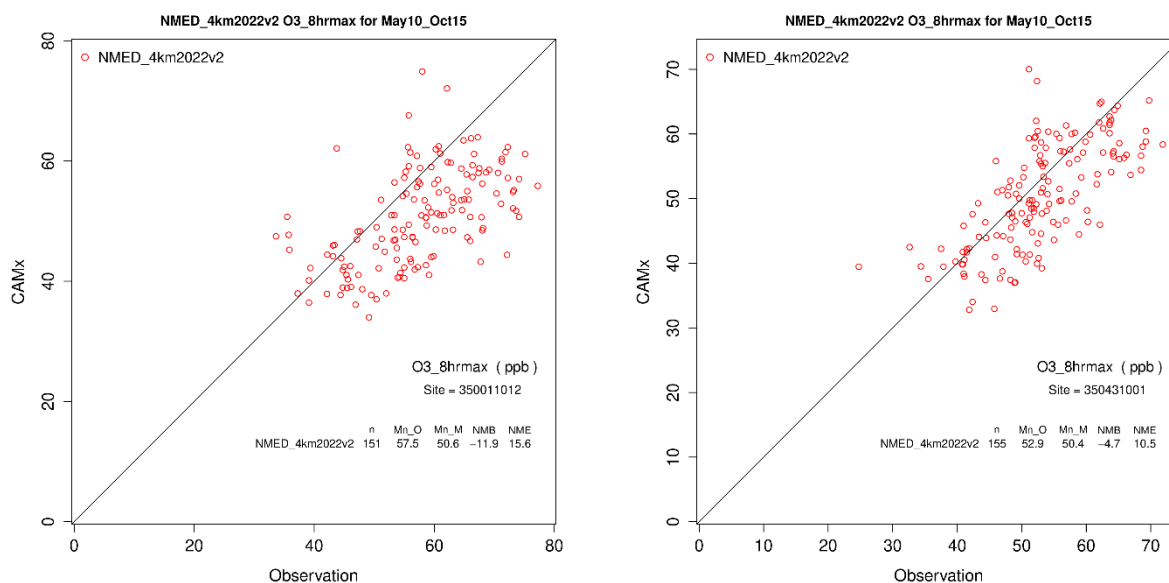


Figure 4-20. Scatter plots of predicted and observed MDA8 ozone concentrations at the Foot Hills (350011012; left) site in Bernalillo County and Bernalillo (350431001; right) site in Sandoval County in Central New Mexico.

The time series of predicted and observed MDA8 ozone concentrations at the Foot Hills and Bernalillo sites are shown in Figure 4-21 and Figure 4-22. At the Foot Hills site, there is good agreement between modeled and observed MDA8 ozone during April, May, and June, including the very low observed ozone concentrations around June 20. Following this low-ozone period, observed MDA8 ozone concentrations are mostly underestimated in late June and throughout July and August at Foot Hills, with improved performance observed in September (not shown). At the Bernalillo site in Sandoval County, the model underestimates high observed MDA8 ozone during July and August; however, the underestimation is smaller than seen at Foot Hills.

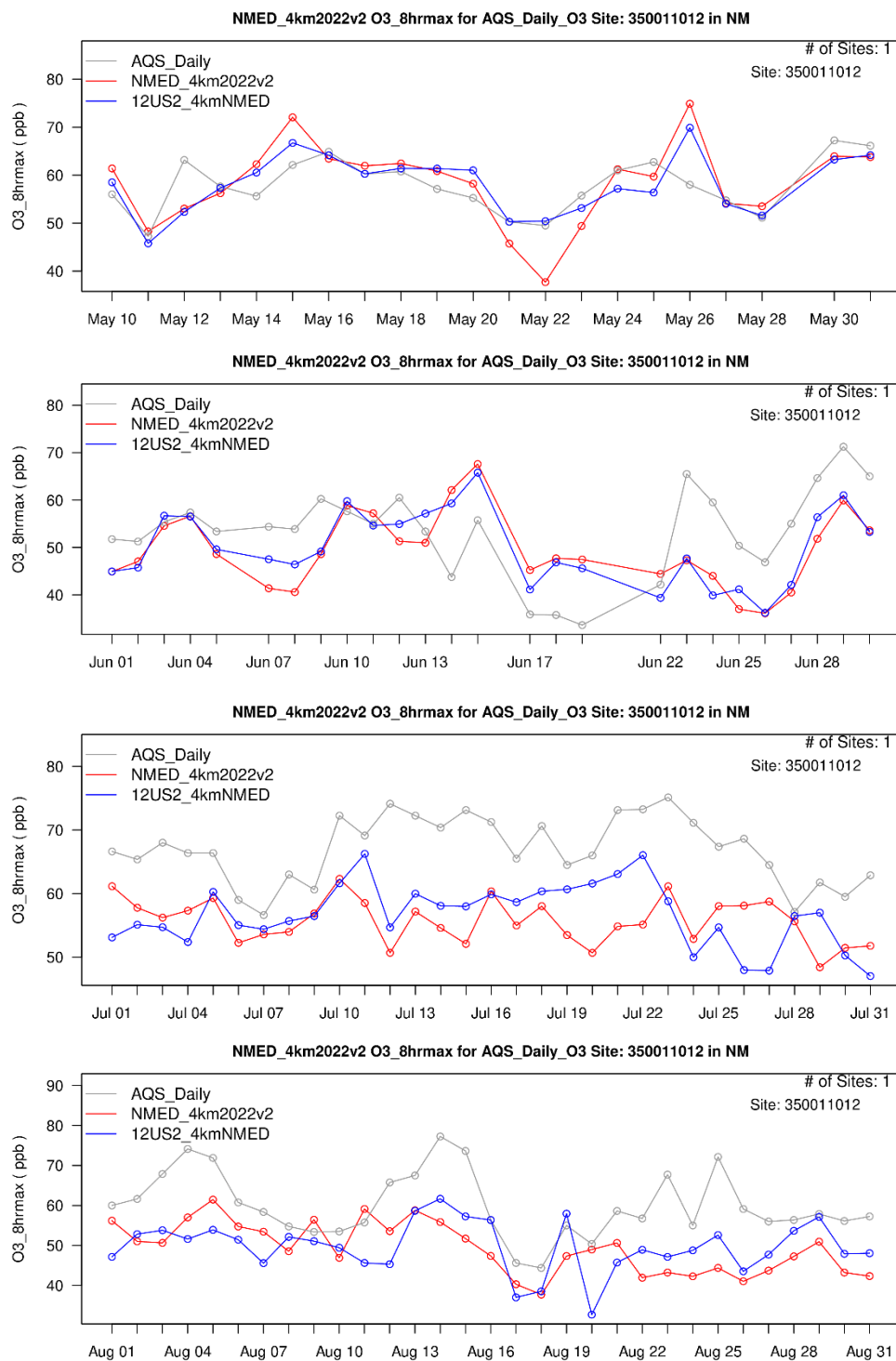


Figure 4-21. Time series plots of predicted and observed MDA8 ozone concentrations at the Foot Hills (350011012) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

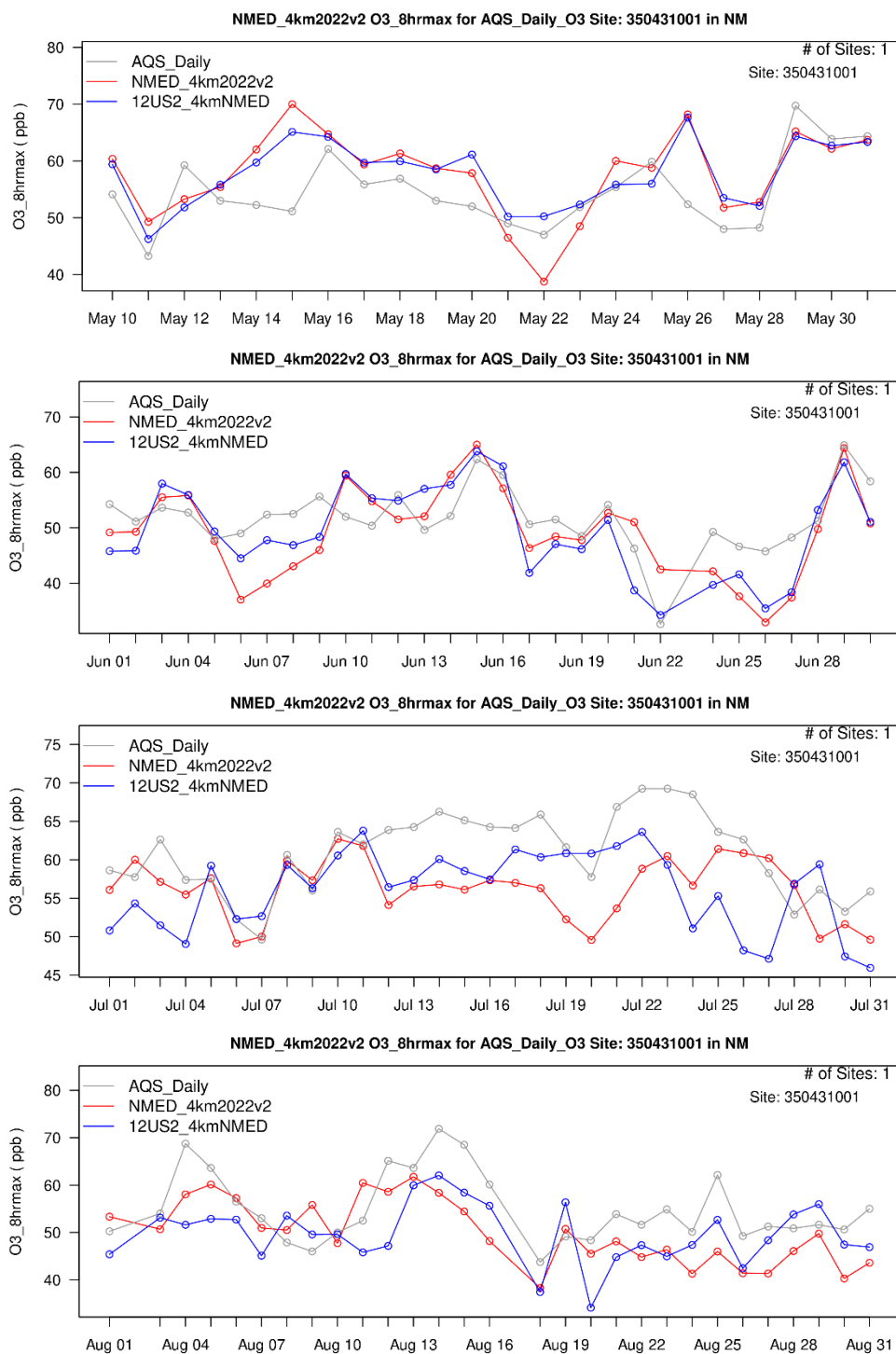


Figure 4-22. Time series plots of predicted and observed MDA8 ozone concentrations at the Bernalillo (350431001) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

Figure 4-23 shows the hourly ozone scatter plot at the Foot Hills site, which illustrates how the model underestimates high ozone values and simultaneously overestimates the low observed hourly ozone concentrations, resulting in an overall underestimation tendency with an NMB of -8% . In contrast, better hourly ozone performance is observed at the Bernalillo site, which exhibits a positive NMB of 4% due to overestimation of low observed hourly ozone concentrations. At this site, observed hourly ozone frequently falls below 20 ppb, whereas modeled values rarely do so. At both Central New Mexico sites, when observed hourly ozone concentrations exceed 70 ppb, modeled hourly ozone concentrations are usually not greater than 60 ppb.

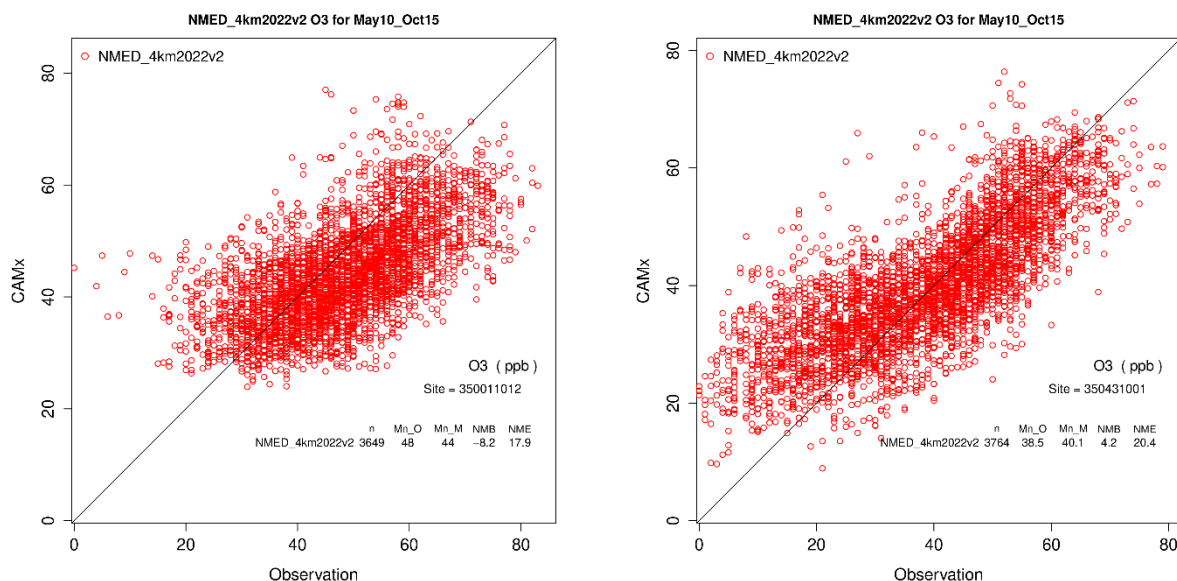


Figure 4-23. Scatter plots of predicted and observed hourly ozone concentrations at the Foot Hills (350011012) site in Bernalillo County and Bernalillo (350431001) site in Sandoval County in Central New Mexico.

Time series comparing predicted and observed hourly ozone concentrations at the Foot Hills and Bernalillo Central New Mexico sites are shown in Figure 4-24. For the first episode (May 14–16), the model reproduces the afternoon hourly ozone concentrations at both sites well, although nighttime low ozone concentrations are overestimated. This overestimation of nighttime ozone is also evident during other episodes at the Bernalillo site, consistent with the hourly ozone scatter plot (Figure 4-23, right panel). During the second episode (May 25–30), observed hourly ozone concentrations are well reproduced by the model at both sites. For the remaining four episodes in July and August, observed afternoon hourly ozone concentrations are underestimated at the Foot Hills site, whereas hourly ozone at the Bernalillo site is generally reproduced well on most days.

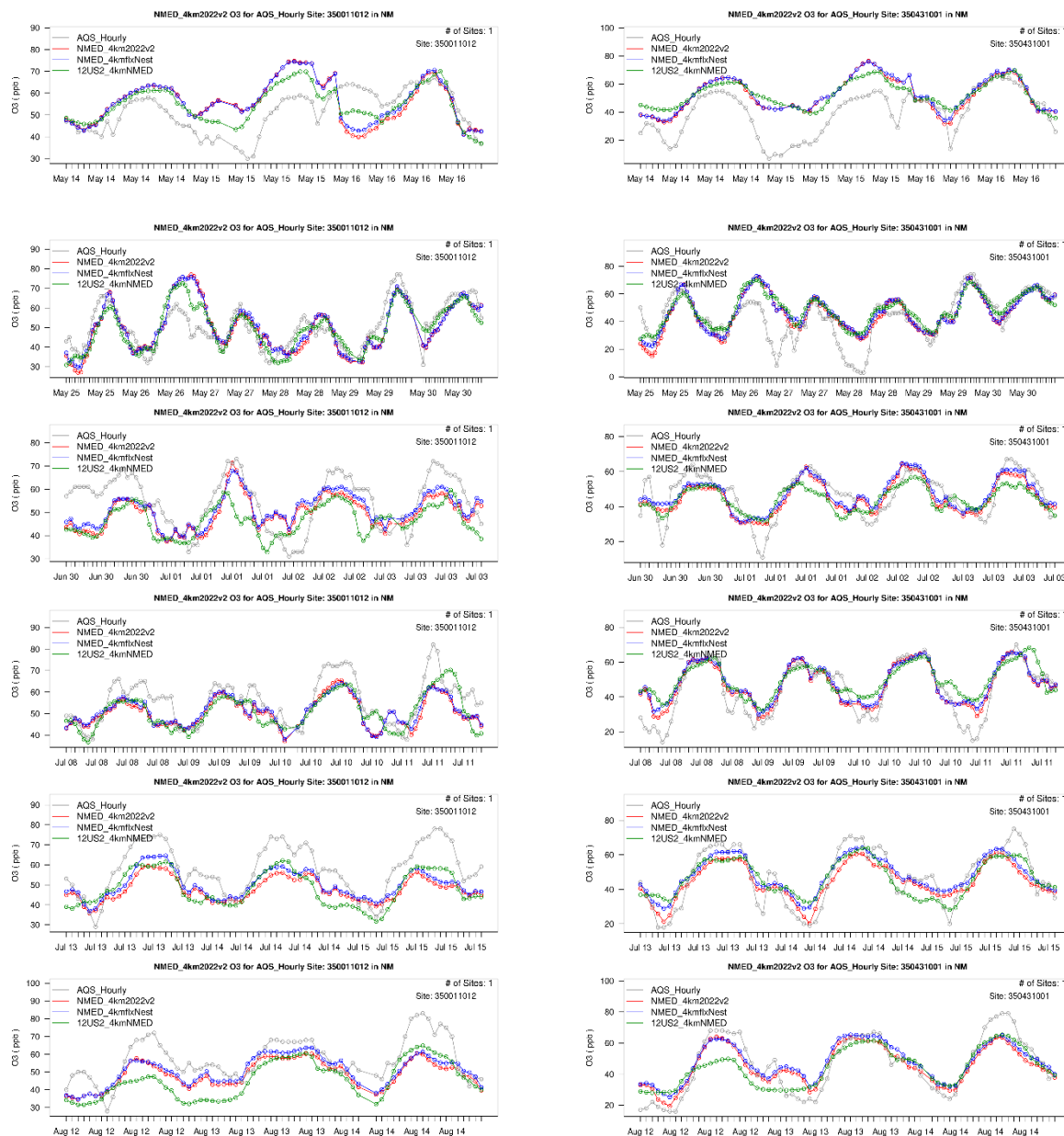


Figure 4-24. Time series of predicted and observed hourly ozone concentration at the Foot Hills (350011012) site in Bernalillo County and Bernalillo (350431001) site in Sandoval County in Central New Mexico for six episodes during the summer 2022 and the CAMx 2022v1 12 km base case simulation.

4.8 Ozone Model Performance in the South San Juan Basin in Northwest New Mexico

There are five ozone monitoring sites in the South San Juan Basin region of northwest New Mexico, including four sites in San Juan County and one site in Rio Arriba County. Except for the Coyote site in Rio Arriba County, which exhibits a positive MDA8 ozone NMB of +6%, the remaining four San Juan County sites achieve the bias Performance Goal for both MDA8 ozone NMB and NME (Table 4-3). Similarly, MDA8 ozone NMB values at all San Juan County sites meet the bias Performance Criterion, except for the Coyote site which overestimates observed concentrations., with approximately half of the sites hourly ozone also meeting the bias Performance Goal (Table 4-4).

Although scatter plots of MDA8 ozone concentrations show considerable spread, the 1:1 line of perfect agreement generally passes through the center of the predicted and observed MDA8 ozone distributions (Figure 4-25). This results in low bias at the Navajo Lake (−5%) and Sub Station (−4%) monitoring sites, which also exhibit low error (10%), with both bias and error meeting the bias and error Performance Goals. Time series plots (Figure 4-26 and Figure 4-27) indicate substantially better agreement between modeled and observed MDA8 ozone concentrations at the northwest New Mexico sites compared to those in southern and southeastern New Mexico. Agreement is strong across most of the summer 2022 modeling period, although the model underestimates observed MDA8 ozone during the second half of July and early August at the Navajo Lake site. Overall, better MDA8 ozone performance is observed at the Sub Station site.

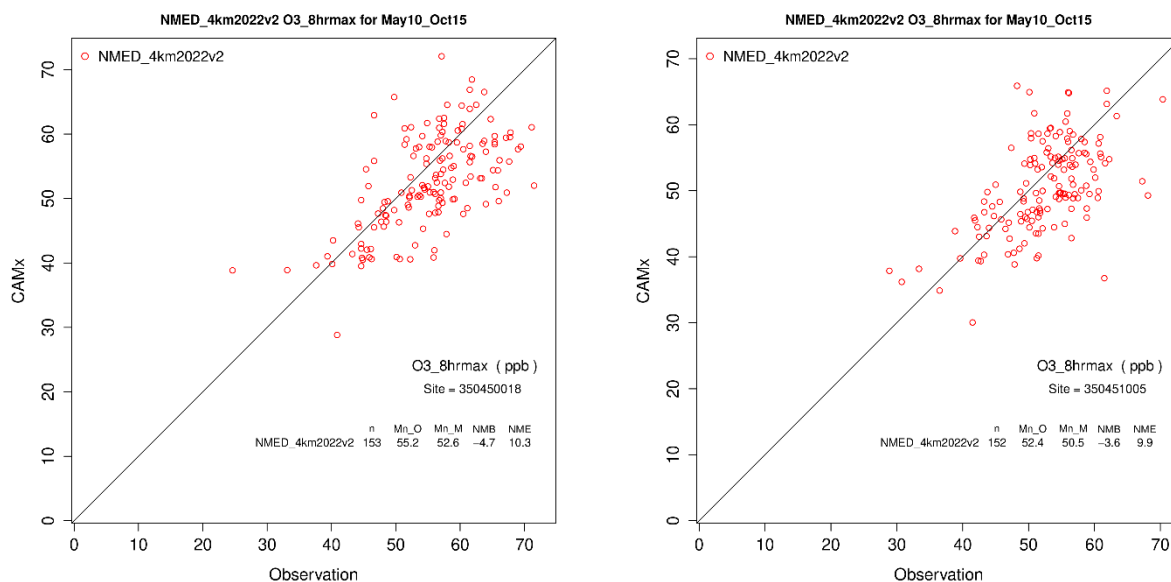


Figure 4-25. Scatter plots of predicted and observed MDA8 ozone concentrations at the Navajo Lake (350450018; left) and Sub Station (350451005; right) sites in San Juan County in Northwest New Mexico.

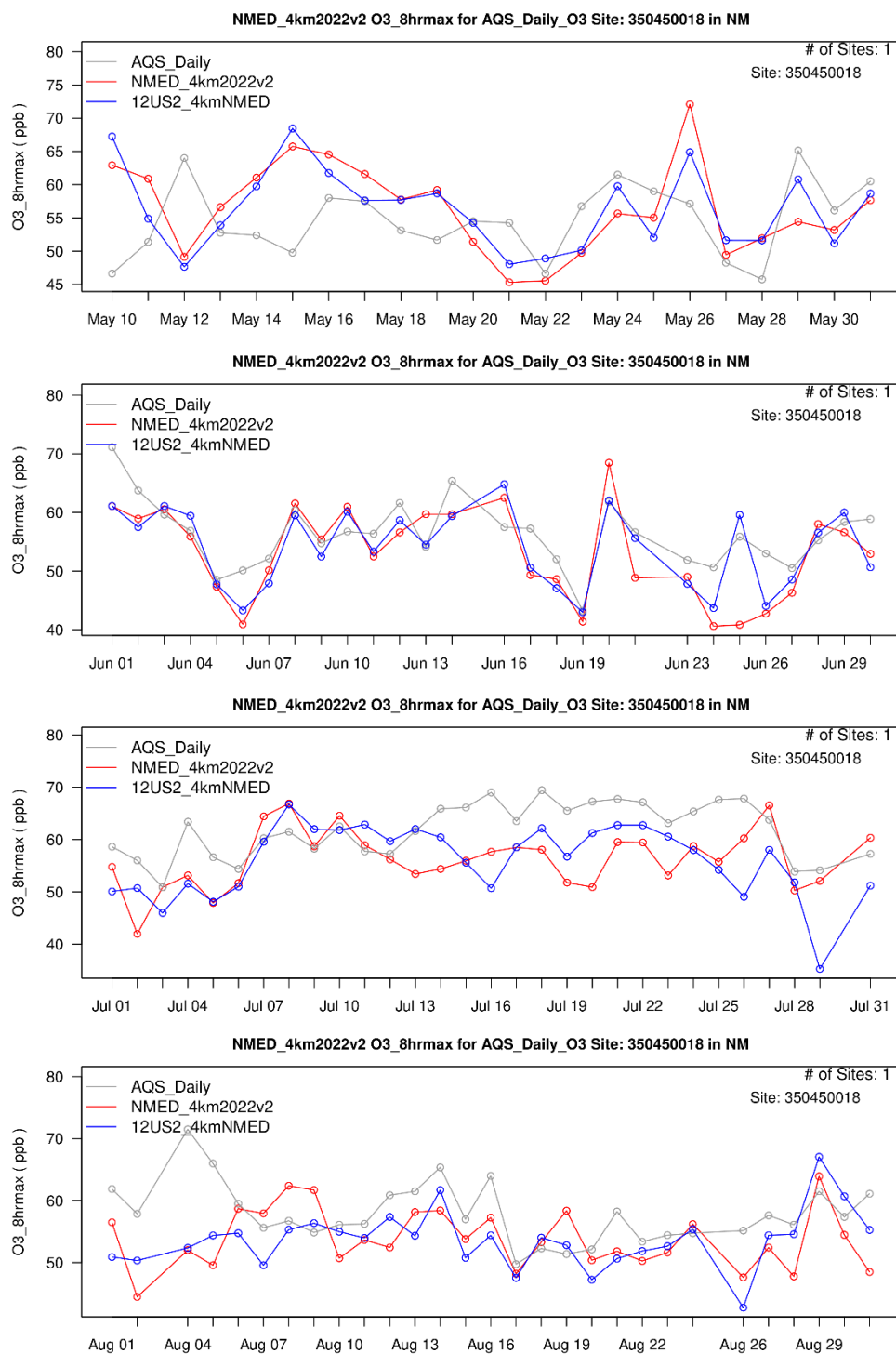


Figure 4-26. Time series plots of predicted and observed MDA8 ozone concentrations at the Navajo Lake (350450018) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

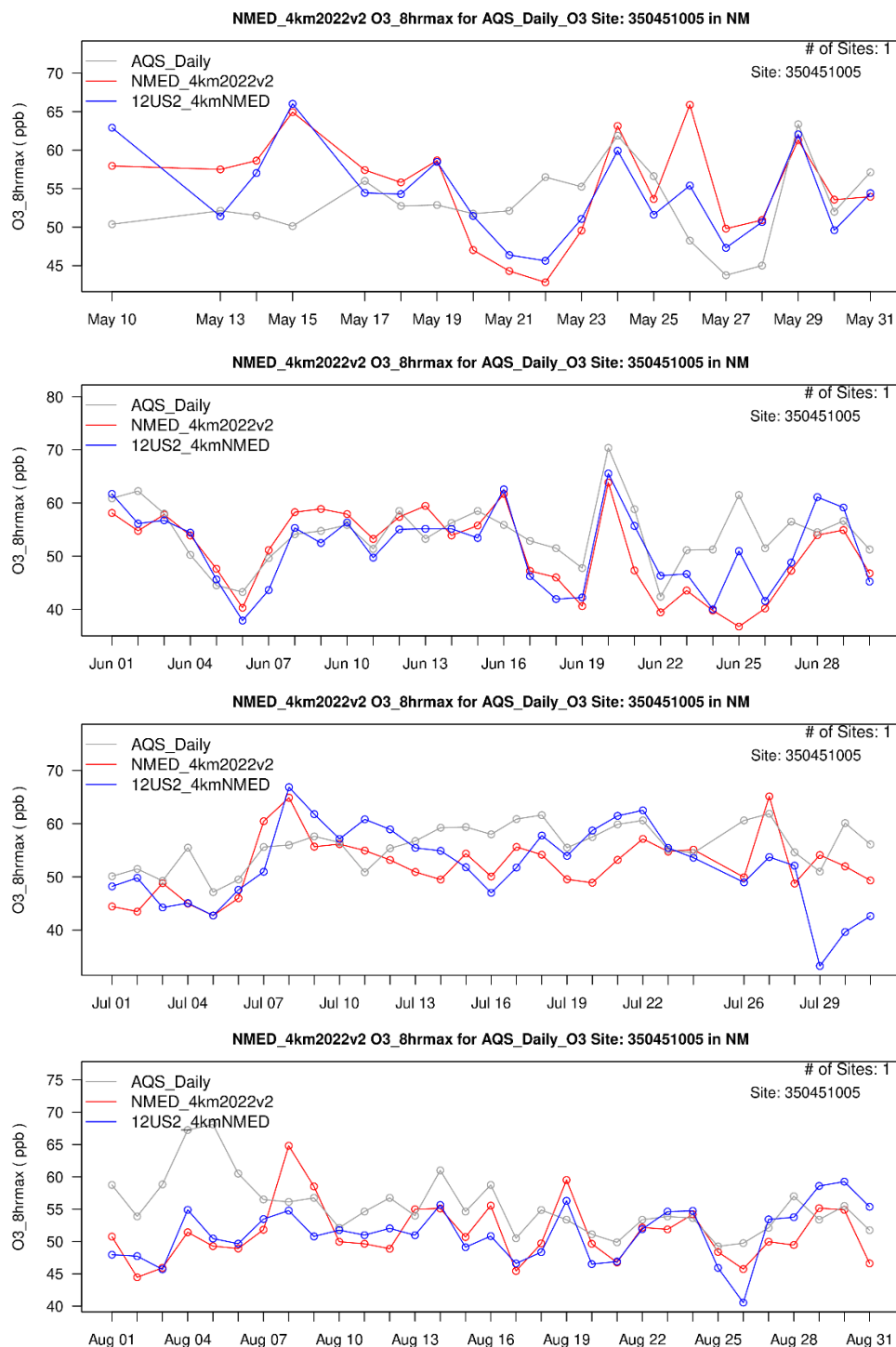


Figure 4-27. Time series plots of predicted and observed MDA8 ozone concentrations at the Sub Station (350451005) monitoring site the May, June, July and August months (top to bottom) and the Phase II CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12/4 km flexinest (blue) base case simulations.

The hourly ozone scatter and time series plots for the Navajo Lake and Sub Station sites are shown in Figure 4-28. There is generally good agreement between modeled and observed hourly ozone concentrations at these two northwest New Mexico sites, except for the underestimation of lower nighttime observed ozone at Navajo Lake, which results in an hourly ozone NMB of -12% and NME of 21% that falls between the Performance Goal and Criterion. Consistent with the MDA8 ozone results, hourly ozone performance at the Sub Station site has NMB of -2% and an NME of 15% which meets the bias and error Performance Goals.

Unlike the southern New Mexico sites, which exhibited degraded ozone model performance during July and August, the Navajo Lake and Sub Station sites demonstrate skill in reproducing both day-to-day and diurnal variations in observed hourly ozone concentrations throughout the summer 2022 modeling period (Figure 4-29).

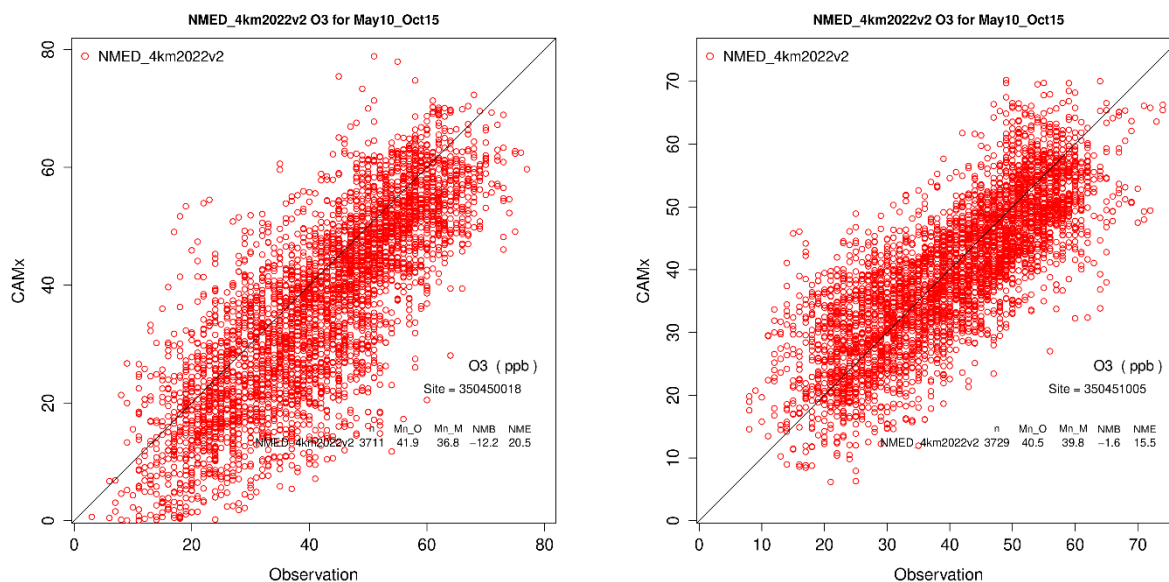


Figure 4-28. Scatter plots of predicted and observed hourly ozone concentrations at the Navajo Lake (350450018) and Sub Station (350451005) sites in San Juan County in Northwest New Mexico.

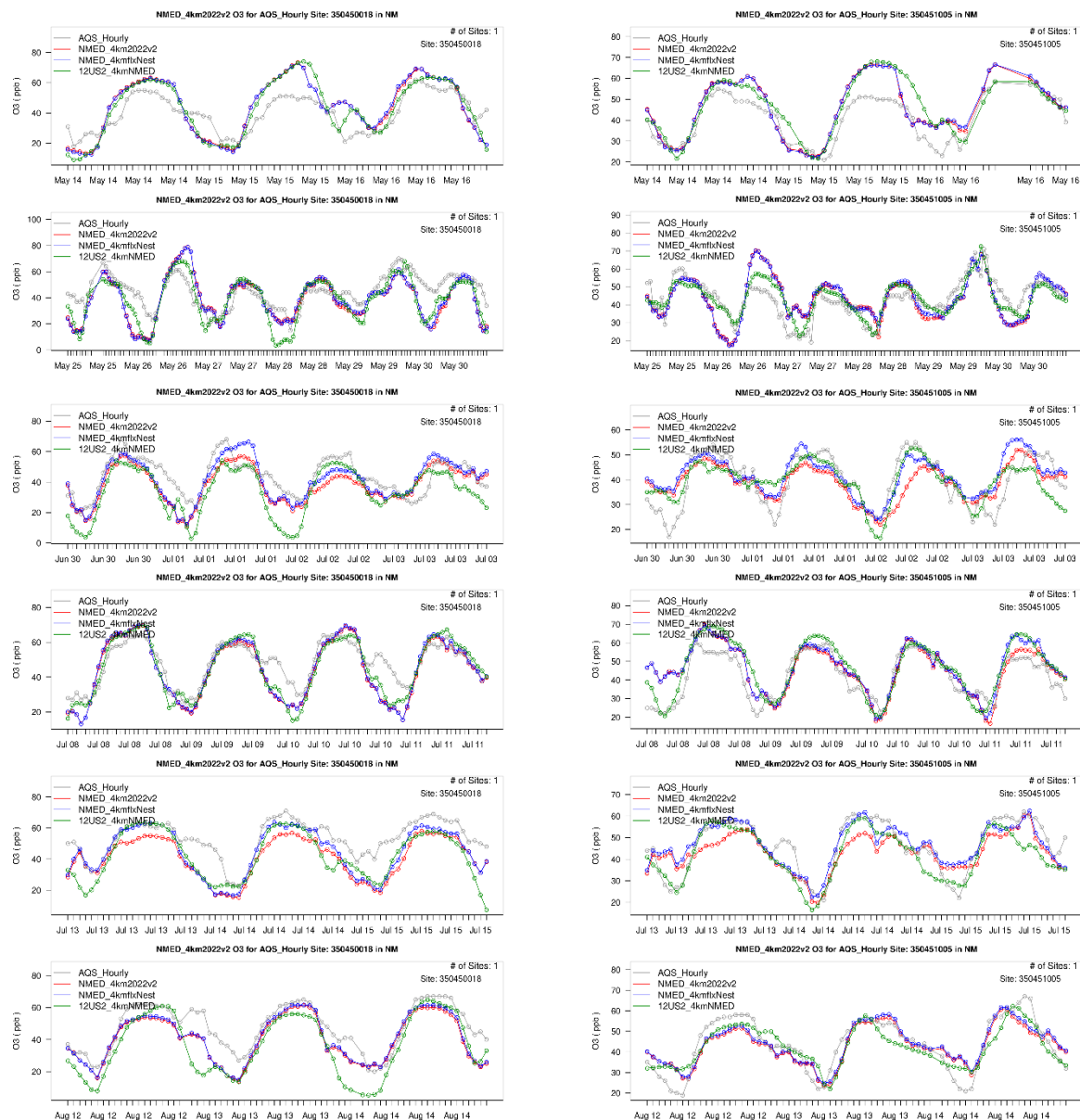


Figure 4-29. Time series of predicted and observed hourly ozone concentration at the Navajo Lake (350450018) and Sub Station (350451005) sites in San Juan County in Northwest New Mexico for six episodes during the summer 2022 and the CAMx 2022v1 12 km base case simulation.

4.9 NO_x Model Performance

The main sources of oxides of nitrogen (NO_x) emissions are combustion sources, although soil NO_x emissions and lightning also contribute. NO_x is emitted predominantly (80–90%) as nitric oxide (NO), with the remaining fraction primarily nitrogen dioxide (NO₂).

Photochemical Grid Models (PGMs) generally do not reproduce observed NO_x concentrations well because NO_x is a primary pollutant emitted mainly from point sources so there is incommensurability issues between the point measurement and grid cell average model estimate. When NO_x sources are located near a monitoring site, CAMx tends to underestimate observed NO_x concentrations due to instantaneous mixing of emissions within a grid cell, such as the 4 km grid resolution used in the CAMx 2022v2 4 km base case simulation. Because most NO_x is emitted as NO, it is expected that the model will underestimate the highest observed NO concentrations, making evaluation of modeled NO less meaningful. In the NMED Phase I modeling (Ramboll, 2025b), the CAMx 2022v1 12 km base case was evaluated for NO, NO₂, and NO_x (NO_x = NO + NO₂). As noted above, the NO evaluation did not provide useful information, and the NO_x evaluation was essentially identical to the NO₂ evaluation. Therefore, this section focuses on evaluating the current CAMx 2022v2 4 km base case against observed NO₂ concentrations.

Figure 4-30 presents scatter plots of predicted and observed hourly NO₂ concentrations matched by time and location for six New Mexico monitoring sites located across the state. At the Carlsbad City and Hobbs sites in the Permian Basin (Figure 4-30, top panels), there is substantial scatter, with NO₂ underestimated by –33% at Carlsbad City (average observed and modeled concentrations of 5.3 and 3.6 ppb, respectively). In contrast, the Hobbs site shows good agreement on average, with nearly identical observed and modeled NO₂ concentrations (average values of 2.8 and 2.9 ppb, respectively).

At the two Doña Ana County sites (Desert View and Santa Teresa; Figure 4-30, middle panels), the model overestimates average observed NO₂ concentrations by 32% and 57%, respectively. Conversely, at the two Bernalillo County sites (Figure 4-30, bottom panels), the model underestimates observed NO₂ concentrations on average by –18% and –40%, respectively.

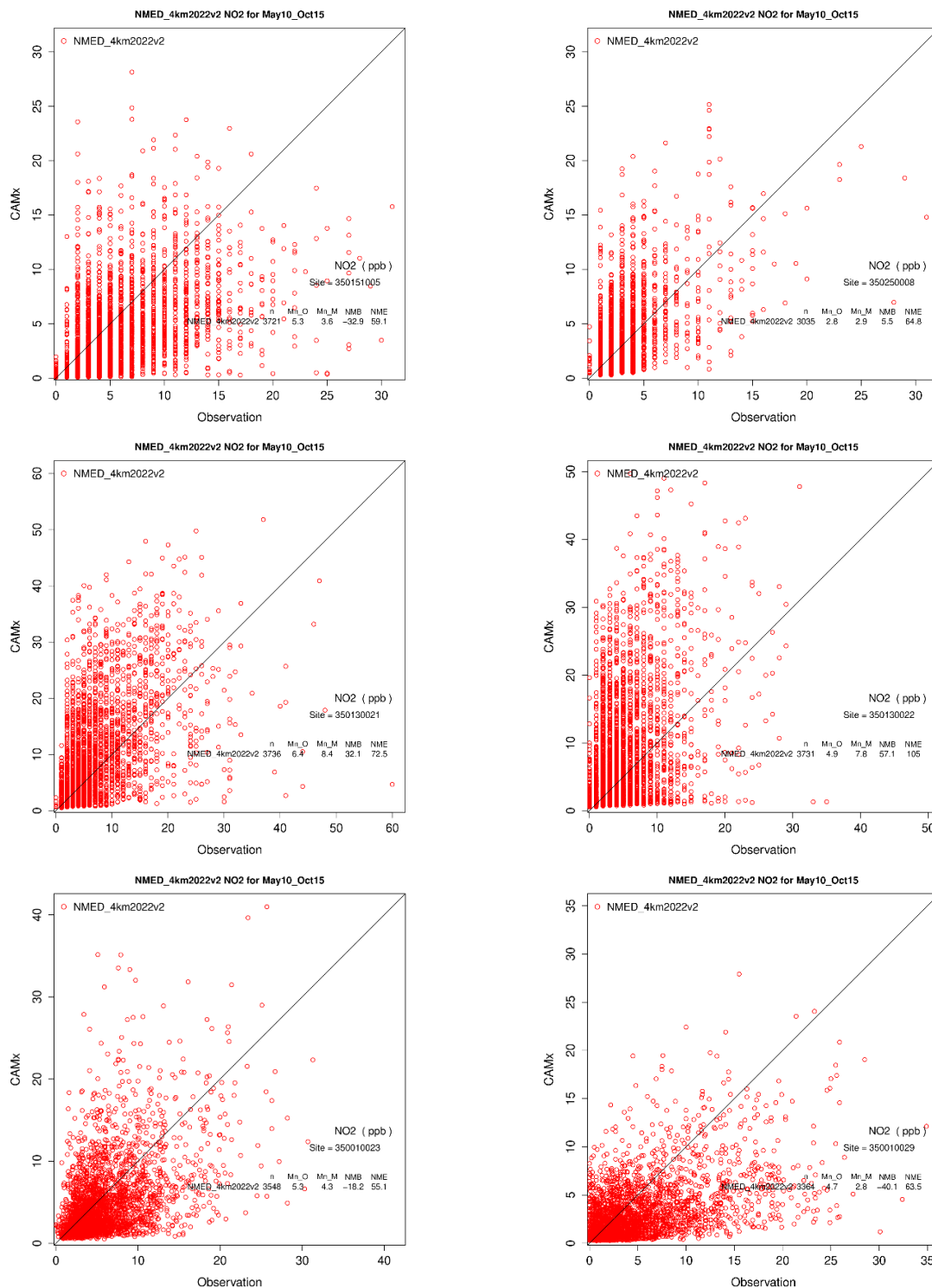


Figure 4-30. CAMx 2022v2 4 km scatter plots for hourly NO₂ concentrations at the: Carlsbad City (350151005; top left) and Hobbs (35025008; top right) sites in the Permian Basin; Desert View (35013021; middle left) and Santa Teresa (35013022; middle right) sites in Doña Ana County; and Del Norte (35001023; bottom left) and South Valley (35001029; bottom right) sites in Bernalillo County.

4.10 Concurrent Hourly Ozone and NO₂ Performance

Ground-level (tropospheric) ozone forms through reactions between volatile organic compounds (VOCs) and oxides of nitrogen (NO_x) in the presence of sunlight. A key atmospheric reaction driving tropospheric ozone formation is the photolysis of NO₂, in which sunlight (ultraviolet radiation) splits NO₂ into nitric oxide (NO) and a highly reactive oxygen atom [O(³P)], which rapidly reacts with molecular oxygen (O₂) to form ozone (O₃). Ozone can subsequently be removed through the titration reaction (NO + O₃ → NO₂ + O₂), resulting in no net ozone production. However, VOCs generate radical species that convert NO to NO₂ without consuming ozone, leading to a net increase in ozone. As a result, both NO_x and VOCs are required for ozone formation. Comparison of predicted and observed hourly ozone and NO₂ concentrations can therefore provide insight into the model's ability to reproduce observed ozone formation processes and is examined in this section.

Figure 4-31 compares predicted and observed hourly ozone and NO₂ concentrations at the Carlsbad City site for July 13–15, 2022. The model generally reproduces the observed morning and early afternoon increase in hourly ozone concentrations. However, the modeled ozone increase levels off later in the afternoon while observed ozone continues to rise (e.g., July 15 in Figure 4-31). Vertical lines are included in Figure 4-31 to identify the approximate afternoon hours when modeled and observed ozone concentrations begin to diverge. At these times, modeled hourly NO₂ concentrations approach zero, whereas measured NO₂ concentrations remain substantially higher. A similar pattern is shown in Figure 4-32 for the Hobbs monitoring site. These results suggest that one potential contributor to the CAMx afternoon ozone underestimation is insufficient modeled surface NO₂ concentrations, which would limit NO₂ photolysis and subsequent ozone formation.

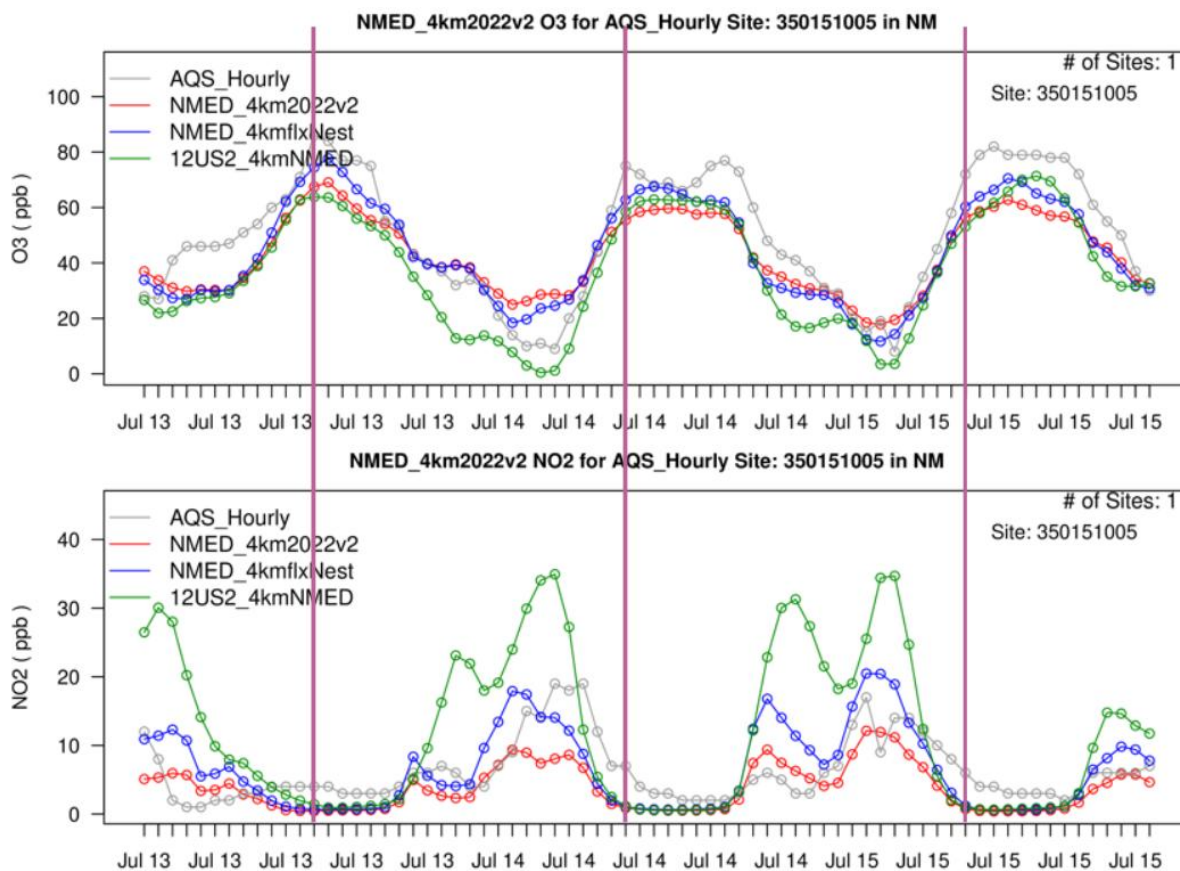


Figure 4-31. Predicted and observed hourly ozone (top) and NO₂ (bottom) concentrations at the Carlsbad City monitoring site on July 13-15, 2022 for the current CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12 km (green) and 12/4 km flexinest (blue) base case simulations.

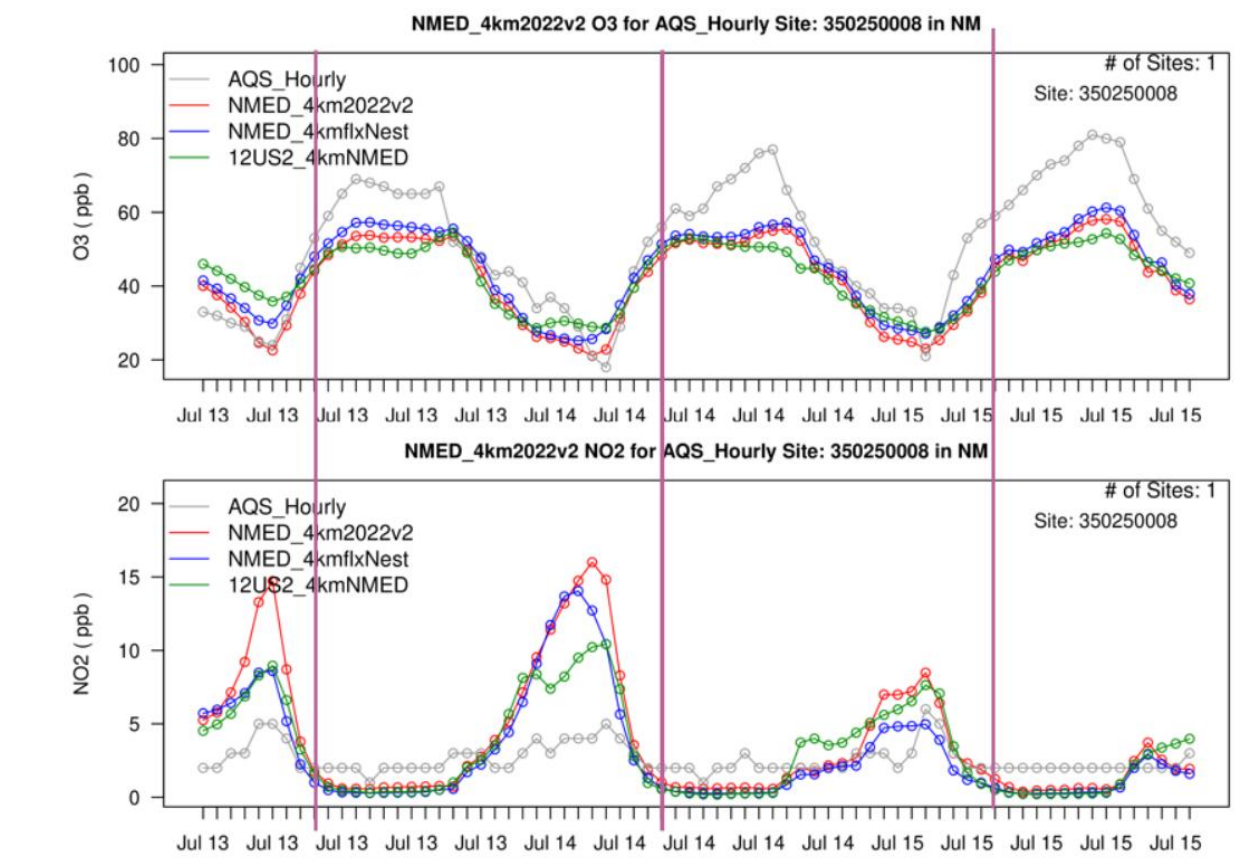


Figure 4-32. Predicted and observed hourly ozone (top) and NO₂ (bottom) concentrations at the Carlsbad City monitoring site on July 13-15, 2022 for the current CAMx 2022v2 4 km (red) and Phase I CAMx 2022v1 12 km (green) and 12/4 km flexinest (blue) base case simulations.

There are several factors that may contribute to the modeled hourly ozone increase leveling off when afternoon modeled NO₂ concentrations are lower than observed values, including:

- Underestimation of NO_x and/or VOC emissions in the emissions inventory.
- Excessive vertical mixing in the model, resulting in dilution of ground-level ozone and NO₂ concentrations.
- Insufficient ozone aloft being entrained to the surface as the mixing height increases.
- Observed NO₂ concentrations approaching the measurement detection limit (e.g., at the Hobbs site in Figure 4-32).
- Interference in NO₂ measurements from other reactive nitrogen species (e.g., PAN, PNA, and HNO₃).

Some of these potential causes are further evaluated through focused sensitivity modeling, as discussed in Chapter 7.

5.0 CAMX 2022V2 12/4 KM MODEL PERFORMANCE EVALUATION USING SPECIAL FIELD STUDY DATA

In this chapter, the CAMx 2022v2 4 km base case simulation is evaluated against special field study measurements collected in the Permian Basin. Colorado State University (CSU), the National Park Service (NPS), and other organizations have conducted three field studies that included measurements of volatile organic compounds (VOCs) and oxides of nitrogen (NO_x) at Carlsbad Caverns National Park. In addition, a Health Effects Institute (HEI) sponsored field study conducted by Boulder AIR collected VOC, NO_x , and other measurements at Loving, New Mexico, located approximately 20 km southeast of Carlsbad City and 35 km east-northeast of the Carlsbad Caverns National Park visitor center.

5.1 Carlsbad Caverns Air Quality Study

Figure 5-1 presents a timeline of the three Carlsbad Caverns Air Quality Studies (CarCavAQS) led by CSU with participation from other organizations. These studies include an initial survey conducted in 2017, a primary 6-week intensive study during the summer of 2019, and a follow-up 4 to 5 week study carried out in the summer of 2021. Figure 5-1 also illustrates trends in ozone design values (DVs) at Carlsbad Caverns alongside oil production in the Permian Basin. The increase in ozone DVs beginning in 2018 coincides with increased oil production in the Permian Basin.

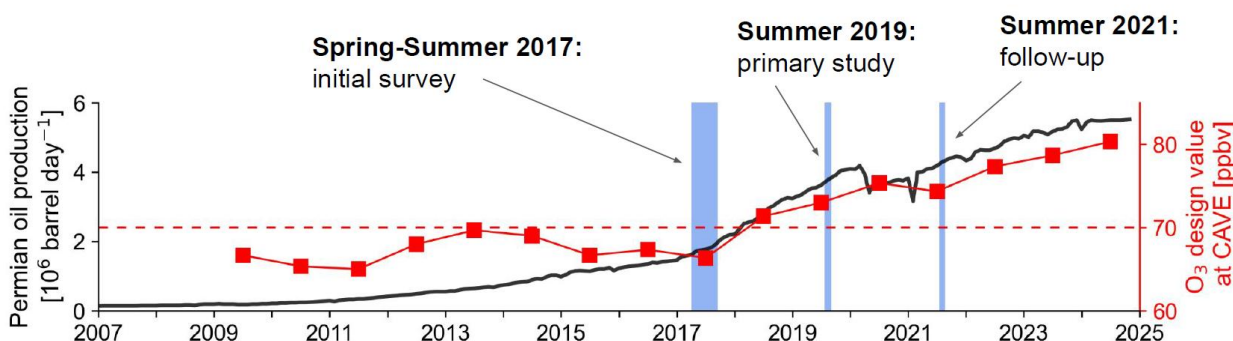


Figure 5-1. Three Air Quality Field Studies at Carlsbad Caverns and trends in Carlsbad Cavern ozone Design Value and oil production in the Permian Basin (Source: A. Marsavin, personal communication September 19, 2025).

Figure 5-2 presents a summary and comparison of the measurements collected during the 2019 and 2021 CarCavAQS. Because the CarCavAQS was conducted in 2017, 2019, and 2021, while the modeling year is 2022, direct day-to-day matching of modeled results and field measurements is not possible. However, the CarCavAQS data was used to evaluate the 2022 modeling results by comparing distributions of ozone precursor species over comparable model and field study periods from the two years. For this evaluation, the 2021 CarCavAQS field study data were used because they are more representative of conditions during the 2022 modeling year than the 2019 field study measurements.

Carlsbad Caverns Intensive Air Quality Study		
2019	Measurements	2021
7/24 → 9/3		7/17 → 8/19
• NO, NO₂, NO_y • CH₄, NH₃, CO₂ • PAN, PPN • Real-time GC: C₂-C₁₀ NMHCs, C₁-C₅ alkyl nitrates, C₁-C₂ halocarbons, OVOCs, etc. • PTR-MS: VOCs, OVOCs, S cmpds • PM_{2.5} mass and composition (Na⁺, NH₄⁺, K⁺, Mg²⁺, Ca²⁺, Cl⁻, NO₂⁻, NO₃⁻, SO₄²⁻, Acetate, Formate, Glycolate, Oxalate) • 24-hr NH₃, HNO₃, SO₂, & PM_{2.5} composition • Carbonyl cartridges (10 AM – 5 PM) • Aethalometer (black carbon) • NPS/ARS operated real-time O₃, SO₂, CO and meteorology • GUMO O₃ and Meteorology		• NO, NO₂, NO_y • CH₄, C₂H₂, CO₂ • Real-time GC: C₂-C₁₀ NMHCs, C₁-C₅ alkyl nitrates, C₁-C₂ halocarbons, OVOCs, etc. • EPA Remotely Operated Canister Sampler (ROCS) – 4 locations • Sensor PM_{2.5} & PM₁₀ (CAVE & GUMO) • NOAA GEM, THg & RM • UNR Passive Hg Samplers (GUMO) • SENSIT SPOD • Entanglement AROMA-VOC • NPS/ARS operated real-time O₃ & meteorology • GUMO O₃ and Meteorology

Figure 5-2. Comparison and measurements of the 2019 and 2021 CSU field studies (Source: B. Sive et al., AWMA Measurement Conference April 2025 Aurora, CO).

The 2017 initial survey characterized VOC concentrations at four western U.S. national parks, including Carlsbad Caverns (CAVE). The 2017 study found that CAVE exhibited the highest VOC concentrations of the four national parks, which were 7 to 10 times greater than those observed at the other three parks (Benedict et al., 2020).

Results from the 2019 CarCavAQS field study are documented in several peer-reviewed journal publications that are summarized in the Phase II Conceptual Model of ozone formation in New Mexico prepared for the NMED ozone source apportionment modeling study (Ramboll, 2026a). These publications include:

- PM_{2.5} in Carlsbad Caverns National Park: Composition, sources, and visibility impacts (Naimie et al., 2022).
- Observations of ozone, acyl peroxy nitrates, and their precursors during summer 2019 at Carlsbad Caverns National Park, New Mexico (Pollack et al., 2023).
- Source characterization of volatile organic compounds at Carlsbad Caverns National Park (Pan et al., 2023).
- Summertime ozone production at Carlsbad Caverns National Park, New Mexico: Influence of oil and natural gas development (Marsavin et al., 2024).

Data from the 2021 CarCavAQS are currently being analyzed, and manuscripts based on these measurements are in preparation. However, select findings from the 2021 study have been discussed with field study participants, who provided measurement data for use in this model performance evaluation (Marsavin, A., September 19, 2025, personal communication).

5.2 Health Effects Institute Field Study Measurements

The Health Effects Institute (HEI) funded Boulder AIR to collect ozone and ozone precursor measurements (e.g., VOC and NO_x) at Loving, New Mexico (LNM) from May 2023 through June 2024. The LNM Permian Basin measurements were part of an assessment of source contributions to air quality and noise in unconventional oil shale plays in several locations (Franklin et al., 2025). Figure 5-3, reproduced from the HEI report with added additional site locations, shows the location of the LNM monitoring site relative to active wells and flaring; the locations of the Carlsbad City monitoring site and the approximate location of the Carlsbad Caverns site, which is situated slightly west of the map extent, have been added for reference. The HEI LNM measurements were provided by Boulder AIR and were used in the model performance evaluation.

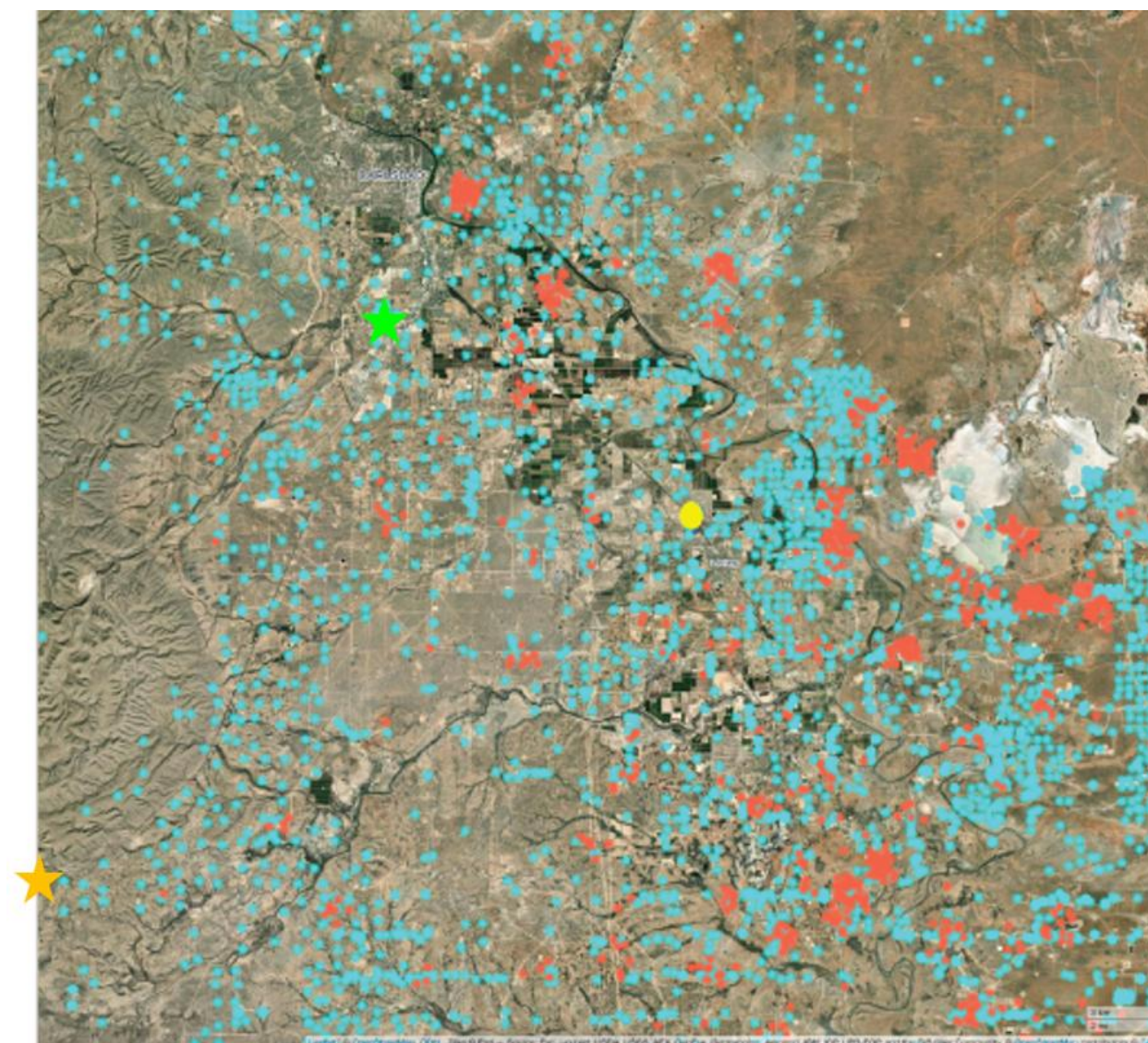


Figure 5-3. Locations of Loving, New Mexico monitoring site (yellow circle), active O&G wells (cyan dots), and satellite detect flaring (red dots) [Source: Franklin et al., (2025)] with locations of Carlsbad City site (green star) and approximate location of the Carlsbad Cavern site (orange star) that lies farther west than the map edge added.

5.3 Evaluation of CAMx 2022v2 4 km Base Case using Field Study VOC Measurements

The CarCavAQS 2021 and HEI Loving, New Mexico 2023 field study VOC and NO_x measurements were used to evaluate the CAMx 2022v2 4 km base case simulation. Because these field study measurements were not collected during the 2022 modeling period, a model evaluation matched by time and location, as was conducted for ozone and NO_x in Chapter 4, was not possible. Instead, frequency distributions of observed and modeled concentrations were compared for common days drawn from different years of the observational and modeling data. The predicted and observed frequency distributions are evaluated using box-and-whisker plots and average diurnal time series plots.

An additional challenge in evaluating field study VOC measurements is that the CAMx modeling employs the Carbon Bond version 7 revision 1 (CB7r1) “lumped” chemical mechanism, which represents thousands of explicit VOC species using approximately 100 surrogate species based on reactive carbon bond structure. In contrast, the field studies measured explicit VOC species, most of which do not directly correspond to species represented in the CB7r1 mechanism. Therefore, the CAMx VOC evaluation focused on eight explicit species included in the CB7r1 chemical mechanism that were also measured during the CarCavAQS field study, as follows:

- Ethane (ETHA; C₂H₆), a natural gas component and indicator of oil and gas emissions.
- Propane (PRPA; C₃H₈), another indicator of oil and gas emissions.
- Benzene (BENZ; C₆H₆), an indicator of gasoline combustion.
- Ethyne (ETHY; C₂H₂), a combustion tracer.
- Isoprene (ISOP; C₅H₈), primarily emitted by vegetation and used as a biogenic tracer.
- Ethene (C₂H₄), an industrial chemical compound.
- Acetone (ACET; (CH₃)₂CO), a solvent that is also used in oil and gas production.
- Acetaldehyde (ALD2; CH₃CHO), which is naturally occurring and secondarily formed in the atmosphere.

5.3.1 Ethane and Propane Evaluation

Figure 5-4 and Figure 5-5 compare predicted and observed hourly ethane and propane concentration distributions using box-and-whisker plots from the CAMx 2022v2 4 km base case and, respectively, the 2021 CarCavAQS and 2023 HEI Loving, New Mexico field studies. In the box-and-whisker plots, the box represents the interquartile range (IQR), spanning the 25th to 75th percentiles, the whiskers represent the highest and lowest values within 1.5 times the IQR, the circles beyond the whiskers denote outliers, and the line within the box indicates the median.

At Carlsbad Caverns (Figure 5-4), observed ethane (ETHA) and propane (PRPA) concentrations are substantially higher than modeled values. For ethane, the 25th percentile of the observed distribution is approximately equal to the 75th percentile of the modeled distribution, and the maximum modeled ethane concentration (~15 ppb) is lower than the 75th percentile of the observed ethane distribution (~19 ppb). A similar pattern is evident for propane, with observed concentrations consistently exceeding modeled values.

Comparable differences between modeled and observed ethane and propane concentrations are also observed at Loving, New Mexico (Figure 5-5). As with the CarCavAQS field study, observed concentrations are much higher than modeled values; however, both observed and modeled concentrations at Loving are substantially higher than those at Carlsbad Caverns.

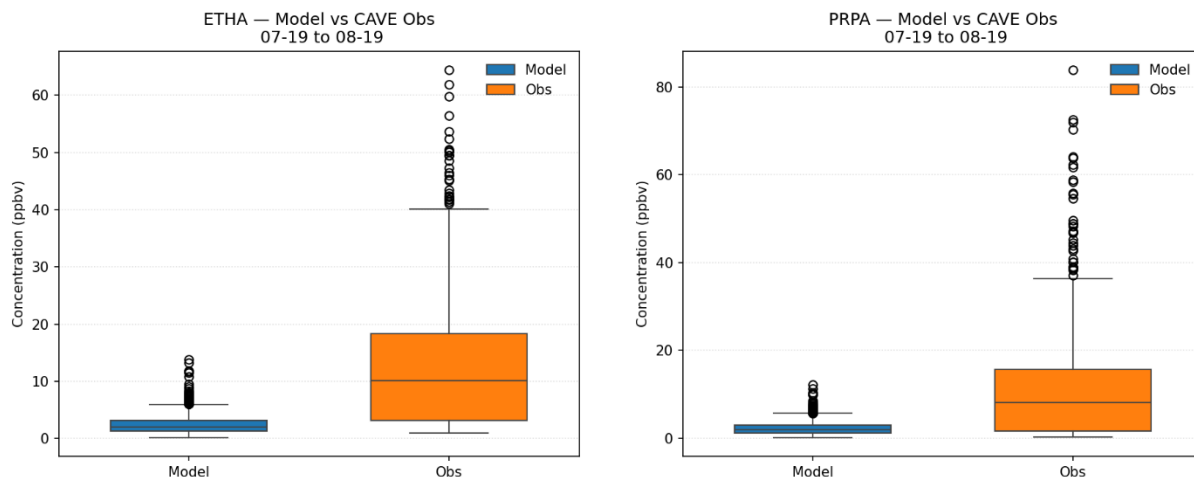


Figure 5-4. Box and Whisker Plots of the distribution of predicted and observed hourly Ethane (left) and Propane (right) concentrations at Carlsbad Caverns from the CarCavAQS July 19 – August 19, 2021 field study and CAMx 2022v2 4 km July 17 – August 19, 2022 base case simulation.

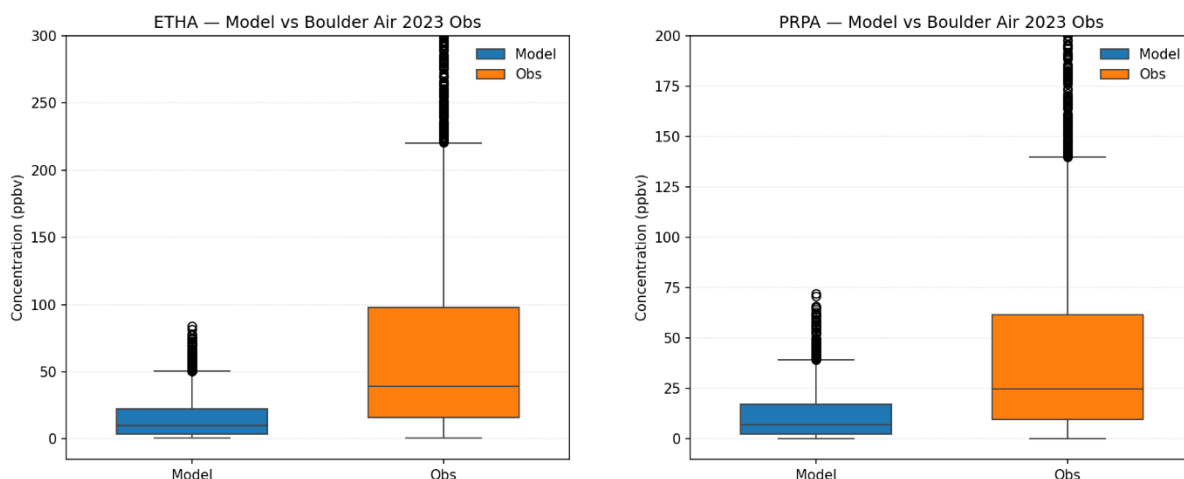


Figure 5-5. Box and Whisker Plots of the distribution of predicted and observed hourly Ethane (left) and Propane (right) concentrations at Loving, New Mexico from the HEI Study Boulder Air May – October 2023 field study and CAMx 2022v2 4 km May – October 2022 base case simulation.

Figure 5-6 displays the average diurnal time series of ethane and propane concentrations using the 2021 CarCavAQS field study and CAMx 2022v2 4 km base case simulation, showing that observed concentrations are higher than modeled values throughout the day.

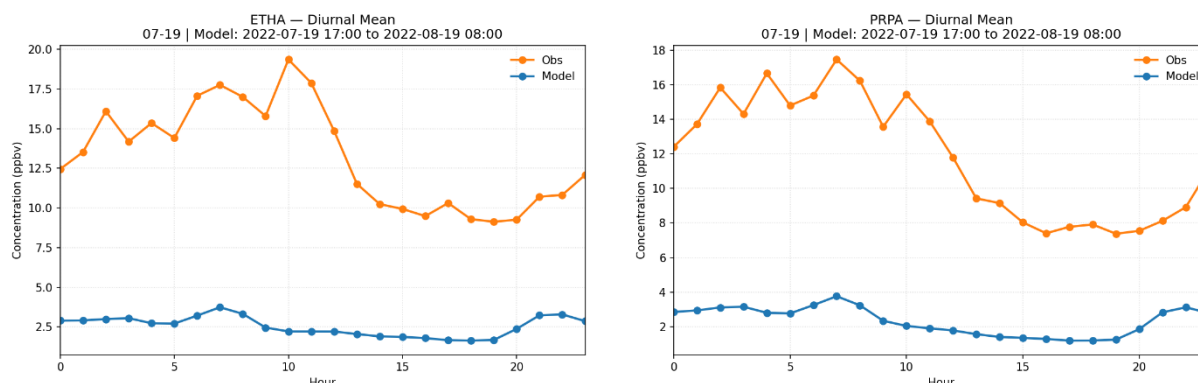


Figure 5-6. Average diurnal predicted and observed hourly Ethane (left) and Propane (right) concentrations at Carlsbad Caverns from the CarCavAQS July 19 – August 19, 2021 field study and CAMx 2022v2 4 km July 17 – August 19, 2022 base case simulation.

Table 5-1 compares predicted and observed mean and median ethane and propane concentrations, along with ratios of observed-to-modeled concentrations, from the two field studies and the CAMx 2022v2 4 km base case. For the 2021 CarCavAQS, observed ethane concentrations are 5.2 times higher than modeled values using both mean and median statistics. Observed propane concentrations at Carlsbad Caverns are 5.2 times higher than modeled values based on the mean and 4.4 times higher based on the median.

At the Loving, New Mexico site, observed ethane concentrations are 5.4 times higher than modeled values using the mean and 3.9 times higher using the median, while observed propane concentrations are 4.4 to 3.5 times higher than modeled values. At both the Carlsbad Caverns and Loving, New Mexico locations, observed ethane and propane, key oil and gas indicator species, are approximately five times higher than CAMx 2022v2 4 km modeled concentrations, suggesting that Permian Basin oil and gas VOC emissions are likely understated in the 2022v2 emissions inventory.

Table 5-1. Comparison of the Mean and Median Observed and Modeled Ethane and Propane concentrations (ppb) and their ratios (Observed/Modeled) from the CarCavAQS and HEI Loving, NM field studies and the CAMx 2022v2 4 km base case simulation.

CarCavAQS Species	N	Model		Observed		Obs/Mod Ratio	
		Mean	Median	Mean	Median	Mean	Median
ETHA	563	2.5	1.9	13.0	10.1	5.2	5.2
PRPA	562	2.3	1.9	11.6	8.2	5.2	4.4
Loving, NM Species	N	Model		Observed		Obs/Mod Ratio	
		Mean	Median	Mean	Median	Mean	Median
ETHA	3385	14.6	9.9	79.3	39.1	5.4	3.9
PRPA	3385	11.3	7.2	50.2	25.0	4.4	3.5

5.3.2 Acetone Evaluation

Acetone is a solvent used in a wide range of applications, including consumer products (e.g., nail polish and paint thinner) and industrial processes. Acetone is also used in oil and gas production as a strong industrial solvent to dissolve paraffin waxes, break up oil sludge, clean drilling equipment, and improve fuel blend efficiency. Figure 5-7 presents box-and-whisker plots and average diurnal profiles comparing predicted and observed acetone concentrations from the 2021 CarCavAQS field study and the CAMx 2022v2 4 km base case simulation. Observed acetone concentrations at Carlsbad Caverns are substantially higher than modeled values, with mean and median observed concentrations being, respectively, 5.0 and 6.1 times greater than modeled concentrations. Although acetone has numerous consumer product sources, the Carlsbad Caverns site is located within a National Park and away from urban areas. Therefore, like the underestimation observed for ethane and propane, these results suggest that Permian Basin oil and gas VOC emissions in the 2022v2 emissions inventory are likely understated.

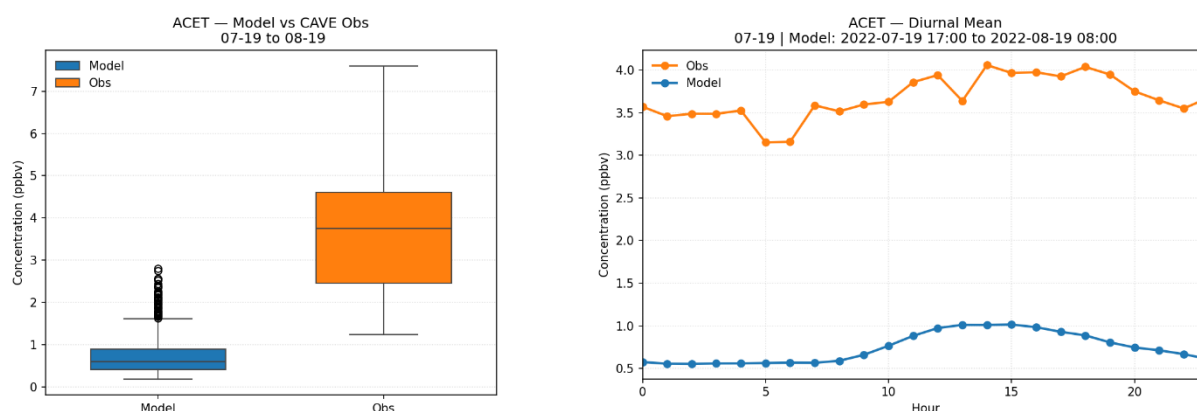


Figure 5-7. Box and Whisker Plot and average diurnal predicted and observed hourly Acetone concentrations at Carlsbad Caverns from the CarCavAQS July 19 – August 19, 2021 field study and CAMx 2022v2 4 km July 19 – August 19, 2022 base case simulation.

5.3.3 Benzene and Ethyne Evaluation

Figure 5-8 presents box-and-whisker plots at Carlsbad Caverns for benzene and ethyne. Observed benzene concentrations are higher than modeled values, which may reflect the monitoring site's proximity to the Carlsbad Caverns National Park visitor center and nearby roadways, resulting in higher measured gasoline combustion products than are represented by concentrations averaged over a 4 km grid cell. In contrast, there is generally good agreement between predicted and observed ethyne concentration distributions. For both benzene and ethyne at Carlsbad Caverns, concentrations are low, with nearly all values below 1 ppb.

At the Loving, New Mexico site, benzene concentrations are higher overall, and there is good agreement between predicted and observed concentration distributions, although the observed data shows outliers with very high values (Figure 5-9).

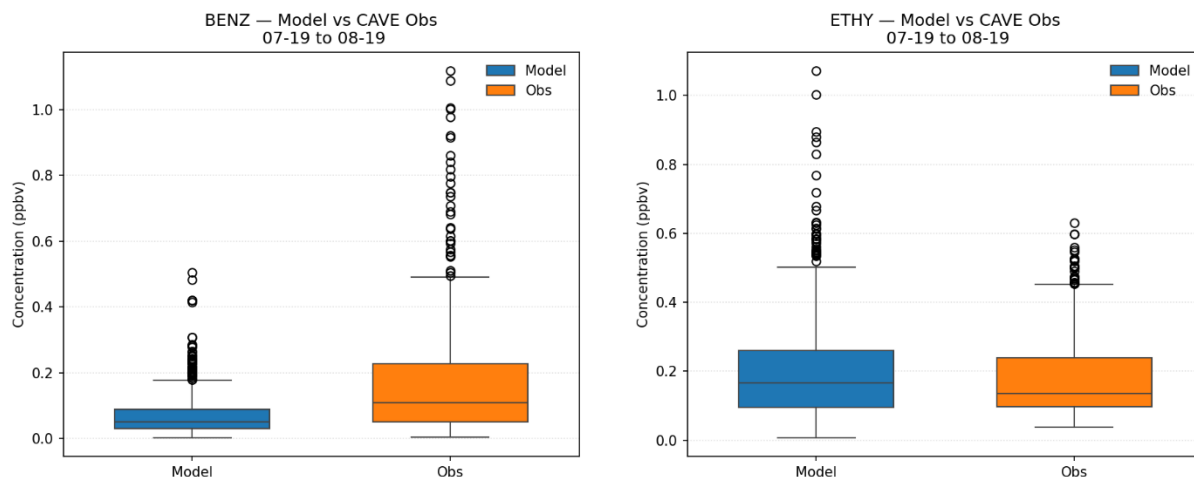


Figure 5-8. Box and Whisker Plots of the distribution of predicted and observed hourly Benzene (left) and Ethyne (right) concentrations at Carlsbad Caverns from the CarCavAQS July 19 – August 19, 2021 field study and CAMx 2022v2 4 km base case simulation during July 17 – August 19, 2022.

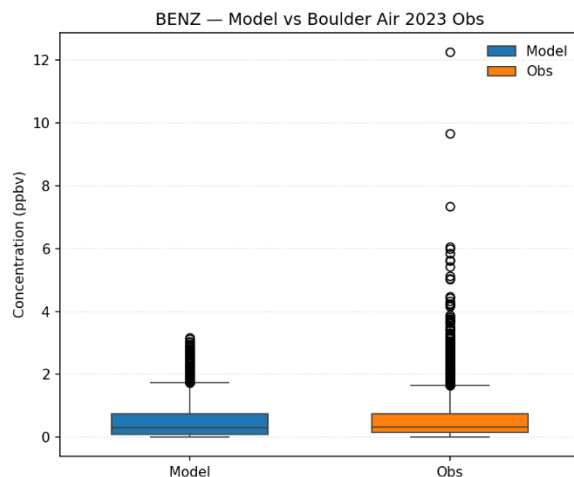


Figure 5-9. Box and Whisker Plots of the distribution of predicted and observed hourly Benzene concentrations at Loving, New Mexico from the HEI Study Boulder Air May – October 2023 field study and CAMx 2022v2 4 km May – October 2022 base case simulation.

The predicted and observed average diurnal variation of benzene at Carlsbad Caverns is similar, although observed concentrations are approximately twice as high as modeled values, likely reflecting the effects of grid-cell averaging in the model (Figure 5-10). In contrast, the diurnal patterns of predicted and observed ethyne concentrations at Carlsbad Caverns differ substantially. Observed ethyne concentrations remain relatively flat throughout the day, whereas modeled values show a pronounced decrease beginning in the late morning and continuing into the afternoon. Ethyne is a relatively reactive VOC species, and this dynamic may indicate a level of discrepancy in the atmospheric chemical reactivity represented in the model with the actual in-situ reactivity of ethyne. Enhanced vertical mixing in the model could also contribute to dilution of modeled ethyne concentrations relative to observed values; however, this is unlikely because this effect is not seen in other VOC modeled species that should also be affected by the vertical mixing in the model.

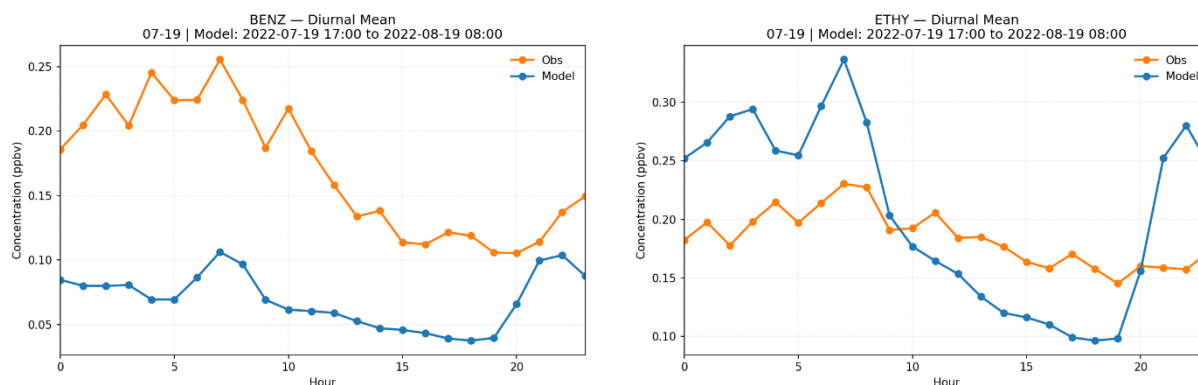


Figure 5-10. Average diurnal predicted and observed hourly Benzene (left) and Ethyne (right) concentrations at Carlsbad Caverns from the CarCavAQS July 19 – August 19, 2021 field study and CAMx 2022v2 4 km July 17 – August 19, 2022 base case simulation.

Table 5-2 compares predicted and observed mean and median benzene and ethyne concentrations, along with their observed-to-modeled ratios, from the two field studies and the CAMx 2022v2 4 km base case simulation. At Carlsbad Caverns, observed benzene concentrations are approximately twice the modeled values, which is likely attributable to grid-cell averaging effects in the model. The Loving, New Mexico site is closer to more roadways and therefore more spatially homogeneous gasoline combustion emissions across the 4 km grid cell, which likely explains the better agreement between predicted and observed benzene concentration distributions, with observed values averaging approximately 10–20% higher than modeled. In contrast, observed ethyne concentrations at Carlsbad Caverns are, on average, 10–20% lower than modeled values.

Given the generally low benzene and ethyne concentrations at Carlsbad Caverns, combined with the mismatch between point measurements near roadways and spatially averaged grid-cell model representations, it is difficult to draw firm conclusions from these comparisons. However, the relatively good agreement between predicted and observed benzene concentrations at the Loving, New Mexico site suggests that gasoline vehicle VOC emissions in the 2022v2 emissions inventory are reasonable.

Table 5-2. Comparison of the Mean and Median Observed and Modeled Benzene and Ethyne concentrations (ppb) and their ratios (Observed/Modeled) from the CarCavAQS and HEI Loving, NM field studies and the CAMx 2022v2 4 km base case simulation.

CarCavAQS Species	N	Model		Observed		Obs/Mod Ratio	
		Mean	Median	Mean	Median	Mean	Median
BENZ	561	0.07	0.05	0.17	0.11	2.4	2.2
ETHY	561	0.20	0.16	0.18	0.14	0.9	0.8
Loving, NM Species	N	Model		Observed		Obs/Mod Ratio	
		Mean	Median	Mean	Median	Mean	Median
BENZ	3385	0.49	0.29	0.58	0.32	1.2	1.1

5.3.4 Ethene and Acetaldehyde Evaluation

The ethene box-and-whisker plot comparisons at Carlsbad Caverns and Loving, New Mexico are shown in Figure 5-11. Observed ethene concentrations at Carlsbad Caverns are higher than modeled values, whereas observed and modeled concentrations are comparable at the Loving, New Mexico site. This pattern supports the interpretation that higher observed ethene concentrations at Carlsbad Caverns may be influenced by grid-cell dilution effects in the model.

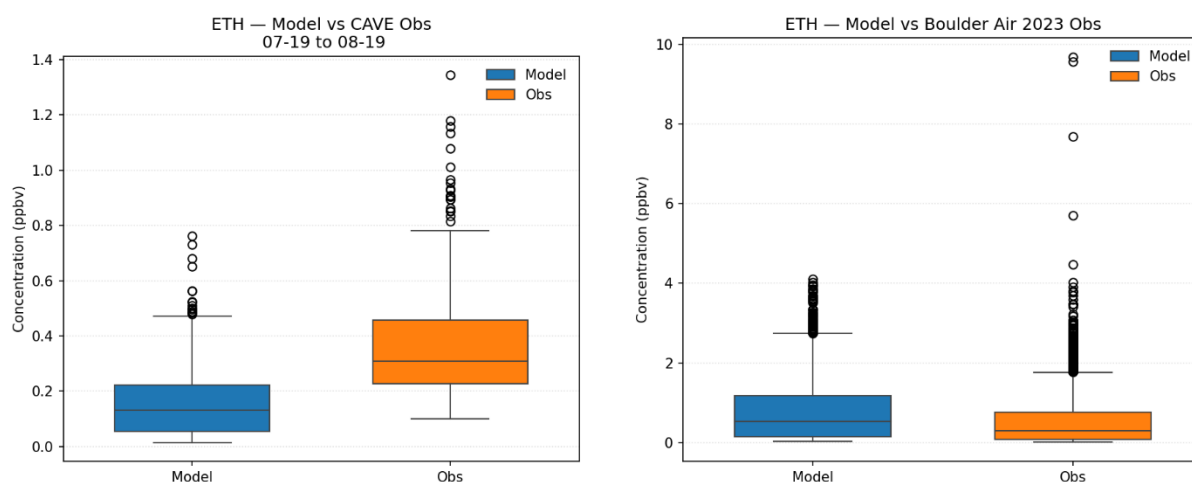


Figure 5-11. Box and Whisker Plots of the distribution of predicted and observed hourly Ethene concentrations at Carlsbad Caverns (left) from the CarCavAQS July 19 – August 19, 2021 field study and at Loving, New Mexico (right) from the HEI Study Boulder Air May – October 2023 field study and CAMx 2022v2 4 km base case simulation.

Direct emissions of acetaldehyde originate from incomplete combustion processes (e.g., vehicles and biomass burning), industrial activities, and natural sources such as plant respiration and decaying organic matter. However, the majority of acetaldehyde is usually formed secondarily in the atmosphere through the oxidation of alkenes and other hydrocarbons.

Box-and-whisker plots and average diurnal profiles of predicted and observed acetaldehyde concentrations at Carlsbad Caverns are shown in Figure 5-12. Observed acetaldehyde concentrations are substantially higher than modeled values. While this difference may be partially attributable to grid-cell dilution in the modeled concentrations, insufficient secondary acetaldehyde formation from alkene emissions associated with oil and gas sources may also contribute to the model underestimation.

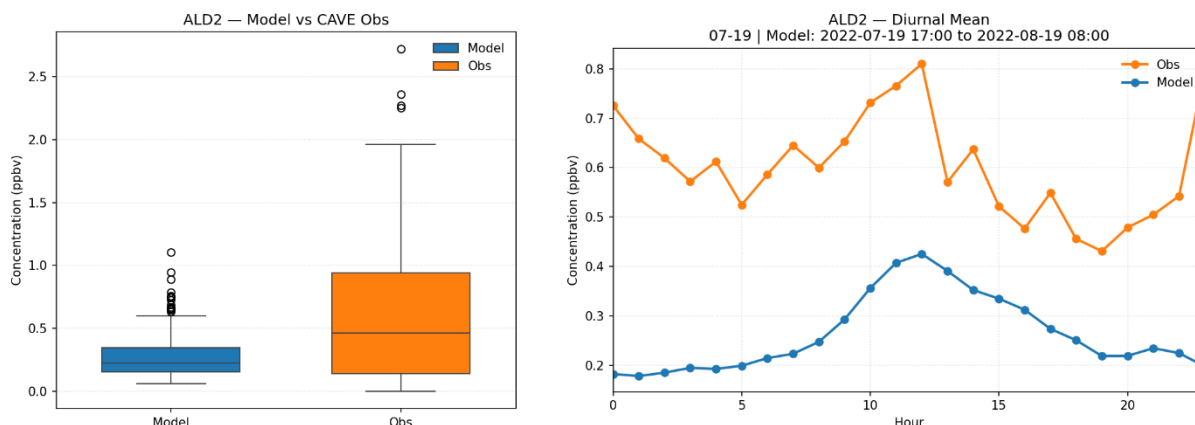


Figure 5-12. Box and Whisker Plots of the distribution of predicted and observed hourly Acetaldehyde concentrations (left) and diurnal variation of hourly Acetaldehyde concentrations (right) at Carlsbad Caverns (left) from the CarCavAQS July 19 – August 19, 2021 field study and CAMx 2022v2 4 km May – October 2022 base case simulation.

Table 5-3 presents the predicted and observed mean and median ethene and acetaldehyde concentrations and their observed-to-modeled ratios. At Carlsbad Caverns, both ethene and acetaldehyde are underestimated by more than a factor of two. In contrast, at the Loving, New Mexico site, modeled ethene concentrations exceed observed values by factors of 1.8 (median) and 1.4 (mean), suggesting that the ethene underestimation at Carlsbad Caverns may be partially attributable to grid-cell dilution effects. However, because acetaldehyde is predominantly secondary in nature and therefore less influenced by grid-cell dilution, the substantial underestimation of acetaldehyde, together with the large underestimation of ethane and propane, suggests that insufficient secondary acetaldehyde formation from oxidation of alkenes associated with oil and gas sources in the Permian Basin is likely contributing to the modeled underestimation.

Table 5-3. Comparison of the Mean and Median Observed and Modeled Ethene and Acetaldehyde concentrations (ppb) and their ratios (Observed/Modeled) from the CarCavAQS and HEI Loving, NM field studies and the CAMx 2022v2 4 km base case simulation.

CarCavAQS Species	N	Model		Observed		Obs/Mod Ratio	
		Mean	Median	Mean	Median	Mean	Median
ETH	560	0.15	0.13	0.36	0.31	2.4	2.4
ALD2	550	0.27	0.22	0.60	0.46	2.3	2.1
Loving, NM Species	N	Model		Observed		Obs/Mod Ratio	
		Mean	Median	Mean	Median	Mean	Median
ETH	3385	0.75	0.52	0.54	0.29	0.7	0.6

5.3.5 Isoprene Evaluation

The comparison of frequency distributions of predicted and observed hourly isoprene concentrations at Carlsbad Caverns and Loving, New Mexico is shown in Figure 5-13. Both observed and modeled isoprene concentrations at these sites are very low, with mean and median values less than 0.01 ppb, although the observations exhibit more outliers than the modeled values. Aside from these outliers, average afternoon isoprene concentrations at Carlsbad Caverns are approximately 0.01 ppb, with near-zero concentrations during nighttime hours. Both the observations and the model indicate that local biogenic VOC emissions are not a significant contributor to elevated ozone concentrations in the vicinity of Carlsbad in Eddy County, New Mexico.

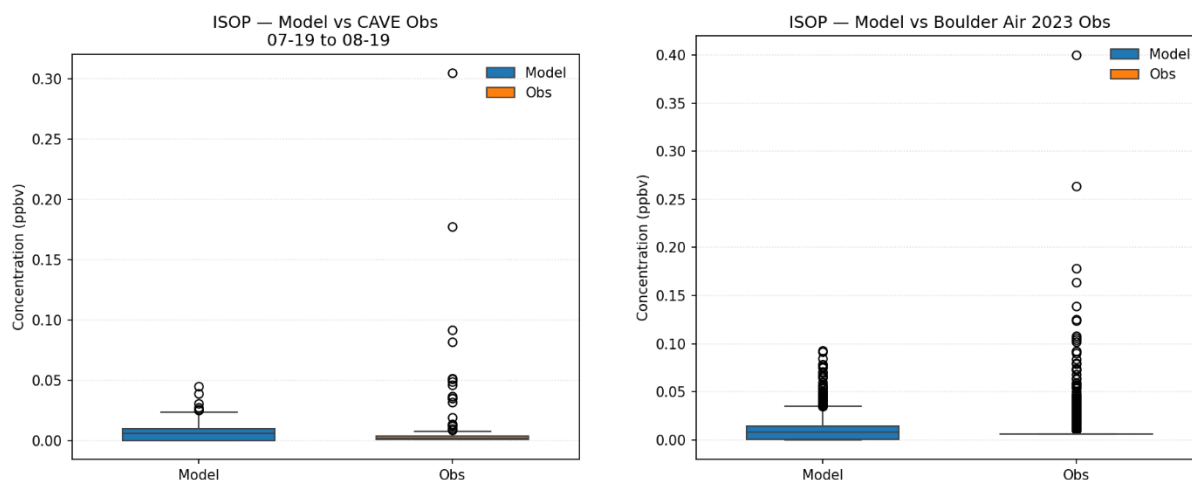


Figure 5-13. Box and Whisker Plots of the distribution of predicted (CAMx 2022v2 4 km) and observed hourly Isoprene concentrations at Carlsbad Caverns (left) from the CarCavAQS July 19 – August 19, 2021 field study and Loving, New Mexico (right) from the HEI Study Boulder Air May – October 2023 field study.

5.4 Evaluation of CAMx 2022v2 4 km Base Case using Field study NO_x Measurements

Research-grade measurements of nitric oxide (NO), nitrogen dioxide (NO₂), oxides of nitrogen (NO_x = NO + NO₂), and total reactive nitrogen oxides (NO_y = NO + NO₂ + N₂O₅ + HNO₃ + PANs+ other) were collected at Carlsbad Caverns during the 2021 CarCavAQS. Figure 5-14 and Figure 5-15 present comparisons between these nitrogen species measurements and results from the CAMx 2022v2 4 km base case using box-and-whisker plots and average diurnal profiles, respectively. Primary emitted NO is underestimated by the model by factors of 4.1 (median) and 2.5 (mean), which is expected given that the Carlsbad Caverns site is located near roadways in a semi-rural setting. Observed NO₂ concentrations also exceed modeled values by factors of 1.5 (median) and 1.8 (mean). Because NO₂ concentrations are generally higher than NO concentrations, NO_x performance closely mirrors that of NO₂, with observed NO_x values exceeding modeled values by factors of 1.6 (median) and 1.9 (mean). NO, NO₂, and NO_x concentrations peak during the morning hours, when a stable surface layer traps emissions near the ground and decrease in the afternoon as vertical mixing increases (Figure 5-15). In contrast, the NO_y diurnal profile is relatively flat, with non-NO_x secondary reactive nitrogen species exhibiting lower concentrations in the morning (~0.5 ppb) and higher concentrations in the afternoon (~2 ppb) as photochemical activity increases.

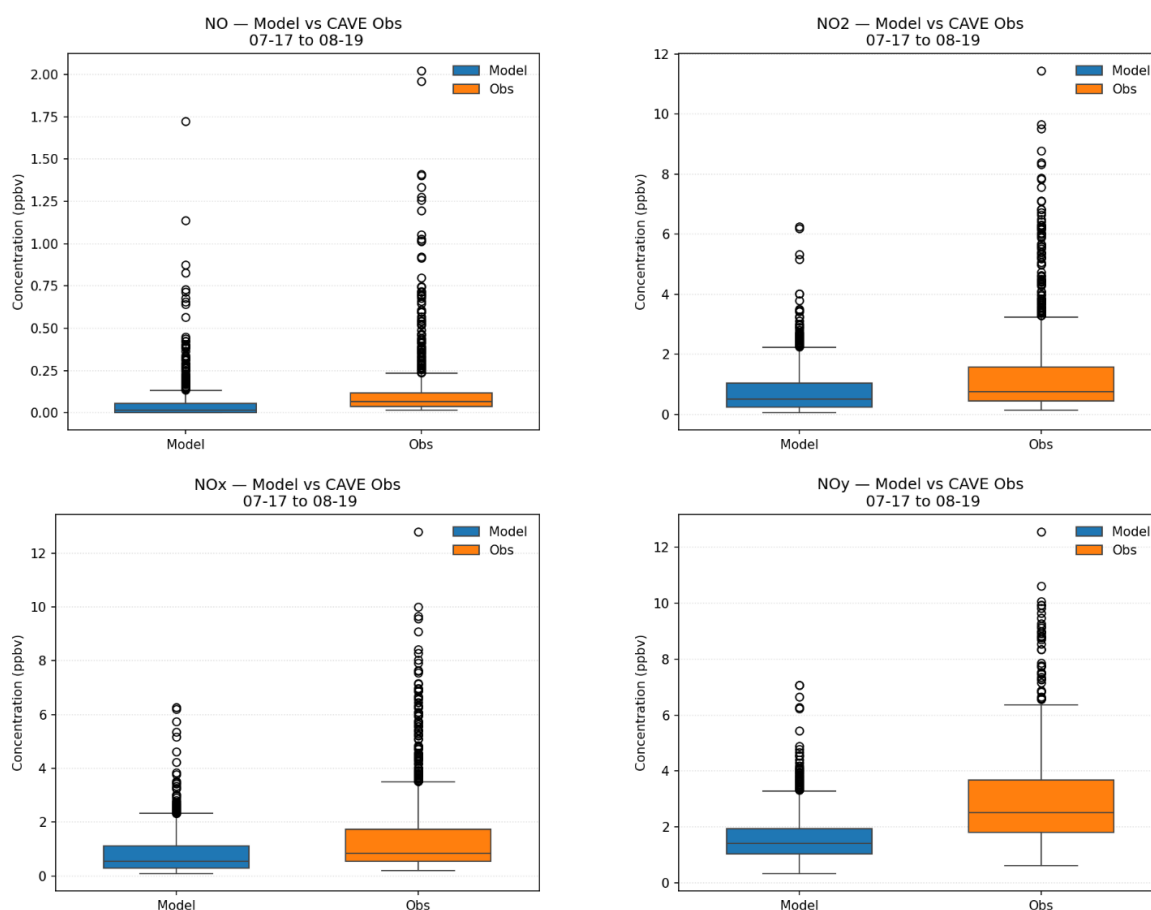


Figure 5-14. Predicted and observed Box and Whisker Plots at Carlsbad Caverns for NO (top left), NO₂ (top right), NO_x (bottom left) and NO_y (bottom right) from the 2021 CarCavAQS field study and the CAMx 2022v2 4 km base case simulation.

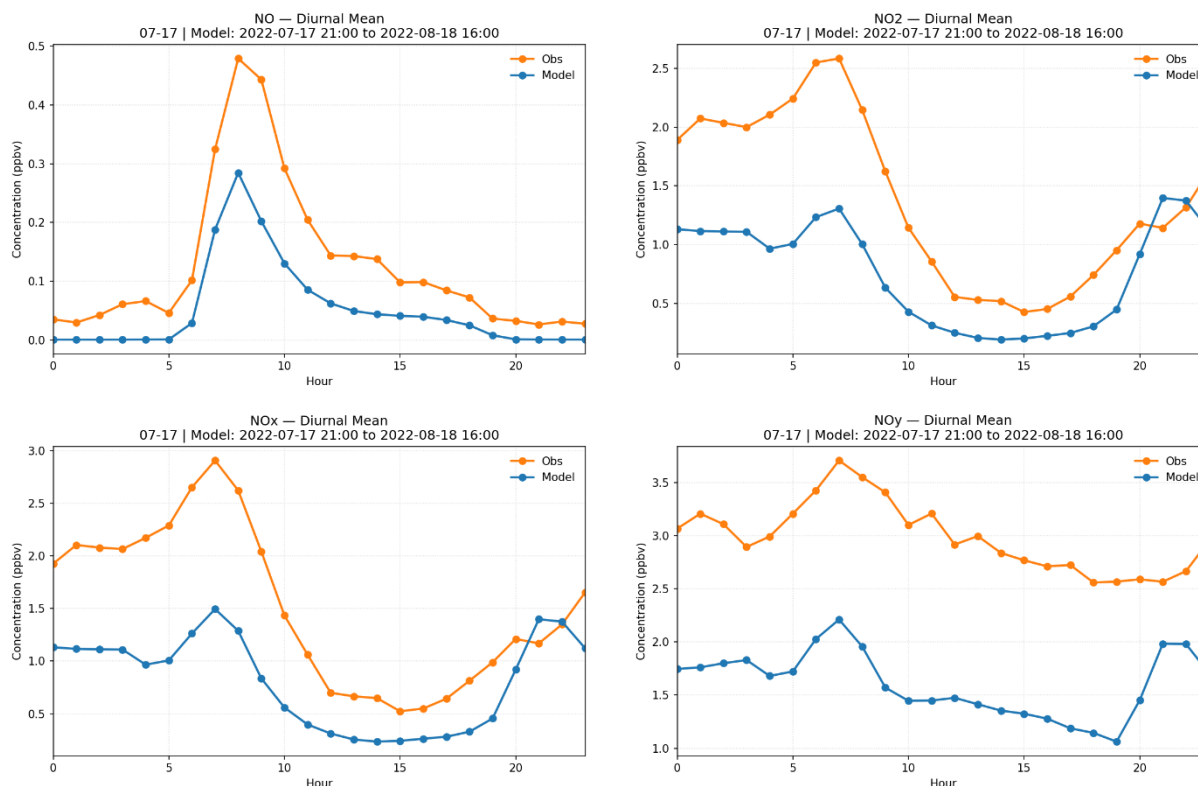


Figure 5-15. Predicted and observed average diurnal variation at Carlsbad Caverns for NO (top left), NO₂ (top right), NO_x (bottom left) and NO_y (bottom right) from the 2021 CarCavAQS field study and the CAMx 2022v2 4 km base case simulation.

Figure 5-16 compares the predicted and observed frequency distributions of the NO_x/NO_y ratios which is metric that measures NO_x aging in the atmosphere. There is good agreement between the observed and modeled 25th to 75th percentiles of NO_x/NO_y ratios with mean and median values of approximately 0.4.

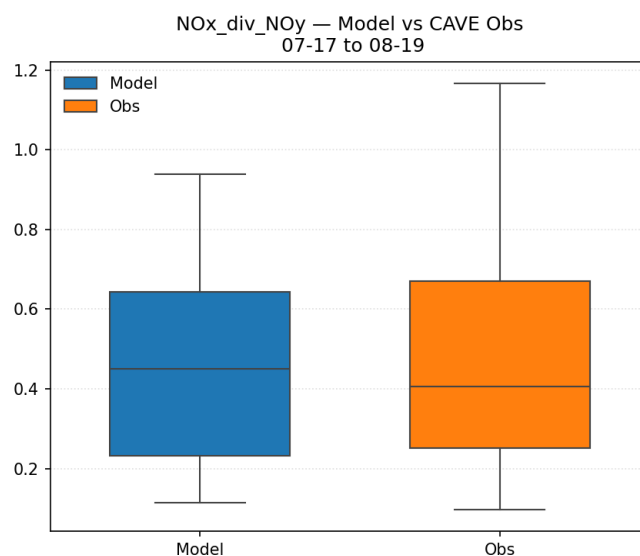


Figure 5-16. Comparison of predicted and observed NO_x to NO_y ratios at Carlsbad Caverns.

Figure 5-17 compares the predicted and observed NO, NO₂ and NO_x Box and Whisker Plots for the Loving, New Mexico site. The median of the observed and modeled NO_x values at Loving are, respectively, 8 and 10 times higher than they are at Carlsbad Caverns. There is reasonable agreement between the observed and modeled nitrogen compound frequency distributions with the modeled NO_x concentrations being 1.2 times (median) and 1.4 times (mean) lower than the observed values.

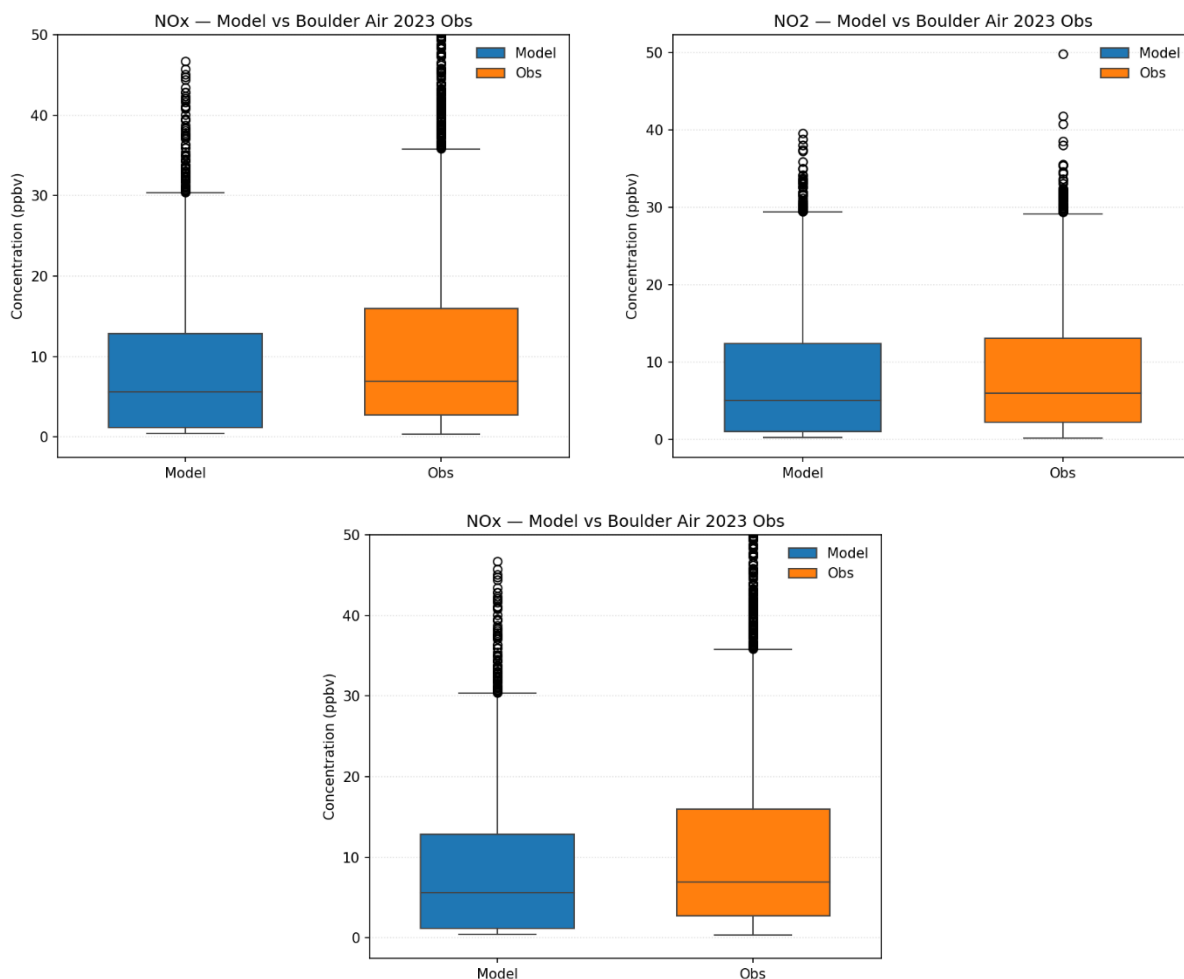


Figure 5-17. Predicted (CAMx 2022v2 4 km) and observed Box and Whisker Plots at Loving, New Mexico for NO (top left), NO₂ (top right) and NO_x (bottom) from the 2023 HEI Boulder AIR measurement study.

5.5 Implications of CAMx 2022v2 4 km Evaluation Against Special Field Study Data

Observed and modeled concentrations at the Loving, New Mexico site are substantially higher than those at Carlsbad Caverns, with the relative differences between the two locations being generally consistent for both observed and modeled values, as shown in Table 5-4. Despite the large absolute differences in ethane and propane concentrations between the sites, modeled ethane and propane concentrations at both locations are, on average, approximately five times lower than observed values, indicating that Permian Basin oil and gas VOC emissions are likely understated in the 2022v2 emissions platform. Modeled NO_x concentrations are approximately 1.5 to 2.0 times lower than observed, which may be partially attributable to differences between point measurements and grid-cell averaged model predictions, particularly at Carlsbad Caverns. While NO_x emissions in the 2022v2 emissions platform may also be understated, the evidence is less conclusive than for VOC emissions.

Table 5-4. Comparison of observed and modeled species concentrations at Loving, New Mexico (LNM) versus Carlsbad Caverns (CAVE) and summary of model evaluation at the two sites.

Species	Observed LNM vs CAVE	Modeled LNM vs CAVE	Model Bias (against Observations)
Ethane	4-6× higher	5-6× higher	~4-5× too low
Propane	3-4× higher	4-5× higher	~4-5× too low
NO _x	8x Higher	10x Higher	~1.5-2× too low

6.0 EVALUATION OF CAMX 2022V2 4 KM BASE CASE AGAINST SATELLITE DATA

The TROPospheric Monitoring Instrument (TROPOMI) is an imaging spectrometer aboard the European Copernicus Sentinel-5 Precursor (S5P) satellite, which was launched in October 2017. TROPOMI vertical column density (VCD) measurements of NO₂ and formaldehyde (HCHO) for 2022 were used to support evaluation of the CAMx 2022v2 4 km base case simulation. TROPOMI collects NO₂ and HCHO observations over New Mexico once per day in the afternoon, with an approximate horizontal resolution of 7 × 3.5 km².

The CAMx 2022v2 4 km base case simulation was configured to output three-dimensional concentrations, from which modeled NO₂ and HCHO VCDs were calculated for each day at the approximate satellite overpass hour. Spatial maps of TROPOMI-derived and CAMx-derived VCD NO₂ and HCHO were generated and compared.

Satellite measurements are subject to greater uncertainty than ground-based observations, and atmospheric or surface conditions such as cloud cover, smoke, or highly reflective surfaces can interfere with retrievals. As a result, interpretation of TROPOMI data is more robust when based on longer-term averages, whereas short-term comparisons can appear highly pixelated and are more difficult to interpret.

6.1 Satellite NO₂ and HCHO Evaluation Over the Permian Basin

Figure 6-1 compares TROPOMI satellite and CAMx VCD HCHO concentrations, along with their differences, over the Permian Basin for the May 14 through September 30, 2022 modeling period. Even when averaged over nearly five months, the TROPOMI HCHO spatial maps remain highly pixelated. Both the satellite and modeled HCHO VCD fields show elevated concentrations in areas of oil and gas development in southern Eddy and Lea Counties and extending across the border into Texas. However, the TROPOMI spatial patterns suggest that CAMx may be overstating HCHO concentrations in these regions.

Figure 6-2 presents a similar comparison for VCD NO₂ concentrations. Elevated NO₂ associated with areas of intense oil and gas development in southern Eddy and Lea Counties is evident in both the modeled results and the TROPOMI satellite observations. In contrast, across the border in Texas, TROPOMI indicates higher VCD NO₂ concentrations than are simulated by the model. This discrepancy is reflected in the difference map shown in the right panel of Figure 6-2, where blue shading indicates that modeled VCD NO₂ concentrations are lower than those reported by TROPOMI on the Texas portion of the Permian Basin adjacent to Eddy and Lea Counties.

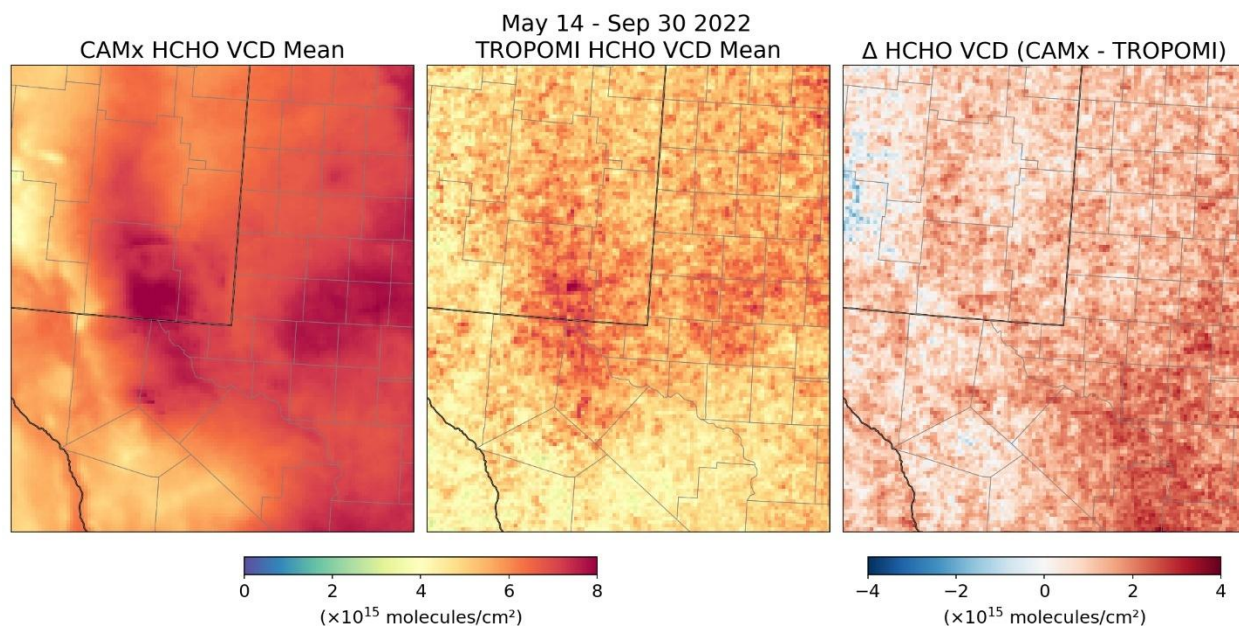


Figure 6-1. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) VCD HCHO concentrations and their differences (right) over the Permian Basin for May 14 – September 30, 2022.

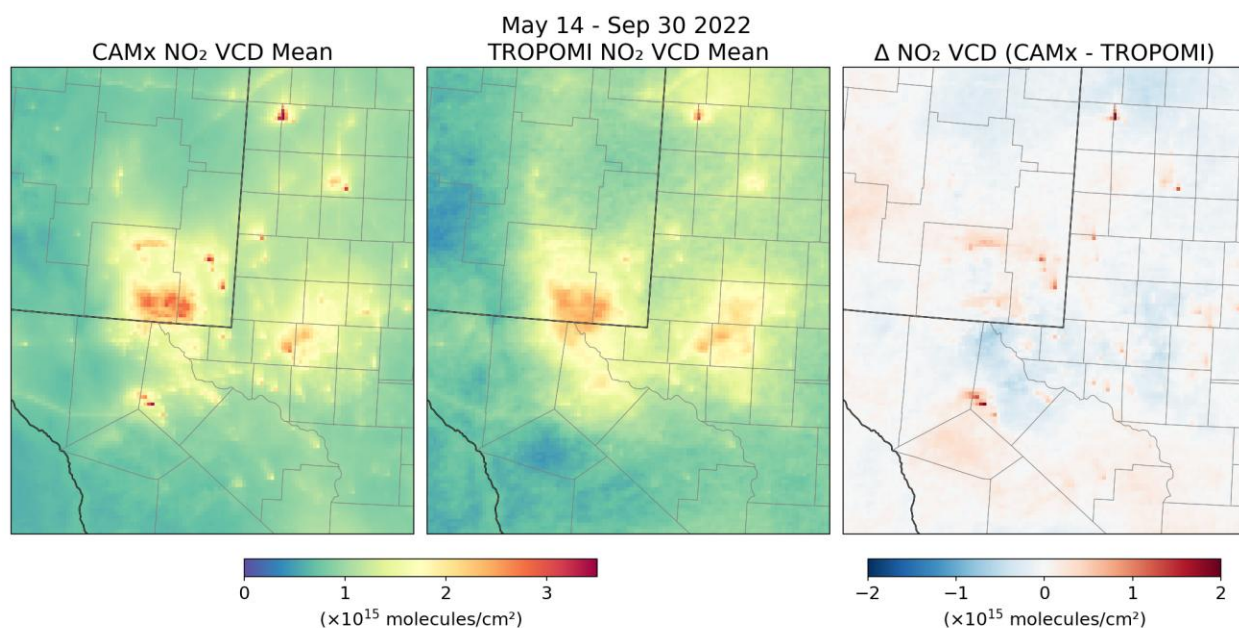


Figure 6-2. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) VCD NO₂ concentrations and their differences (right) over the Permian Basin for May 14 – September 30, 2022.

6.1.1 Formaldehyde to NO₂ Ratio (FNR) Comparisons over the Permian Basin

Several studies have proposed using the formaldehyde-to-NO₂ ratio (FNR) as an indicator of whether ozone formation is more NO_x-sensitive, meaning that NO_x emission reductions are more effective at reducing ozone concentrations than VOC reductions, or more

VOC-sensitive, where VOC emission reductions are more effective and NO_x reductions may even increase ozone. Ozone formation is rarely exclusively NO_x- or VOC-sensitive, and the sensitivity can vary from day to day or even within a single day, with ozone formation often being more VOC-sensitive in the morning and shifting toward greater NO_x-sensitivity later in the afternoon.

Table 6-1 summarizes FNR threshold values reported in peer-reviewed literature that are commonly used to infer whether ozone formation is VOC-sensitive, NO_x-sensitive, or within a transitional regime. Based on these studies, a color-shading scheme was developed for plotting FNR values, as shown in the last row of Table 6-1, with the following interpretation:

- **Black:** clearly VOC-sensitive
- **Dark Blue:** likely VOC-sensitive, but possibly transitional
- **Purple:** likely transitional, but possibly VOC-sensitive
- **Light Blue:** transitional
- **Yellow:** likely NO_x-sensitive
- **Orange and Red:** clearly NO_x-sensitive

Table 6-1. Several peer-reviewed papers suggesting when the formaldehyde to NO₂ ratio (FNR) indicates ozone formation is more VOC-sensitive or more NO_x-sensitive or in a transitional zone between the two.

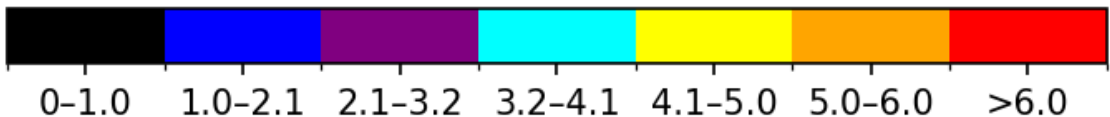
Reference	Data	VOC-Sensitive	Transitional	NO _x -Sensitive
Duncan et al., 2010	Model, OMI	FNR < 1.0	1.0 < FNR < 2.0	FNR > 2.0
Jin et al., 2020	Surface Obs	FNR < 3.2	3.2 < FNR < 4.1	FNR > 4.1
Souri et al., 2020	Box Model+	FNR < 1.0	1.0 < FNR < 4.0	FNR > 4.0
				

Figure 6-3 compares CAMx-derived and TROPOMI-derived FNR along with their differences, across the Permian Basin. The TROPOMI data indicate a larger area of VOC-sensitive and transitional ozone formation regimes within oil and gas development regions of the Permian Basin than is represented by the model. This difference suggests that the model may understate the potential ozone reductions attributable to VOC emission reductions in the Permian Basin.

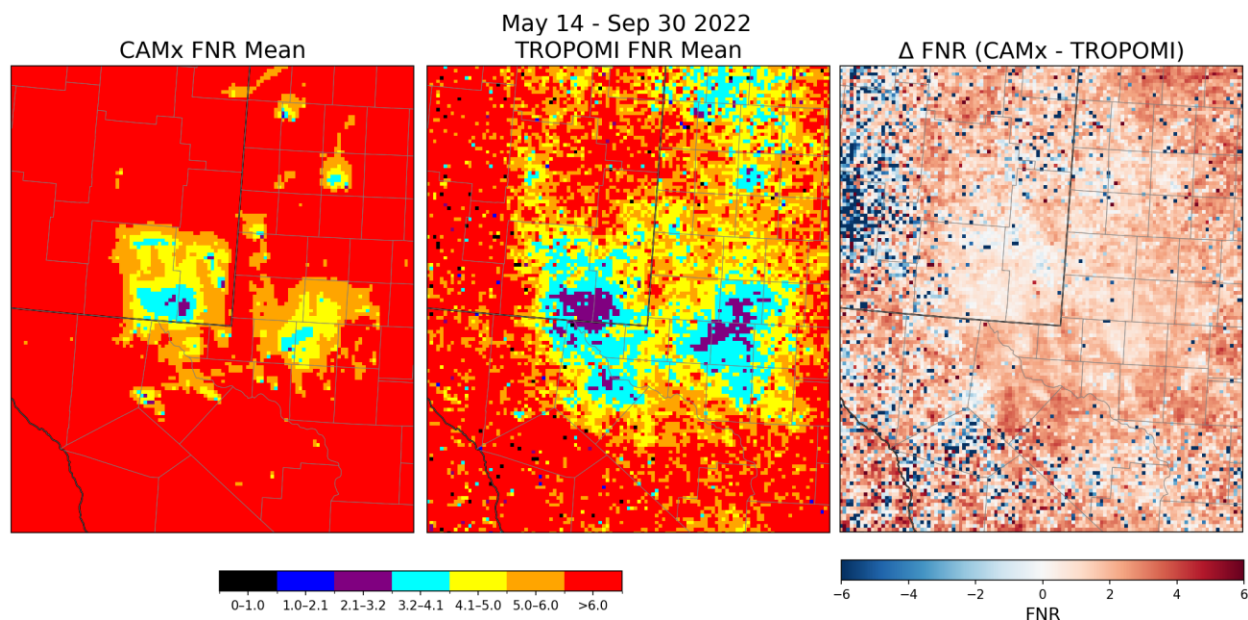


Figure 6-3. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) formaldehyde to NO₂ ratios (FNR) and their differences (right) over the Permian Basin for May 14 – September 30, 2022.

6.1.2 Statistical Comparison of the TROPOMI HCHO and NO₂ Concentrations with CAMx 2022v2 4 km Base Case in the Permian Basin

The May–September 2022 episode-average TROPOMI VCD HCHO and NO₂ concentrations were gridded to the 4 km New Mexico modeling domain and matched with corresponding CAMx values to generate scatter plots for three geographic regions: (1) the New Mexico portion of the Permian Basin; (2) the Texas portion of the Permian Basin; and (3) the full New Mexico 4 km modeling domain. The grid-cell masks for the New Mexico and Texas portions of the Permian Basin were based on the Source Region map used in the NMED Phase I CAMx 2026v1 12 km ozone source apportionment modeling, shown in Figure 6-4.

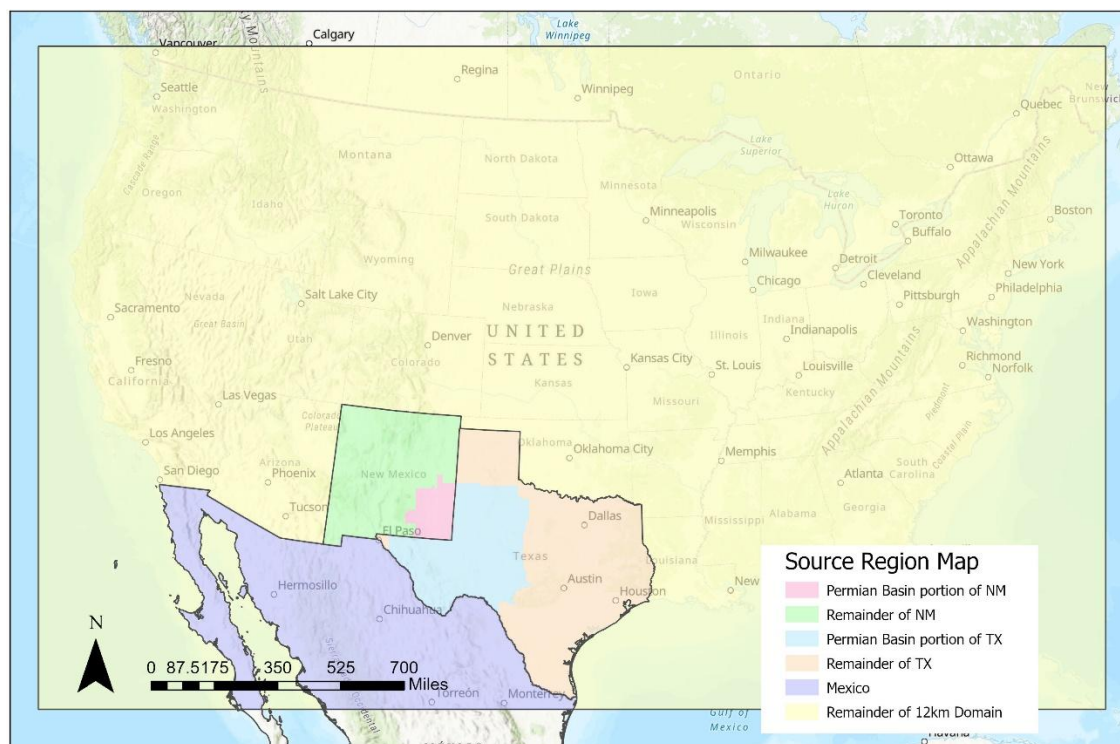


Figure 6-4. Six Source Regions used in the NMED Phase I CAMx 2026v1 12 km APCA ozone source apportionment simulation including the New Mexico (pink) and Texas (blue) portions of the Permian Basin used in the TROPOMI satellite VCD HCHO and NO₂ evaluation.

Figure 6-5 and Figure 6-6 compare TROPOMI satellite and CAMx 2022v2 4 km VCD HCHO and NO₂ concentrations across the New Mexico portion of the Permian Basin. Consistent with the spatial comparison shown in Figure 6-1, the model overestimates TROPOMI HCHO concentrations with an NMB of 19.0%, with a comparable NME of 19.3% that indicates the HCHO overestimation is systematic (Figure 6-5).

For VCD NO₂, there is good agreement between TROPOMI and CAMx 2022v2 concentrations in the New Mexico portion of the Permian Basin with near-zero bias (NMB = 0.1%) and low error (NME = 7.7%) (Figure 6-6). Some modeled VCD NO₂ values exceed those observed by TROPOMI, which is likely attributable to fossil-fuel-fired electric generating units (EGUs; e.g., the Cunningham and Hobbs EGUs in Lea County) or other non-EGU industrial point sources. This pattern is also evident in Figure 6-2, where the higher-resolution CAMx results show elevated VCD NO₂ concentrations at major NO_x point source locations that are not fully resolved in the lower-resolution TROPOMI observations.

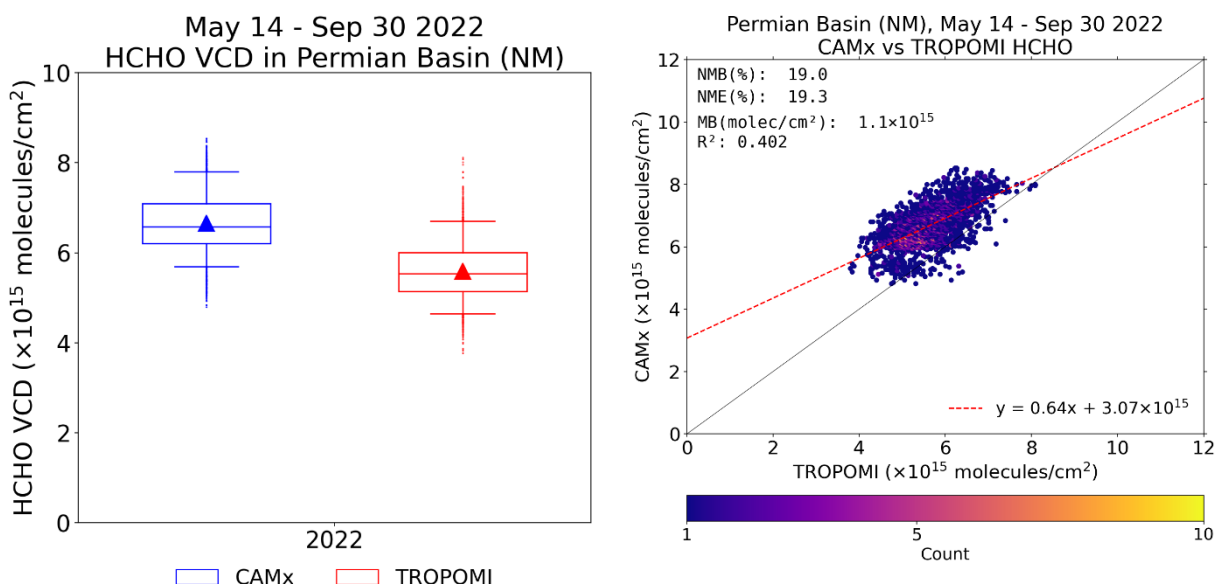


Figure 6-5. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD HCHO concentrations for the New Mexico portion of the Permian Basin.

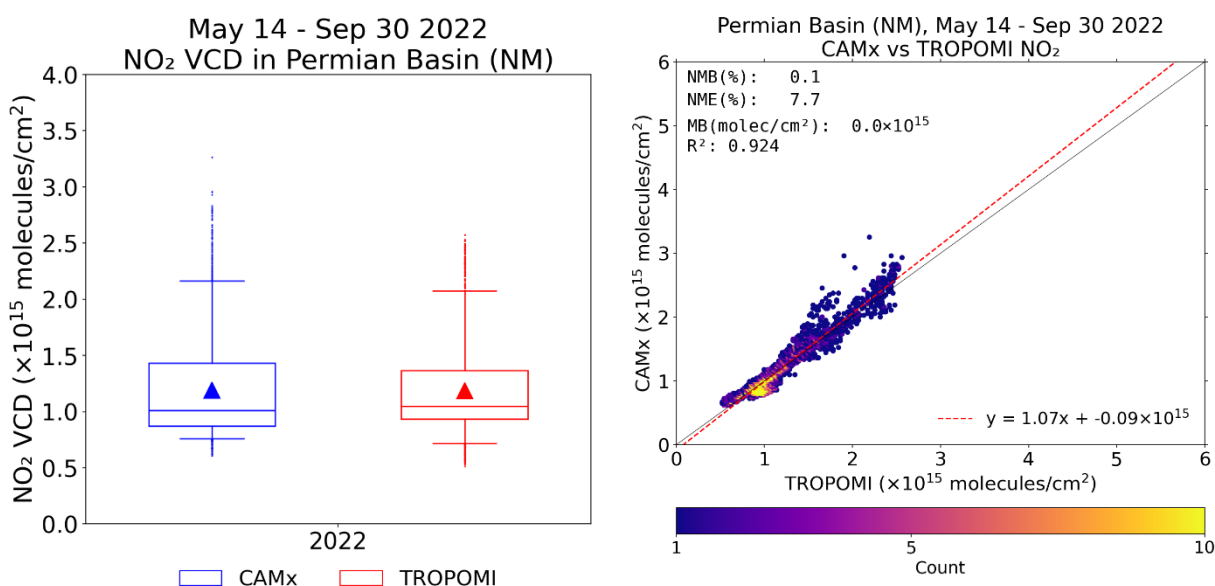


Figure 6-6. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD NO₂ concentrations for the New Mexico portion of the Permian Basin.

Because NO_x emissions originate from numerous source types, and oil and gas (O&G) sources represent only a relatively small fraction of total NO_x emissions in the New Mexico portion of the Permian Basin (Figure 6-4), it is difficult to draw conclusions regarding the accuracy of O&G NO_x emissions based solely on total VCD NO₂ comparisons across this region. Figure 6-7 is similar to Figure 6-6, but restricts the VCD NO₂ comparison to 4 km grid cells in the New Mexico portion of the Permian Basin that have 2022v2 O&G NO_x emissions greater than 0.02 tons per day (TPD). Because CAMx has finer spatial resolution

than TROPOMI, it tends to produce higher VCD NO₂ concentrations in grid cells containing major O&G NO_x sources (e.g., midstream facilities). Overall, there is reasonable agreement between CAMx and TROPOMI VCD NO₂ concentrations in 4 km grid cells with O&G emissions in the New Mexico portion of the Permian Basin, with low bias (4.5%) and low error (7.9%).

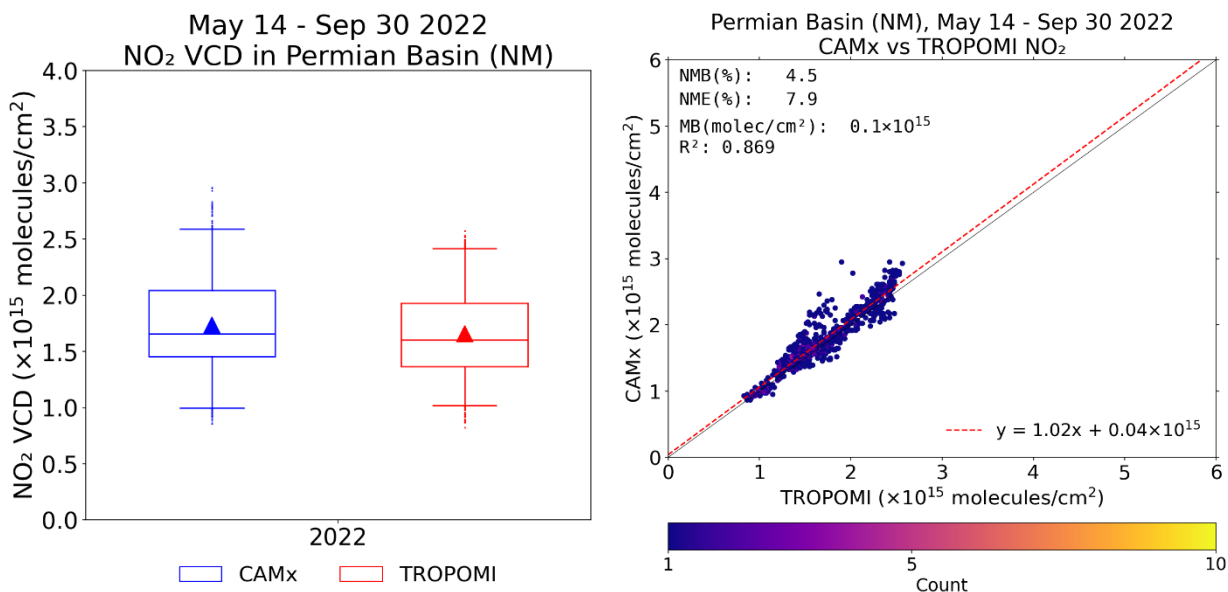


Figure 6-7. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD NO₂ concentrations for the New Mexico portion of the Permian Basin in 4 km grid cells with O&G NO_x emissions greater than 0.02 TPD.

Figure 6-8 and Figure 6-9 present comparisons of TROPOMI and CAMx VCD HCHO and NO₂ concentrations across the Texas portion of the Permian Basin. This region is spatially extensive (see Figure 6-4) and contains numerous emission sources, while areas dominated by oil and gas activity represent only a small subset of the overall basin. Across the Texas portion of the Permian Basin, the model overestimates TROPOMI VCD HCHO concentrations by nearly 30%. Biogenic emissions are more prevalent in this region, and oxidation of biogenic isoprene is a major contributor to ambient HCHO concentrations. Agreement between modeled and TROPOMI VCD NO₂ concentrations is generally better across the Texas portion of the Permian Basin; however, several 4 km grid cells exhibit modeled VCD NO₂ values that are substantially higher than TROPOMI, likely reflecting the finer spatial resolution of CAMx at locations of electric generating units or other non-EGU point sources.

Figure 6-10 compares CAMx and TROPOMI VCD NO₂ concentrations for 4 km grid cells in the Texas portion of the Permian Basin that have 2022v2 oil and gas NO_x emissions exceeding 0.02 TPD. As in previous comparisons, some grid cells show much higher modeled VCD NO₂ concentrations than TROPOMI due to the higher resolution of the CAMx results. However, for most 4 km grid cells with oil and gas emissions in the Texas portion of the Permian Basin, the modeled VCD NO₂ concentrations are lower than those observed by TROPOMI. This pattern suggests that oil and gas NO_x emissions in the Texas portion of the Permian Basin may be understated in the 2022v2 emissions inventory.

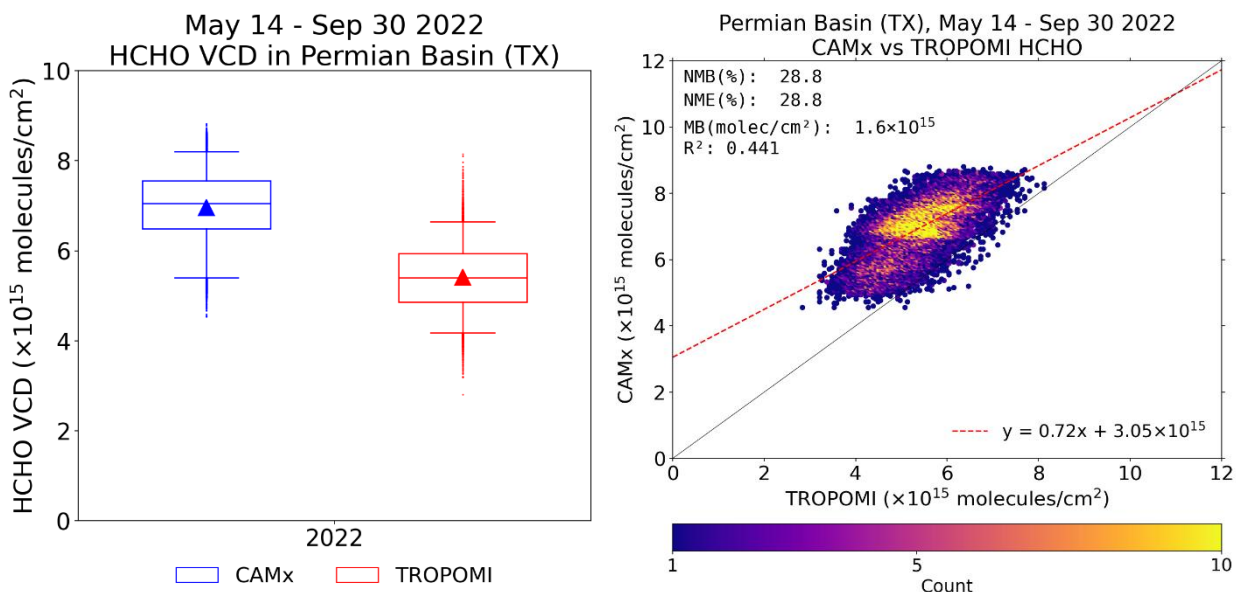


Figure 6-8. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD HCHO concentrations for the Texas portion of the Permian Basin.

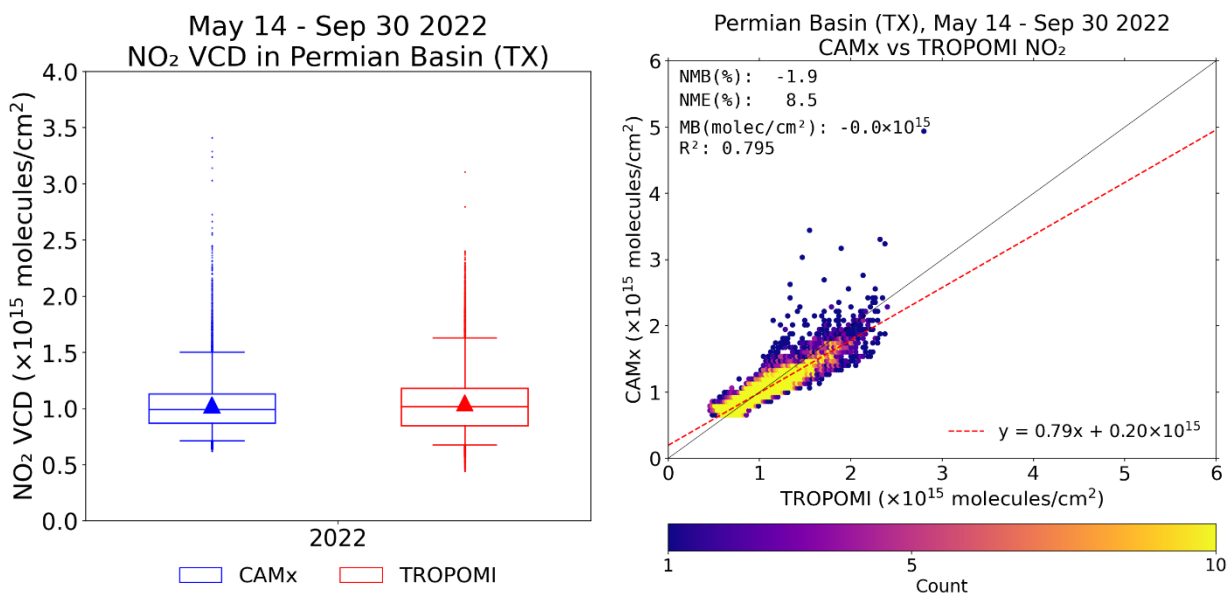


Figure 6-9. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD NO₂ concentrations for the Texas portion of the Permian Basin.

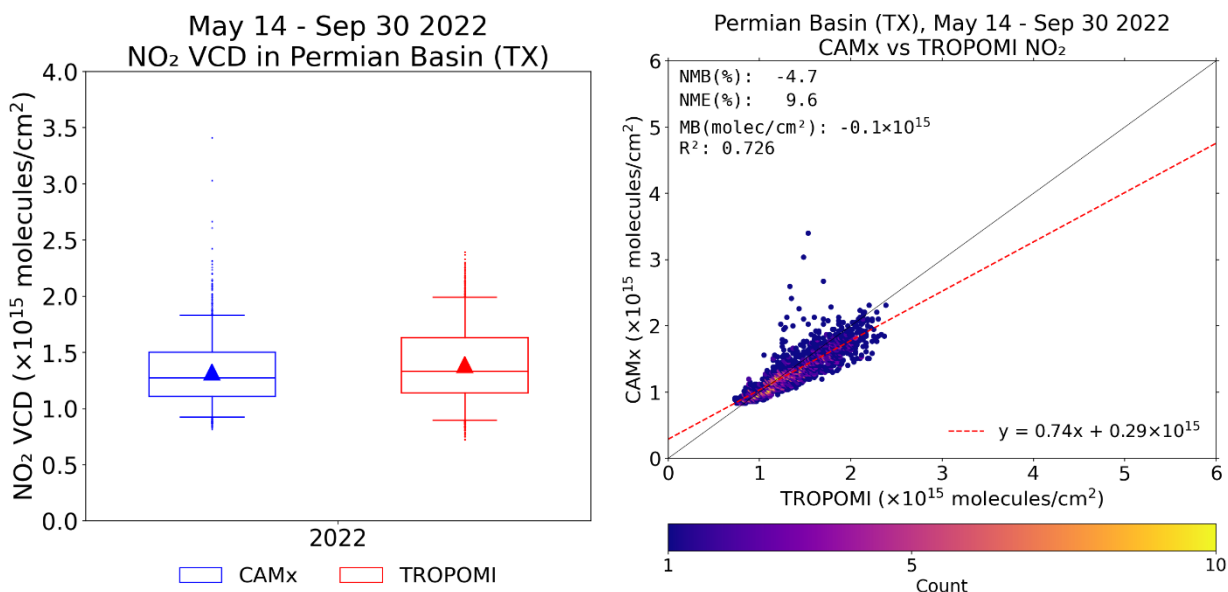


Figure 6-10. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD NO₂ concentrations for the Texas portion of the Permian Basin in 4 km grid cells with O&G NO_x emissions greater than 0.02 TPD.

6.2 Satellite NO₂ and HCHO Evaluation Over the New Mexico 4 km Domain

Figure 6-11 through Figure 6-13 present comparisons of TROPOMI VCD HCHO and NO₂ concentrations and formaldehyde-to-NO₂ ratios (FNR) across the 4 km New Mexico modeling domain. The locations of the two largest wildfires in New Mexico during 2022, the Calf Canyon/Hermits Peak fire and the Black fire, are evident in both the modeled and TROPOMI VCD HCHO fields, with the modeled HCHO concentrations appearing higher and more spatially pronounced. Elevated HCHO concentrations associated with oil and gas development on the New Mexico side of the Permian Basin and emissions influences from Ciudad Juárez in Mexico are also apparent in the HCHO comparison plots.

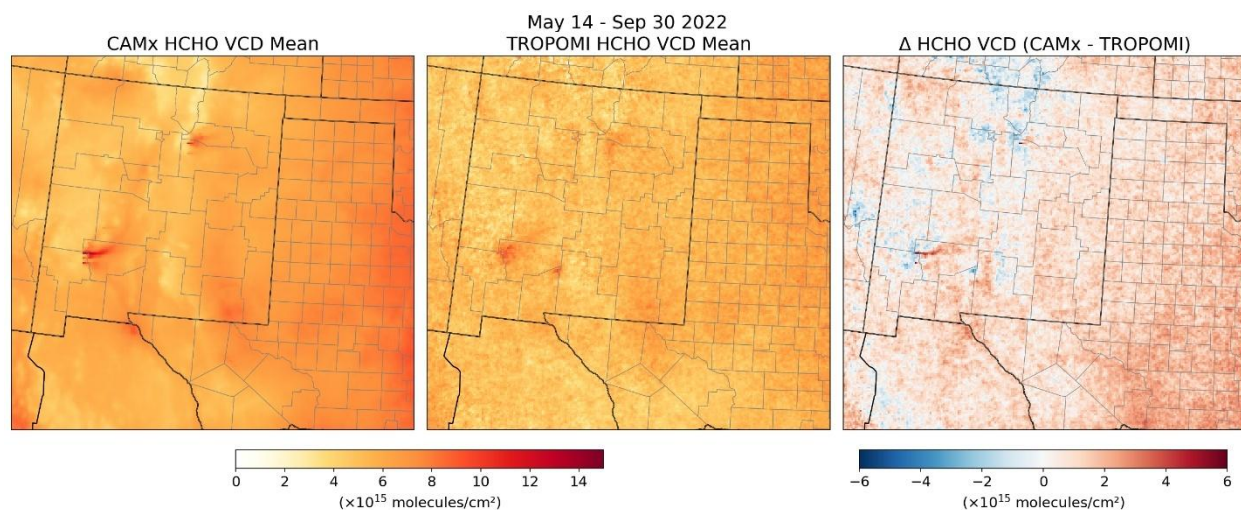


Figure 6-11. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) VCD HCHO concentrations and their differences (right) over the New Mexico 4 km domain for May 14 – September 30, 2022.

The major features evident in the VCD NO₂ comparisons across the New Mexico 4 km domain (Figure 6-12) include major urban areas (e.g., Ciudad Juárez and Albuquerque), oil and gas development regions (the Permian and San Juan Basins), and fossil-fuel-fired electric generating units (e.g., the Four Corners and San Juan facilities in northwest New Mexico and the Coronado and Springerville facilities in eastern Arizona near the New Mexico border). Because TROPOMI has a coarser horizontal resolution than the CAMx 4 km grid, TROPOMI-derived VCD NO₂ fields appear smoother than the corresponding CAMx results.

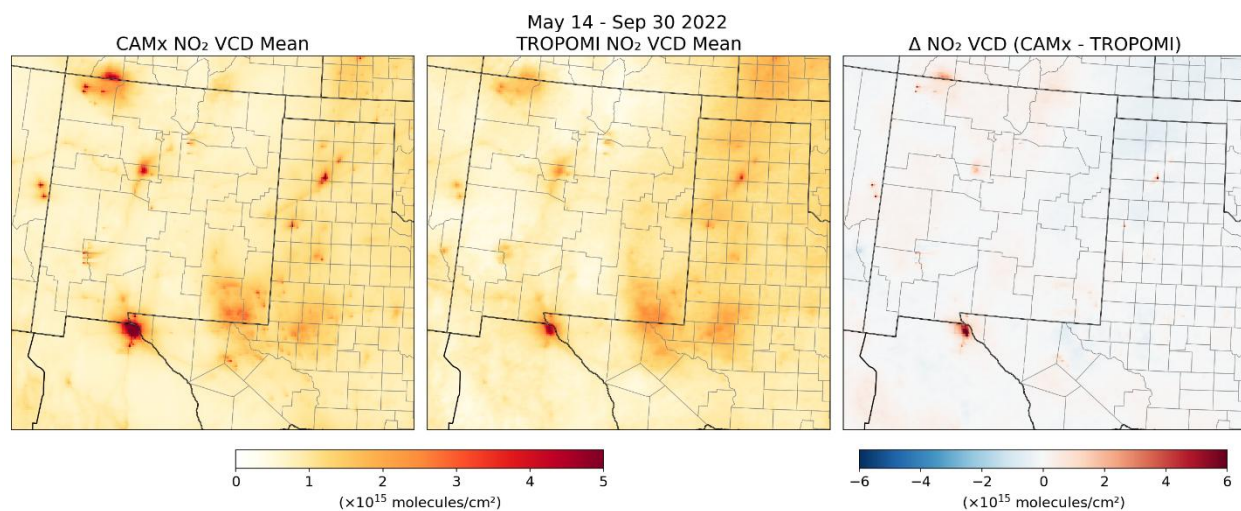


Figure 6-12. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) VCD NO₂ concentrations and their differences (right) over the New Mexico 4 km domain for May 14 – September 30, 2022.

The TROPOMI-derived FNR indicates a larger extent of potential VOC-sensitive and transitional ozone formation regimes than the CAMx-derived FNR, which is largely confined to the two largest urban areas (ciudad Juárez and Albuquerque), oil and gas development areas in the Permian Basin, and the San Juan Basin near major coal-fired electric generating units in northwest New Mexico and southwest Colorado (Figure 6-13). This difference suggests that the model may understate the potential benefits of VOC emission reductions for decreasing ozone concentrations.

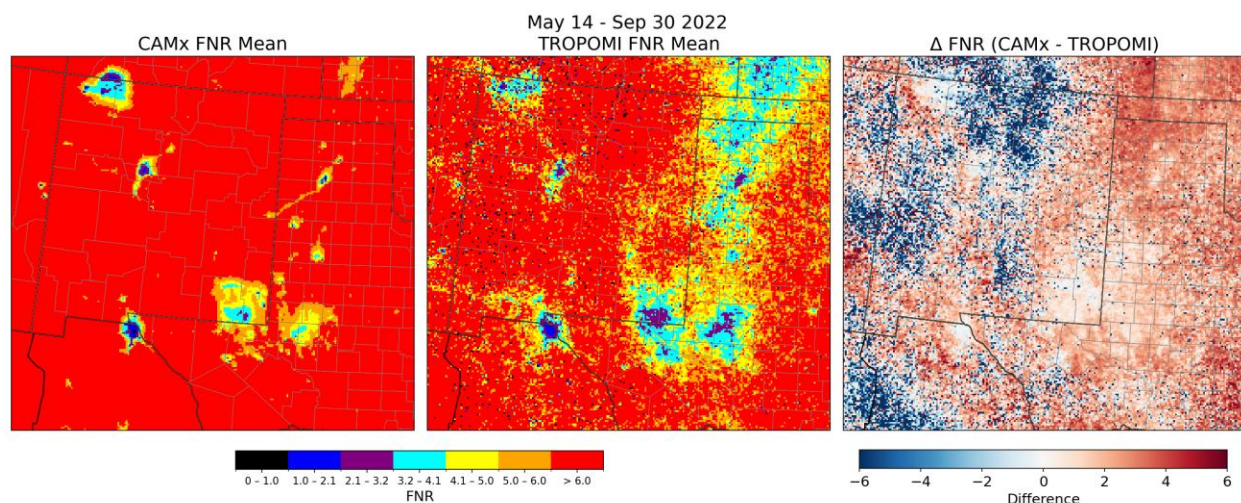


Figure 6-13. Comparison of CAMx modeled (left) and TROPOMI satellite (middle) formaldehyde to NO₂ ratios (FNR) and their differences (right) over the New Mexico 4 km domain for May 14 – September 30, 2022.

6.2.1 Statistical Comparison of the TROPOMI HCHO and NO₂ Concentrations with CAMx 2022v2 4 km Base Case in the New Mexico 4 km Domain

There are more modeled VCD HCHO outliers across the New Mexico 4 km domain than are present in the TROPOMI VCD HCHO data, which is likely attributable to wildfire influences that may overstate HCHO emissions in the model and/or to the higher spatial resolution of the CAMx simulation (4 km) relative to TROPOMI (Figure 6-14). Overall, the model overestimates TROPOMI VCD HCHO concentrations by nearly 20% on average.

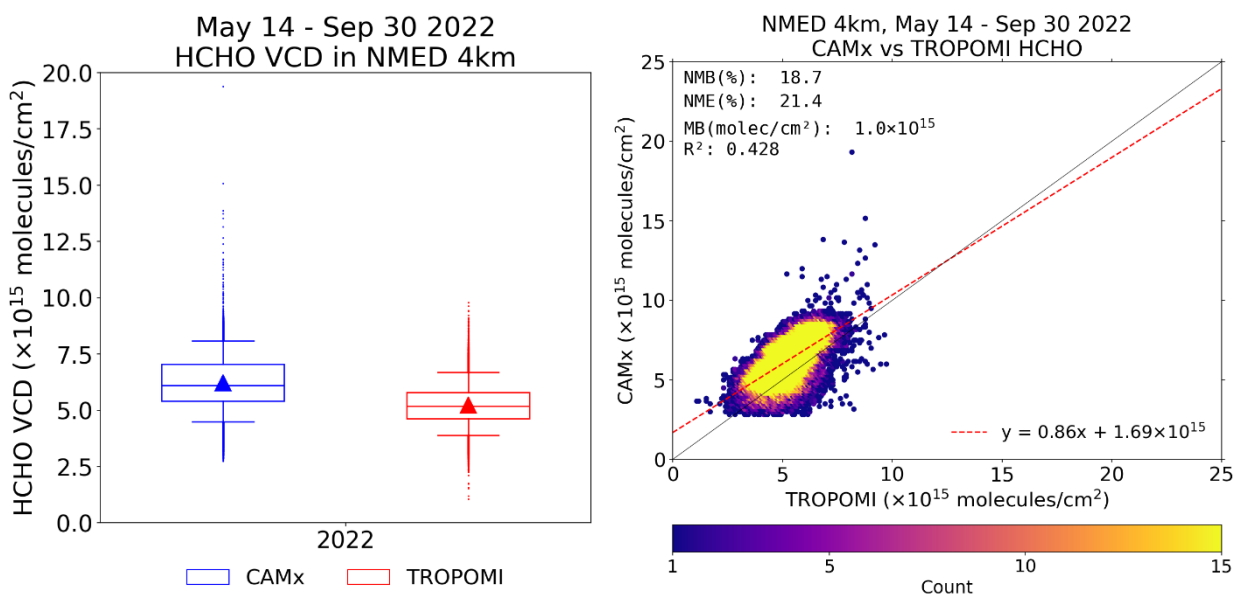


Figure 6-14. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD HCHO concentrations for the New Mexico 4 km domain.

For the highest VCD NO₂ concentrations, modeled values are much higher than those observed by TROPOMI, as reflected in the scatter plot shown in Figure 6-15. These points likely correspond to locations of large electric generating units or other NO_x point sources, which produce elevated VCD NO₂ concentrations within the modeled 4 km grid cells containing the source, whereas the lower-resolution TROPOMI data appear considerably smoother. At lower NO₂ concentrations, agreement between TROPOMI and modeled VCD NO₂ improves, with modeled values generally lower than those observed by TROPOMI.

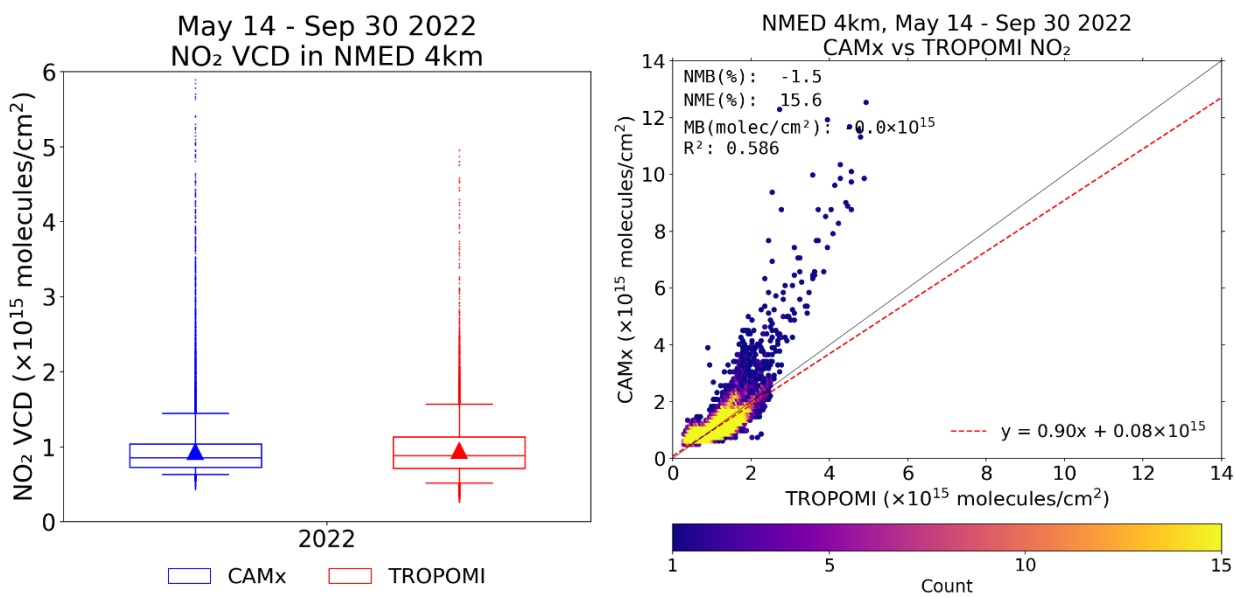


Figure 6-15. Comparison of TROPOMI satellite versus CAMx 2022v2 4 km base case VCD NO₂ concentrations for the New Mexico 4 km domain.

7.0 CAMX SENSITIVITY MODELING

CAMx sensitivity tests were conducted using the 2022v2 12/4 km modeling platform to evaluate sensitivity to key model inputs and configuration options, with the objective of identifying factors influencing performance and opportunities for model improvement.

7.1 Modeling Episode for Sensitivity Tests

A shorter modeling episode was selected for sensitivity modeling to reduce computational requirements and overall runtime for the CAMx sensitivity simulations. A 20-day episode from June 28 to July 17, 2022, was chosen for this analysis. As shown in Table 1-1, this period represents approximately 15 percent of the days within the May–October modeling period but includes approximately 40 percent of the days with observed ozone exceedances at the Carlsbad City monitoring site. This episode captures a concentrated period with a high number of exceedance days and provides a cost-effective and efficient basis for evaluating the sensitivity of the CAMx 2022v2 modeling platform to key inputs.

7.2 Overview of Sensitivity Tests

Seven (7) CAMx 2022v2 12/4 km sensitivity tests were performed for the 20-day episode, focusing on ozone and ozone precursor performance at sites in the New Mexico portion of the Permian Basin. Key CAMx 2022v2 12/4 km performance issues in the Permian Basin include underestimation of afternoon ozone and NO₂ concentrations, as well as substantial underestimation of several VOC species associated with oil and gas (O&G) emissions, such as ethane and propane, for which modeled concentrations were approximately five times lower than observed. Two categories of sensitivity tests were conducted: those related to meteorology (e.g., vertical mixing defined by Kv) and those related to emissions, with the emissions-focused tests evaluating oil and gas emissions in either the New Mexico (NM) or Texas (TX) portions of the Permian Basin (PB). The seven CAMx sensitivity tests are summarized in Table 7-1 and are described in the following two sections.

Table 7-1. Summary of the seven CAMx 2022v2 12/4 km sensitivity tests conducted for the June 28 – July 17, 2022 episode.

Name	Type	Description
Base Case	Base	2022v2 Emissions with Kv(YSU) with KvPatch100
Sens1	Meteorology	2022v2 Emissions with Kv(YSU) no KvPatch100
Sens2	Meteorology	2022v2 Emissions with Kv(CMAQ) no KvPatch100
Sens3	Emissions	3 x NM PB O&G NO_x with Kv(YSU) with KvPatch100
Sens4	Emissions	3 x NM PB O&G VOC NM PB with Kv(YSU) with KvPatch100
Sens5	Emissions	3 x O&G NO_x & VOC NM PB with Kv(YSU) with KvPatch100
Sens6	Meteorology	Base Case with No Cloud Cover
Sens7	Emissions	3 x O&G VOC & NO_x TX PB with Kv(YSU) with KvPatch100

7.2.1 Description of Meteorological Sensitivity Tests

One potential reason for underestimation of afternoon ozone and NO₂ concentrations in the Permian Basin is excessive vertical mixing in the CAMx 2022v2 12/4 km modeling platform, which could dilute surface ozone and NO₂ concentrations. Meteorological inputs for the CAMx 2022v2 12/4 km platform were generated by processing output from the WRF simulation described in Chapter 2 using the WRFCAMx processor. WRFCAMx largely passes

through and reformats WRF meteorological variables. However, it also generates vertical turbulent exchange coefficients, or diffusivities (Kv), which define the rate of vertical mixing in the CAMx simulation. There are two options in WRFCAMx for generating vertical Kv profiles for CAMx: YSU and CMAQ. For the CAMx 2022v2 12/4 km base case simulation, the WRFCAMx YSU Kv option was selected [Kv(YSU)].

To account for the urban heat island effect, which can enhance near-surface vertical mixing, the KvPatch program is applied to set a minimum Kv in the lowest 100 m of the atmosphere from 0.1 m²/s to 2.0 m²/s, depending on the fraction of urban land use within each grid cell (100 percent urban corresponds to 2.0 m²/s). The CAMx 2022v2 12/4 km base case vertical mixing therefore used Kv(YSU) with KvPatch applied. The first sensitivity test (Sens1) used Kv(YSU) diffusivities without KvPatch, which reduces vertical mixing in grid cells containing urban land use. The second sensitivity test (Sens2) used the alternative WRFCAMx CMAQ Kv option [Kv(CMAQ)] without KvPatch to evaluate a different approach to vertical mixing.

In addition, excessive cloud cover generated by the WRF model could overstate attenuation of incoming solar radiation, thereby reducing NO₂ photolysis and other photolysis reactions that are important for ozone formation. To assess this potential influence, a sensitivity test (Sens6) was performed in which all cloud cover was eliminated in the 4 km New Mexico domain to evaluate whether cloud cover contributes to the ozone underestimation bias.

7.2.2 Description of Emission Sensitivity Tests

The VOC evaluation at Carlsbad Caverns and Loving, New Mexico, indicates that O&G VOC emissions in the Permian Basin are understated in the 2022v2 emissions inventory. Numerous reports on the NMED website⁴ document excess emissions from O&G sources in the Permian Basin that are not represented in the 2022v2 inventory, and additional unreported excess emissions are also likely present.

There are numerous peer-reviewed journal publications that document how current emission inventory estimates understated O&G emissions (Helmig and Caputi, 2025). Most of these studies address the underreporting of methane (CH₄) emissions from O&G emission inventories. Like ethane and propane, methane emissions are a marker for O&G production and the O&G processes that emit methane also emit ethane and propane. Specific to the New Mexico portion of the Permian Basin, Chen et al., (2022) used aerial surveys and found that O&G methane emissions were underestimated by a factor of approximately eight. Robertson et al., (2020) used a ground-based mobile measurement laboratory and inverse modeling and estimated that methane emissions from the western portion of the Permian Basin (Delaware Basin) were a factor of 5 to 9 times higher than EPA's emissions estimates.

To evaluate the sensitivity of modeled concentrations to the potential O&G emission underestimates, four Permian Basin O&G emissions sensitivity tests were conducted:

- Sens3: Three times O&G NO_x emissions in the New Mexico portion of the Permian Basin.
- Sens4: Three times O&G VOC emissions in the New Mexico portion of the Permian Basin.
- Sens5: Three times O&G NO_x and VOC emissions in the New Mexico portion of the Permian Basin.
- Sens7: Three times O&G NO_x and VOC emissions in the Texas portion of the Permian Basin.

⁴ <https://www.env.nm.gov/air-quality/compliance-and-enforcement/>

7.3 Results of the Meteorological Sensitivity Tests

Figure 7-1 and Figure 7-2 present time series of hourly ozone and NO₂ concentrations at the Carlsbad City monitoring site for the CAMx 2022v2 4 km base case, the vertical mixing sensitivity tests, and the June 30–July 3 and July 4–7, 2022 periods. The ozone and NO₂ concentrations from the CAMx vertical mixing sensitivity tests are nearly identical to those from the base case. Results from the simulations using Kv(YSU) diffusivities with KvPatch applied (Base Case; blue) and without KvPatch1 (Sens1; red) are essentially the same, indicating that KvPatch has no effect on modeled ozone and NO₂ concentrations at the Carlsbad City monitoring site. One likely reason for the limited influence of KvPatch is the low fraction of urban land use in grid cells containing and surrounding the ozone monitoring site, as KvPatch is intended primarily for large urban areas rather than the predominantly rural Permian Basin.

When the alternative Kv(CMAQ) vertical mixing option without KvPatch is used (Sens2; green), small and occasionally noticeable differences in hourly ozone and NO₂ concentrations are observed; however, these differences are minor and do not result in any appreciable change in overall model performance.

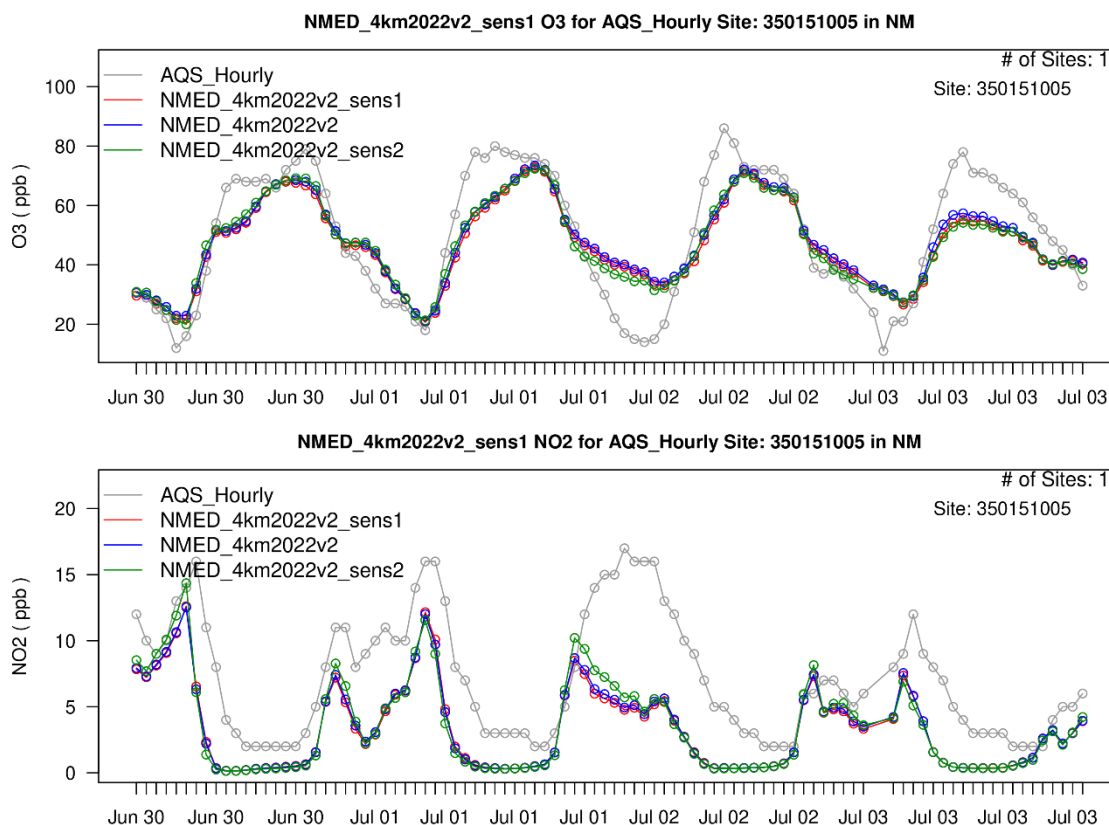


Figure 7-1. Time series of predicted and observed hourly ozone (top) and NO₂ (bottom) concentrations at Carlsbad City monitoring site, June 30 to July 3, 2022, and vertical mixing sensitivity tests: Base Case [Kv(YSU) with KvPatch100; blue]; Sens1 [Kv(YSU) with no KvPatch100; red]; and Sens2 [Kv(CMAQ) with no KvPatch100; green].

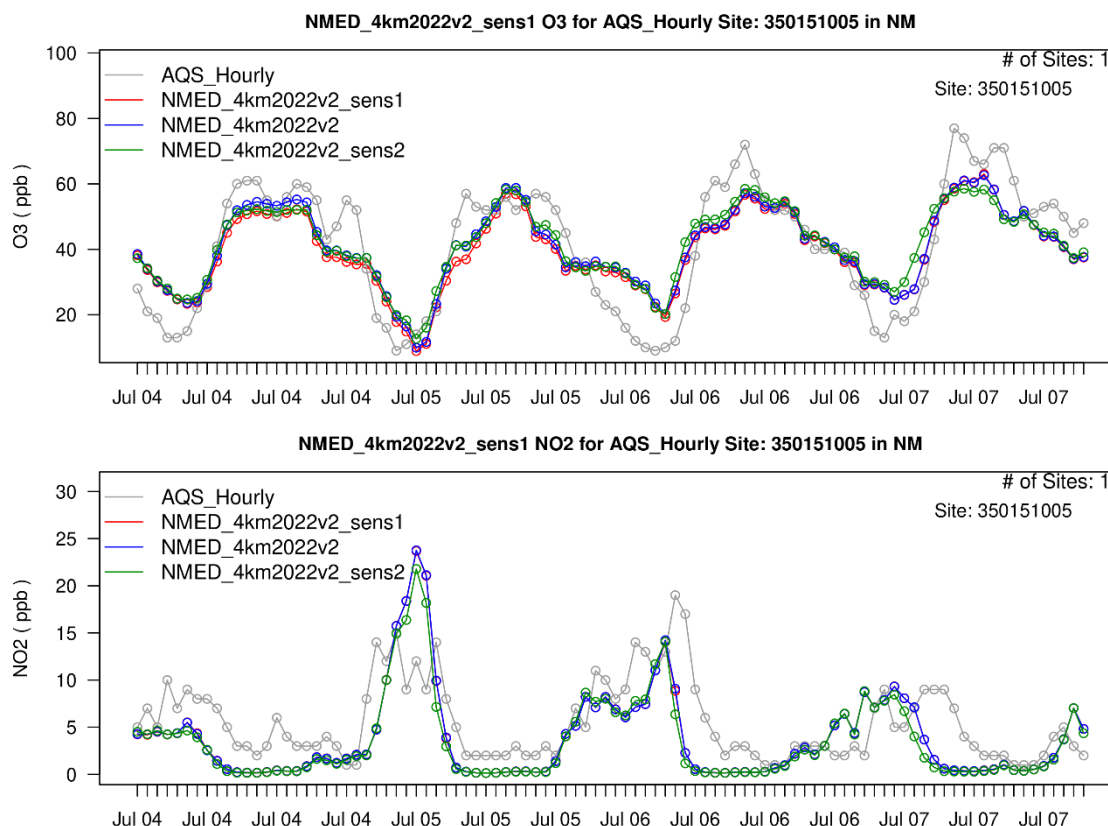


Figure 7-2. Time series of predicted and observed hourly ozone (top) and NO₂ (bottom) concentrations at Carlsbad City monitoring site, July 4 to 7, 2022, and vertical mixing sensitivity tests: Base Case [Kv(YSU) with KvPatch100; blue]; Sens1 [Kv(YSU) with no KvPatch100; red]; and Sens2 [Kv(CMAQ) with no KvPatch100; green].

The Sens6 no cloud cover in the 4 km New Mexico domain meteorological sensitivity test had essentially no effect on the CAMx ozone and NO₂ concentrations estimates (not shown). As noted in Chapter 2 and in Ramboll (2025c), WRF tended to produce less precipitation than PRISM and therefore was also likely to generate less cloud cover.

7.4 Results of the Emissions Sensitivity Tests

Figure 7-3 and Figure 7-4 present time series of hourly ozone and NO₂ concentrations at the Carlsbad City monitoring site for the New Mexico Permian Basin oil and gas (PB O&G) emissions sensitivity tests during the June 30–July 3 and July 8–11, 2022 periods, respectively. Increasing New Mexico PB O&G NO_x emissions by a factor of three, either alone (Sens3) or in combination with a threefold increase in O&G VOC emissions (Sens5), results in improved hourly ozone model performance. However, nighttime NO₂ concentrations are overstated in both the Sens3 and Sens5 simulations, and afternoon NO₂ concentrations remain underestimated relative to observations, although they are higher than in simulations without increased O&G NO_x emissions. Increasing New Mexico PB O&G VOC emissions alone (Sens4; blue) has little effect on the hourly ozone and NO₂ time series. In contrast, increasing O&G VOC emissions in conjunction with increased O&G NO_x emissions (Sens5; green) produces higher ozone concentrations and improved ozone model performance compared to increasing O&G NO_x emissions alone.

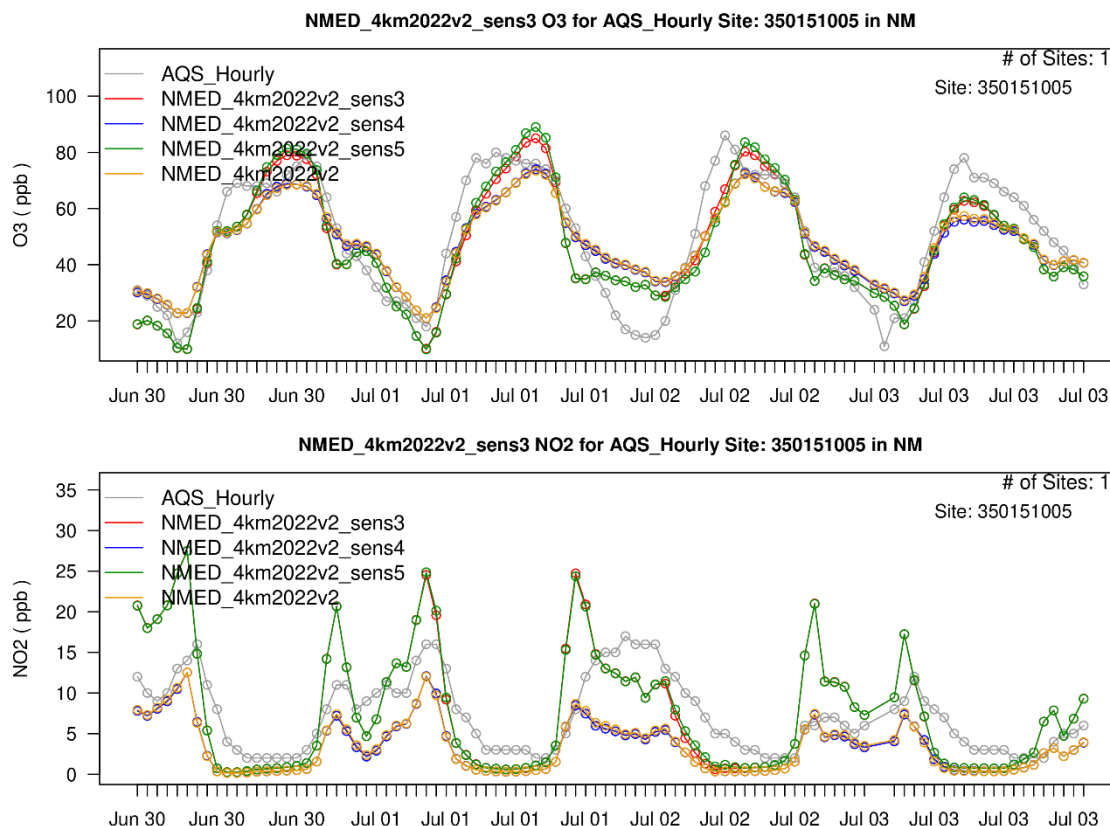


Figure 7-3. Time series of predicted and observed hourly ozone (top) and NO₂ (bottom) concentrations at Carlsbad City monitoring site, June 30 - July 3, 2022, and the New Mexico Permian Basin O&G emissions sensitivity tests: Base Case (orange); Sens3 (3 x NM PB O&G NO_x; red); Sens4 (3 x NM PB O&G VOC; blue), and Sens5 (3 x NM PB O&G NO_x and VOC; green).

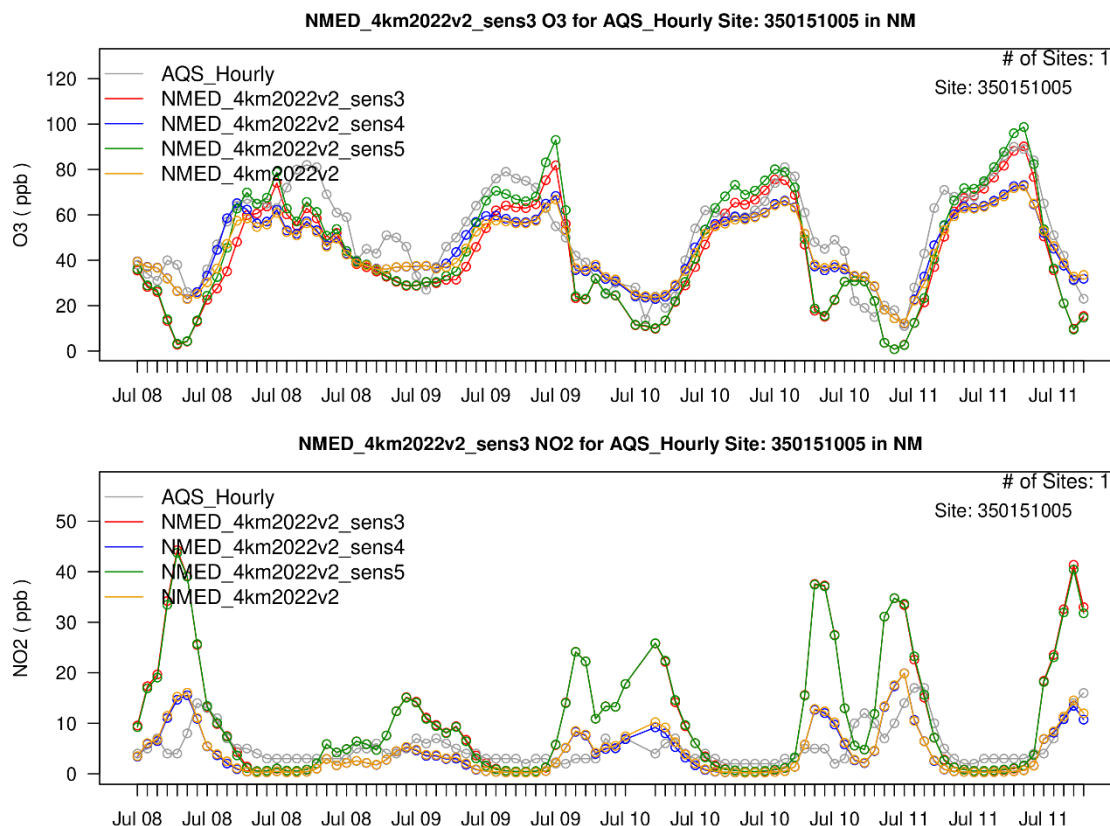


Figure 7-4. Time series of predicted and observed hourly ozone (top) and NO₂ (bottom) concentrations at Carlsbad City monitoring site, June 30 - July 3, 2022, and the New Mexico Permian Basin O&G emissions sensitivity tests: Base Case (orange); Sens3 (3 x NM PB O&G NO_x; red); Sens4 (3 x NM PB O&G VOC; blue), and Sens5 (3 x NM PB O&G NO_x and VOC; green).

Scatter plots and performance statistics for MDA8 and hourly ozone concentrations at the Carlsbad City monitoring site for the New Mexico PB O&G emissions sensitivity tests are shown in Figure 7-5 and Figure 7-6, respectively. The MDA8 ozone scatter plots for the CAMx 2022v2 base case and the Sens4 simulation with three times New Mexico PB O&G VOC emissions show all modeled values below the 1:1 line of perfect agreement. In contrast, when New Mexico PB O&G NO_x emissions are increased by a factor of three, some data points fall on the 1:1 line, and further improvement in MDA8 ozone performance is observed when both O&G NO_x and VOC emissions are increased (Sens5). The MDA8 ozone normalized mean bias (NMB) at Carlsbad City for the CAMx 2022v2 base case is -14%, which barely meets the bias Performance Criterion; this bias improves to -9% when O&G NO_x emissions are increased but remains essentially unchanged when only O&G VOC emissions are increased. When both New Mexico PB O&G NO_x and VOC emissions are increased by a factor of three, the MDA8 ozone NMB is reduced to -3%, achieving the bias Performance Goal, and the scatter plot straddles the 1:1 line of perfect agreement (Figure 7-5, lower right panel).

For hourly ozone (Figure 7-6), increasing O&G NO_x emissions alone raises afternoon peak ozone concentrations but lowers nighttime ozone due to enhanced NO scavenging, resulting in a net worsening of the NMB from -7% to -14%. Increasing O&G VOC emissions alone

has little effect on hourly ozone performance, with Sens4 exhibiting an NMB of -7% , the same as the base case. Increasing both O&G NO_x and VOC emissions produces a substantially improved hourly ozone scatter plot, with many higher ozone values straddling the 1:1 line of perfect agreement; however, persistent underestimation of nighttime ozone results in an overall hourly ozone NMB of -9% .

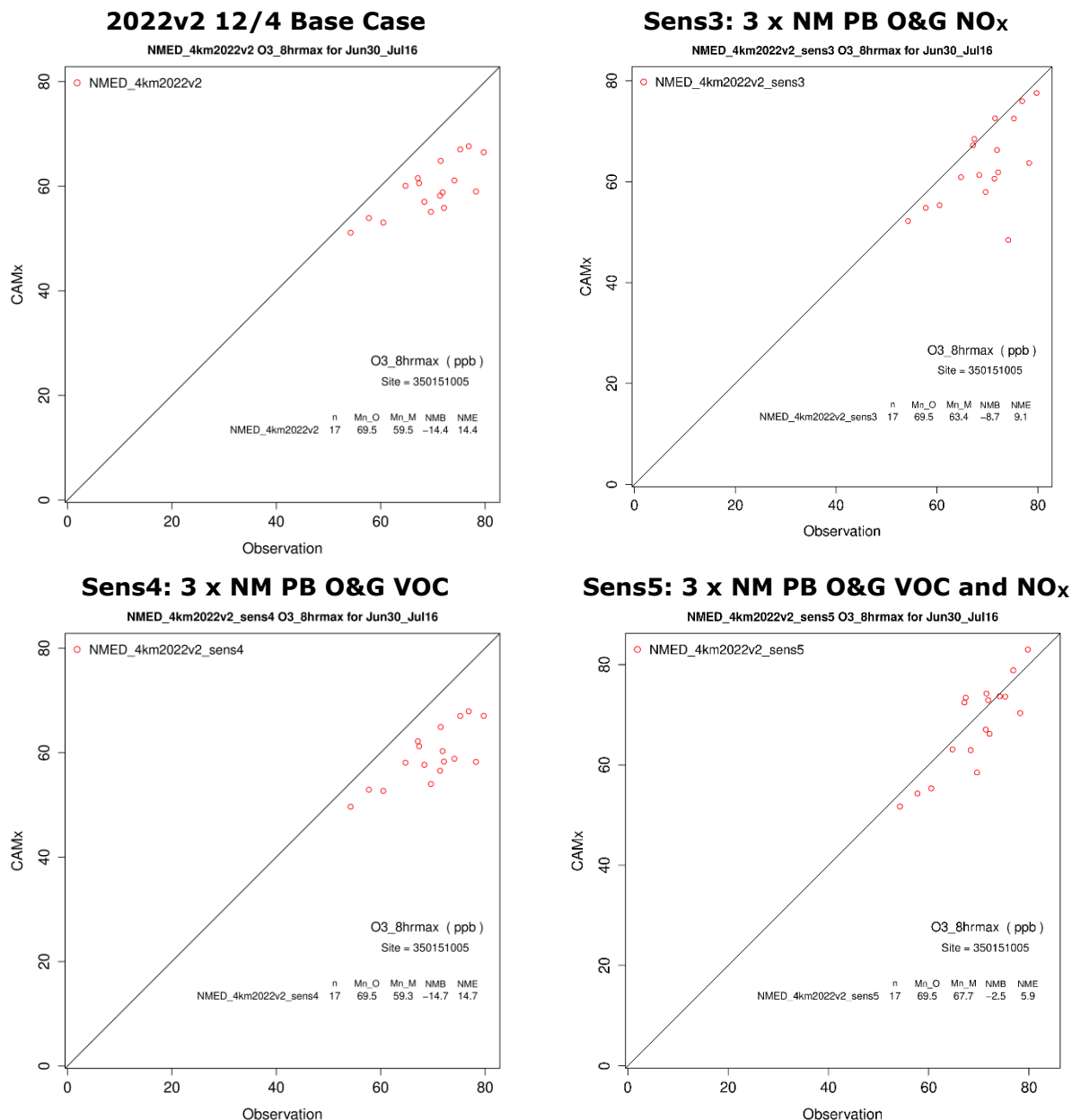


Figure 7-5. Scatter plots of predicted and observed MDA8 ozone concentrations and performance statistics at Carlsbad City monitoring site for the CAMx 2022v2 12/4 km base case and the three New Mexico Permian Basin O&G emissions sensitivity tests.

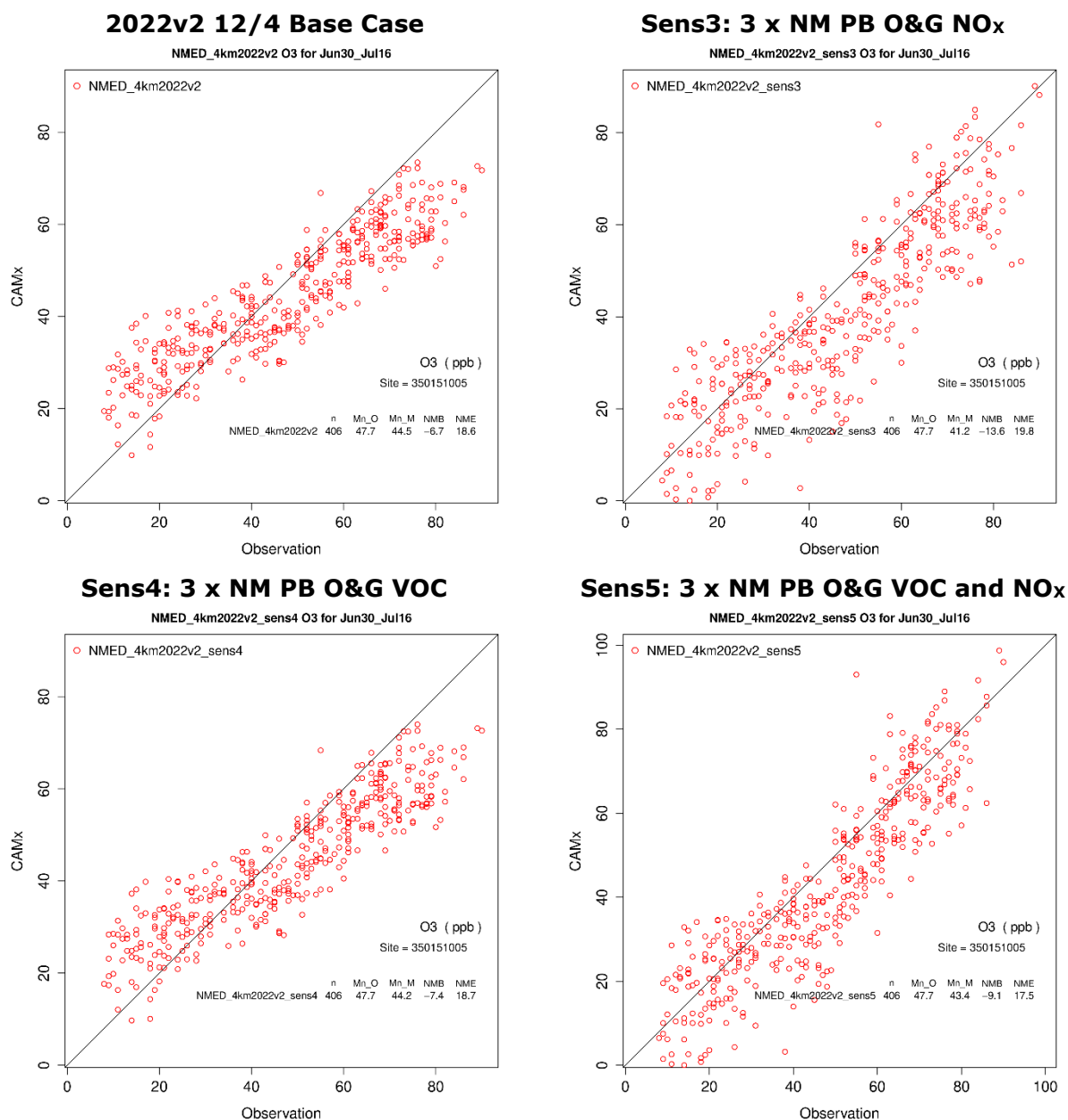


Figure 7-6. Scatter plots of predicted and observed hourly ozone concentrations and performance statistics at Carlsbad City monitoring site for the CAMx 2022v2 12/4 km base case and the three New Mexico Permian Basin O&G emissions sensitivity tests.

Figure 7-7 compares predicted and observed frequency distributions of hourly ethane and propane concentrations at Loving, New Mexico (LNM) for the CAMx 2022v2 base case and the Sens5 test (3 x NM PB O&G NO_x and VOC emissions sensitivity). During the 20-day sensitivity test modeling period, the CAMx 2022v2 base case underestimates observed ethane and propane concentrations by approximately a factor of 4 and 3, respectively. When New Mexico PB O&G NO_x and VOC emissions are increased by a factor of three, model agreement with observed ethane and propane concentrations improves substantially, with remaining underestimation reduced to a factor of approximately 1.5 (i.e., a 50% underestimation) for ethane and factor of 1.2 (20% underestimation) for propane.

However, increasing New Mexico PB O&G VOC emissions by a factor of three leads to overestimation of benzene and ethene concentrations at LNM (Figure 7-8). This result suggests that underestimation of O&G VOC emissions may not be associated with gasoline combustion or O&G engine sources and may instead be related to other O&G VOC sources, such as venting, flashing, fugitive and/or leakage emissions. Increasing New Mexico PB O&G NO_x emissions by a factor of three also results in overestimation of observed NO and NO₂ concentrations at LNM (Figure 7-9), indicating that New Mexico PB O&G NO_x emissions are not underestimated to the same degree as the O&G VOC emissions.

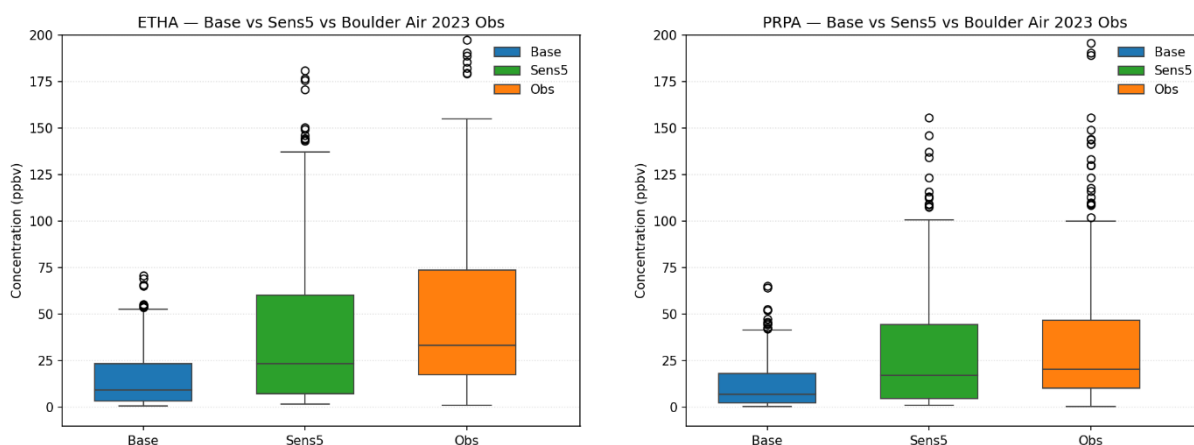


Figure 7-7. Comparison of the frequency distribution of the predicted and observed (orange) hourly Ethane (left) and Propane (right) concentrations at Loving, New Mexico site for the CAMx 2022v2 base case (blue) and 3 times NM PB O&G NO_x and VOC emissions Sens5 sensitivity test (green).

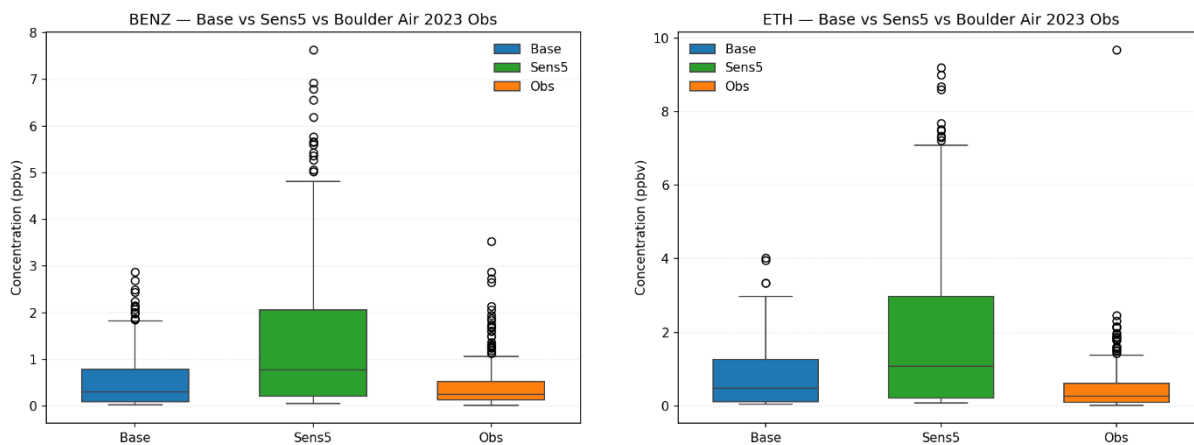


Figure 7-8. Comparison of the frequency distribution of the predicted and observed (orange) hourly Benzene (left) and Ethene (right) concentrations at Loving, New Mexico site for the CAMx 2022v2 base case (blue) and 3 times NM PB O&G NO_x and VOC emissions Sens5 sensitivity test (green).

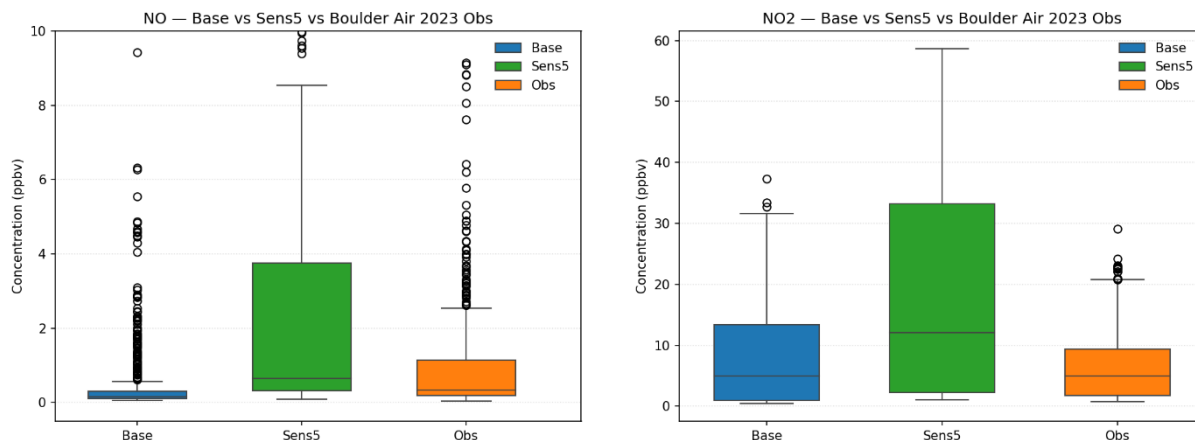


Figure 7-9. Comparison of the frequency distribution of the predicted and observed (orange) hourly NO (left) and NO₂ (right) concentrations at Loving, New Mexico site for the CAMx 2022v2 base case (blue) and 3 times NM PB O&G NO_x and VOC emissions Sens5 sensitivity test (green).

With respect to the Sens7 (Texas PB O&G emissions sensitivity test), Figure 7-10 and Figure 7-11 show time series of predicted and observed hourly ozone and NO₂ concentrations at the Carlsbad City monitoring site for the June 30–July 3 and July 8–11, 2022 periods. The time series show the modeling results for the CAMx 2022v2 4 km base case, Sens5 (three times New Mexico PB O&G NO_x and VOC) and Sens7 (three times Texas PB O&G NO_x and VOC). Increasing O&G NO_x and VOC emissions in either the New Mexico or Texas portions of the Permian Basin improves ozone model performance at Carlsbad City by increasing afternoon hourly ozone concentrations that match observations better. In general, increasing New Mexico O&G emissions produces higher ozone peaks at Carlsbad City than increasing Texas O&G emissions. However, increasing New Mexico Permian Basin O&G NO_x emissions by a factor of three results in overstated nighttime NO₂ concentrations at Carlsbad City, particularly during the June 30–July 3 episode. In contrast, increasing Texas O&G NO_x emissions by a factor of three does not lead to overstated NO₂ concentrations and improves NO₂ model performance at Carlsbad City (e.g., Figure 7-10 and 7-11, bottom panels).

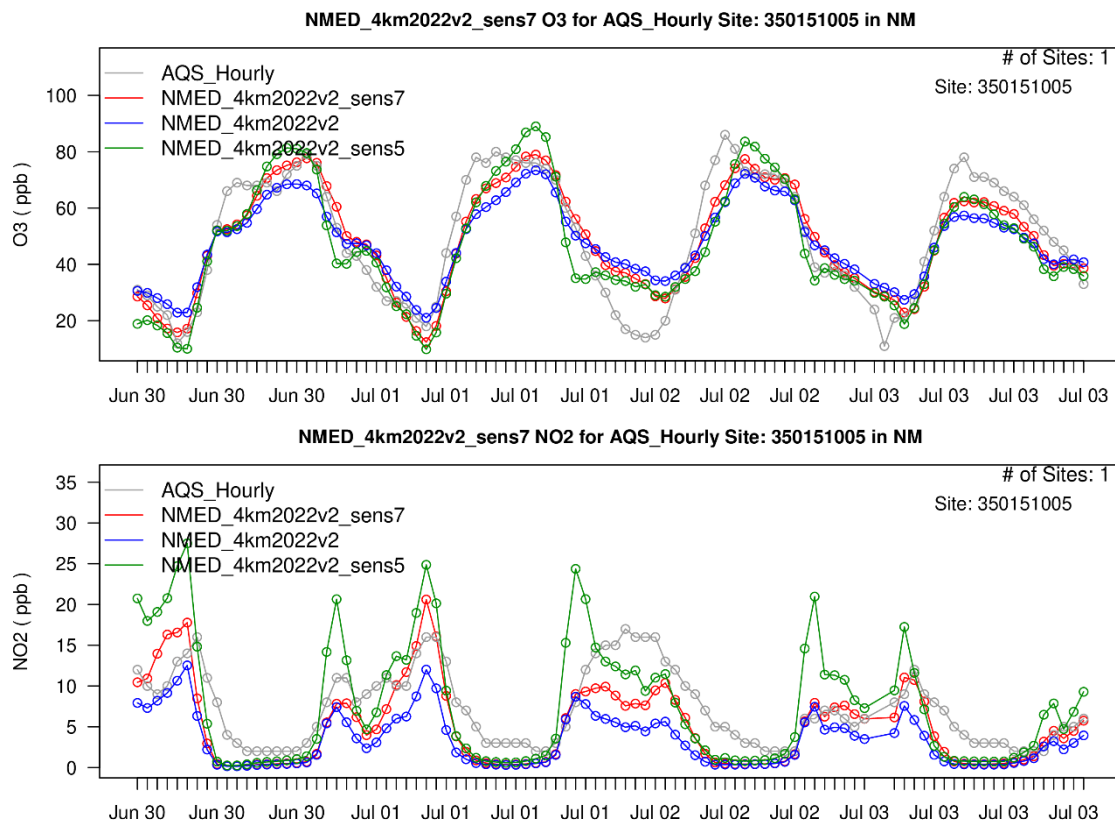


Figure 7-10. Time series of predicted and observed (grey) hourly ozone (top) and NO₂ (bottom) concentrations at Carlsbad City monitoring site, June 30 - July 3, 2022 and the CAMx 2022v2 4 km base case (blue) and the New Mexico (green) and Texas (red) 3 times Permian Basin O&G NO_x and VOC emissions sensitivity tests.

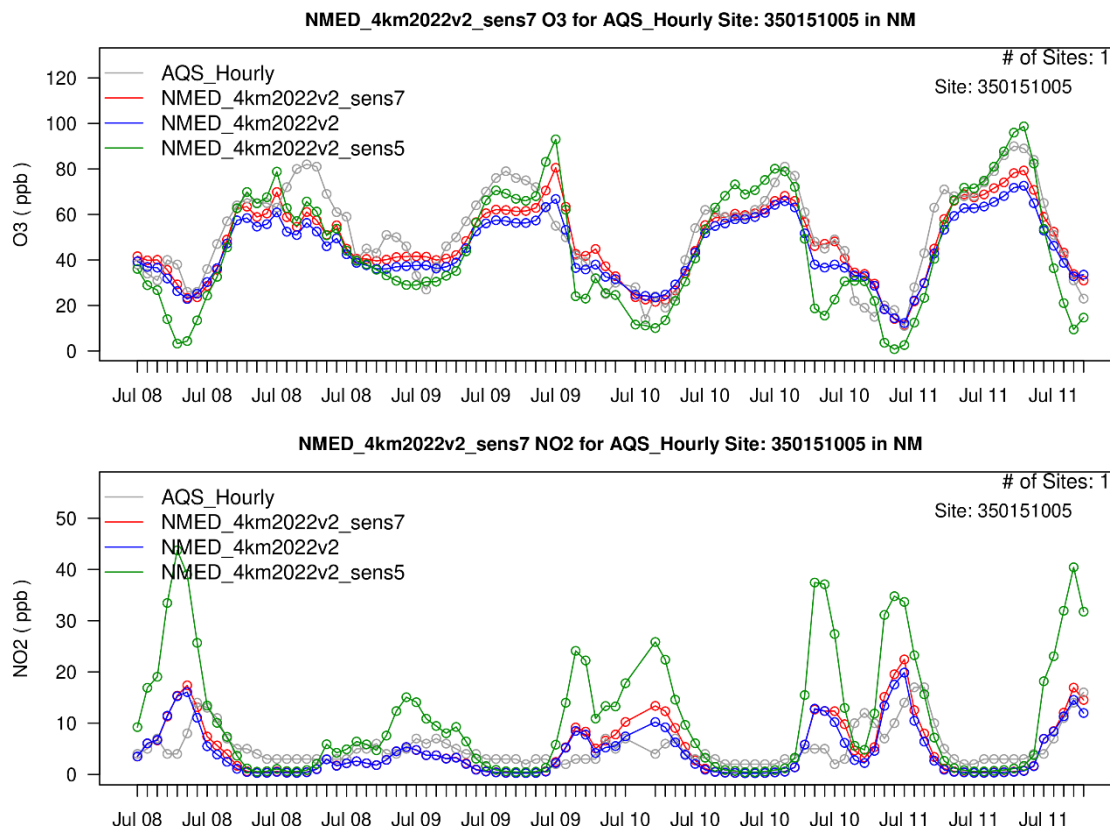


Figure 7-11. Time series of predicted and observed (grey) hourly ozone (top) and NO₂ (bottom) concentrations at Carlsbad City monitoring site, July 8-11, and the CAMx 2022v2 4 km base case (blue) and the New Mexico (green) and Texas (red) 3 times Permian Basin O&G NO_x and VOC emissions sensitivity tests.

Figure 7-12 and Figure 7-13 present hourly ozone time series at the Hobbs monitoring site for sensitivity tests with increased New Mexico and Texas PB O&G NO_x and VOC emissions. At the Hobbs site, increasing Texas PB O&G emissions generally produces larger increases in afternoon ozone concentrations and greater improvements in ozone model performance compared to increases in New Mexico Permian Basin O&G emissions.

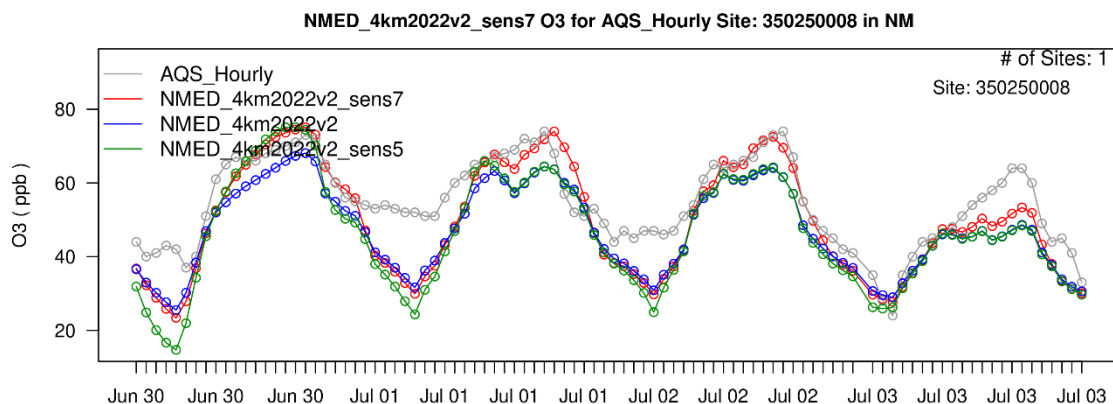


Figure 7-12. Time series of predicted and observed (grey) hourly ozone concentrations at Hobbs monitoring site, June 30-July 3, 2022, and the CAMx 2022v2 4 km base case (blue) and the New Mexico (green) and Texas (red) 3 times Permian Basin O&G NO_x and VOC emissions sensitivity tests.

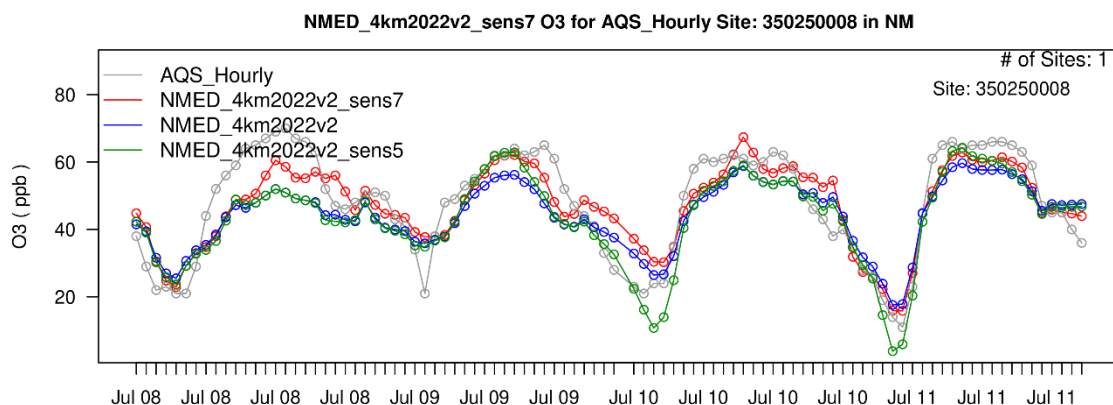


Figure 7-13. Time series of predicted and observed (grey) hourly ozone concentrations at Hobbs monitoring site, July 8-11, 2022, and the CAMx 2022v2 4 km base case (blue) and the New Mexico (green) and Texas (red) 3 times Permian Basin O&G NO_x and VOC emissions sensitivity tests.

Scatter plots and performance statistics for MDA8 ozone concentrations and the CAMx 2022v2 4 km base case and Sens7 Texas PB O&G emissions sensitivity test at Carlsbad City, Hobbs and Guadalupe National Park ozone monitoring sites are shown in Figure 7-14 through Figure 7-16. Increasing the Texas PB O&G emissions by a factor of 3 improves the MDA8 ozone performance at all three of these sites with substantial reductions in the ozone underestimation bias and error as follows:

- At Carlsbad City, the NMB underestimation bias is reduced from -14.4% to -8.5% and NME is reduced from 14.4% to 8.7%.
- At Hobbs, the NMB is reduced from -13.9% to -7.3% and the NME is reduced from 13.9% to 8.5%.
- At Guadalupe Mountains National Park, the NMB is reduced from -14.3% to -7.4% and NME is reduced from 14.3% to 9.2%.

Similar improvements in model performance are seen for hourly ozone when Texas O&G emissions are increased, as shown in the Carlsbad City example in Figure 7-17.

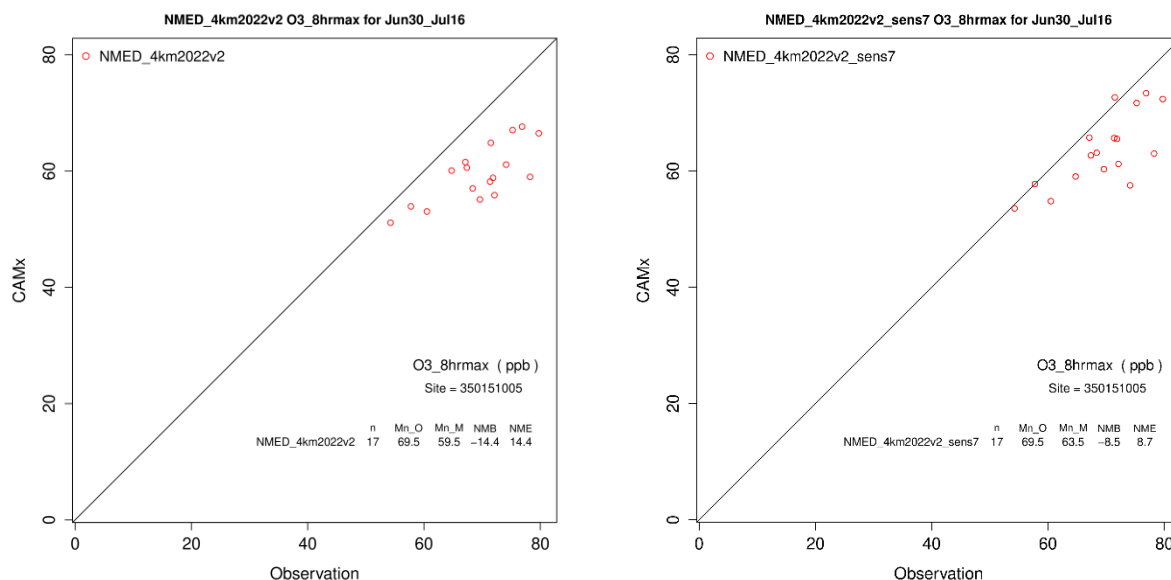


Figure 7-14. Scatter plots of predicted and observed MDA8 ozone concentrations and performance statistics at Carlsbad City for the CAMx 2022v2 4 km base case (left) and Sens7 3 times Texas Permian Basin O&G NO_x and VOC emissions (right).

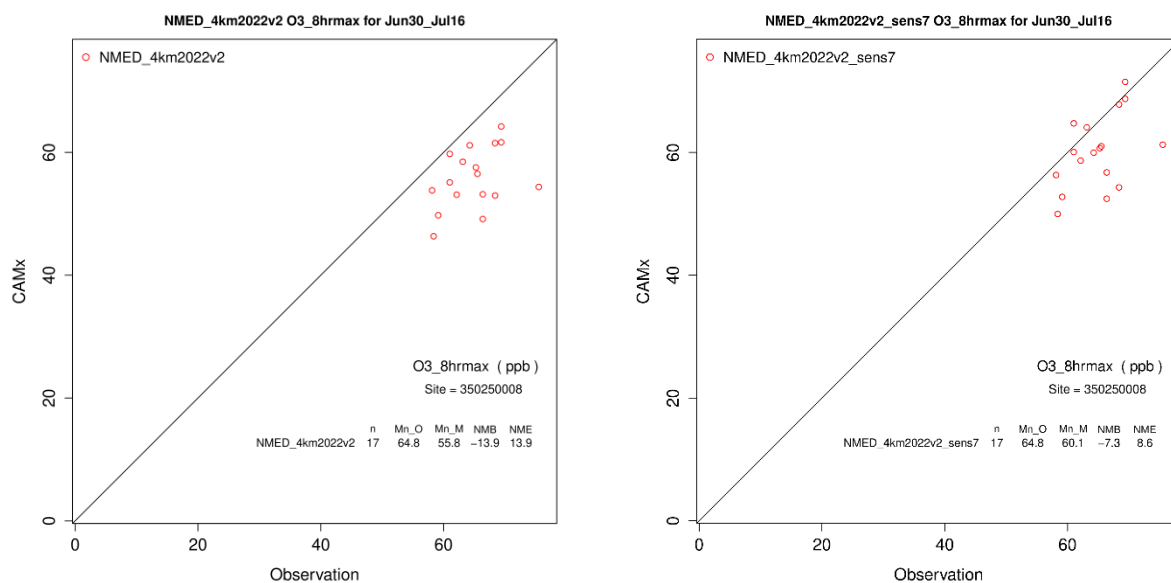


Figure 7-15. Scatter plots of predicted and observed MDA8 ozone concentrations and performance statistics at Hobbs for the CAMx 2022v2 4 km base case (left) and Sens7 3 times Texas Permian Basin O&G NO_x and VOC emissions (right).

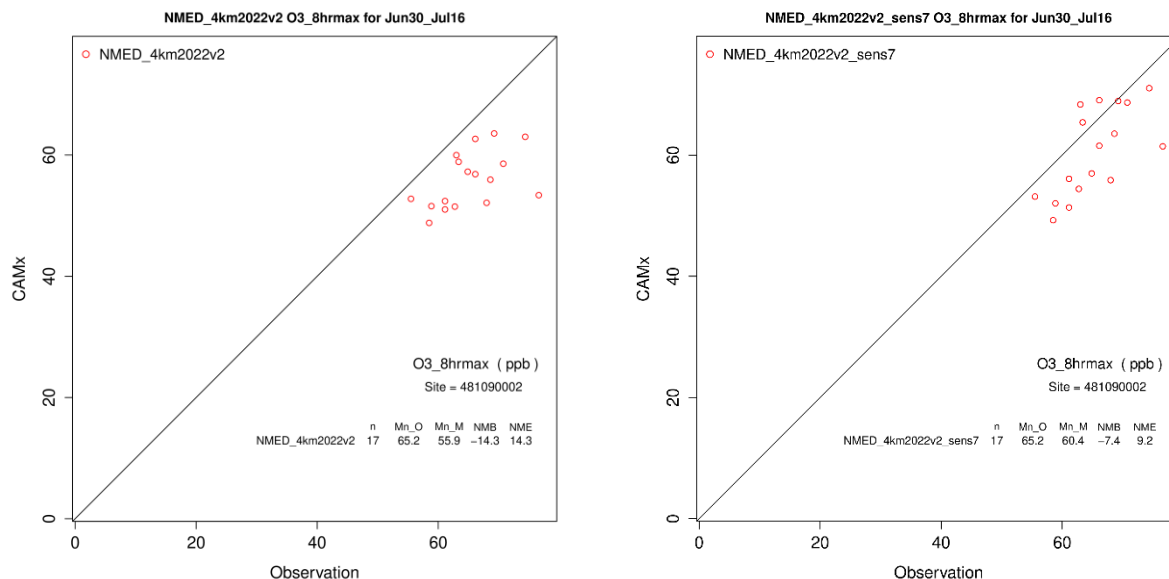


Figure 7-16. Scatter plots of predicted and observed MDA8 ozone concentrations and performance statistics at Guadalupe Mountains National Park for the CAMx 2022v2 4 km base case (left) and Sens7 3 times Texas Permian Basin O&G NO_x and VOC emissions (right).

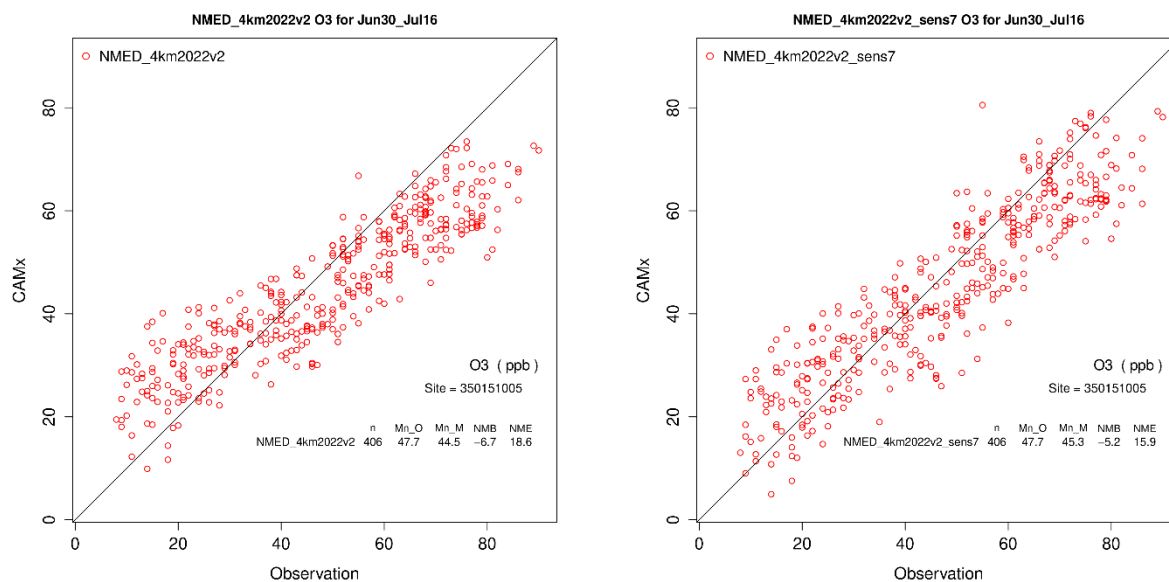


Figure 7-17. Scatter plots of predicted and observed hourly ozone concentrations and performance statistics at Carlsbad City for the CAMx 2022v2 12/4 km base case (left) and Sens7 3 times Texas Permian Basin O&G NO_x and VOC emissions (right).

Figure 7-18 compares predicted and observed frequency distributions of hourly ethane and propane concentrations at LNM from the 2023 HEI Boulder AIR monitoring data and the CAMx 2022v2 4 km base case and Sens7 Texas PB O&G sensitivity test for the period June 28–July 17. Increasing Texas O&G emissions reduces the CAMx underestimation of ethane from a factor of four to three and factor of three to two for propane. These results indicate that missing Texas O&G VOC emissions in the Permian Basin within the 2022v2 emissions

platform are likely contributing to the substantial CAMx underestimation of ethane and propane during specific periods; however, they are not the sole cause, as additional O&G VOC emissions from the New Mexico portion of the Permian Basin are also likely missing in the inventory.

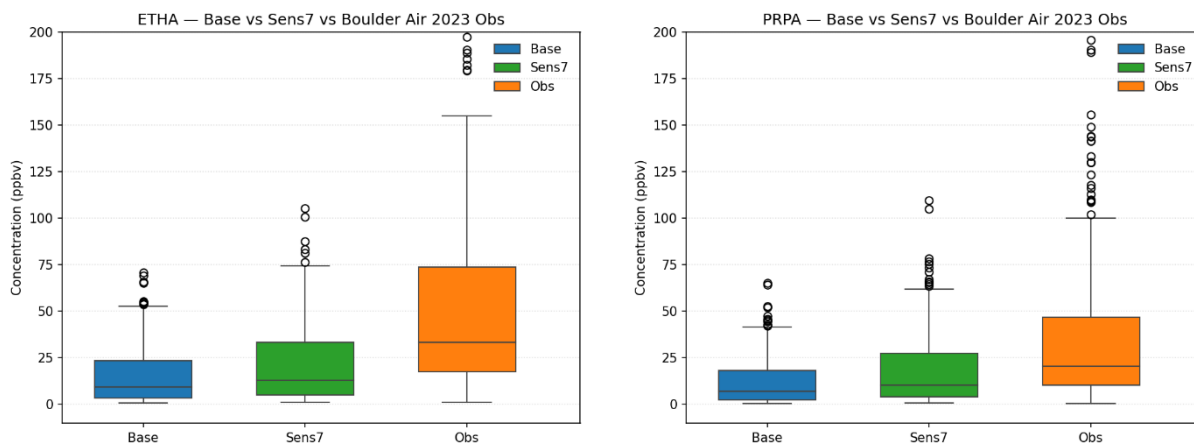


Figure 7-18. Comparison of the frequency distribution of the predicted and observed (orange) hourly Ethane (left) and Propane (right) concentrations at Loving, New Mexico site for the CAMx 2022v2 base case (blue) and 3 times NM PB O&G NO_x and VOC emissions Sens5 sensitivity test.

7.5 Implications of the CAMx Sensitivity Modeling

The vertical mixing and no-cloud-cover meteorological sensitivity tests had little to no effect on CAMx ozone and NO₂ model performance. As a result, there is no reason for modifying the CAMx 2022v2 12/4 km meteorological inputs, as there are no better alternatives available.

The Permian Basin O&G emissions in the 2022v2 emissions platform are known to be understated, including missing reported excess emissions. The model underestimates VOC species associated with O&G production, such as ethane and propane, by approximately a factor of five at two monitoring sites near Carlsbad City. Increasing Permian Basin O&G VOC and NO_x emissions improves ozone model performance and reduces the ethane and propane underestimation bias. Although it may be possible to collect NMED excess emissions reports for 2022 and incorporate the additional emissions into the 2022v2 inventory, this would be a resource-intensive effort, it would represent only a snapshot of reported excess emissions for a single year, and it would likely not capture all missing emissions because unreported events are not included.

When New Mexico NO_x and VOC emissions were increased by a factor of 3 in the CAMx 2022v2 12/4 km Sens5 sensitivity test, there was much better Ethane and Propane model performance, but it caused overestimation of the observed Benzene and Ethene concentrations at the two VOC field study sites. Franklin and co-workers (2025) conducted receptor modeling of the observed VOC concentrations at the Loving, New Mexico site collected by Boulder AIR in the HEI study that is shown in Figure 7-19. They found that Ethane and Propane were emitted primarily by the O&G “Fugitive Venting” factor. However, Ethene was emitted by “Flaring” and “Traffic” factors. And a majority of Benzene came from combined “Produced Water”, “Combustion/Respiration” and “Traffic” factors. Thus, in future

phases of this work more targeted increased O&G VOC sensitivity tests should be considered focusing on “Fugitive/Venting” sources.

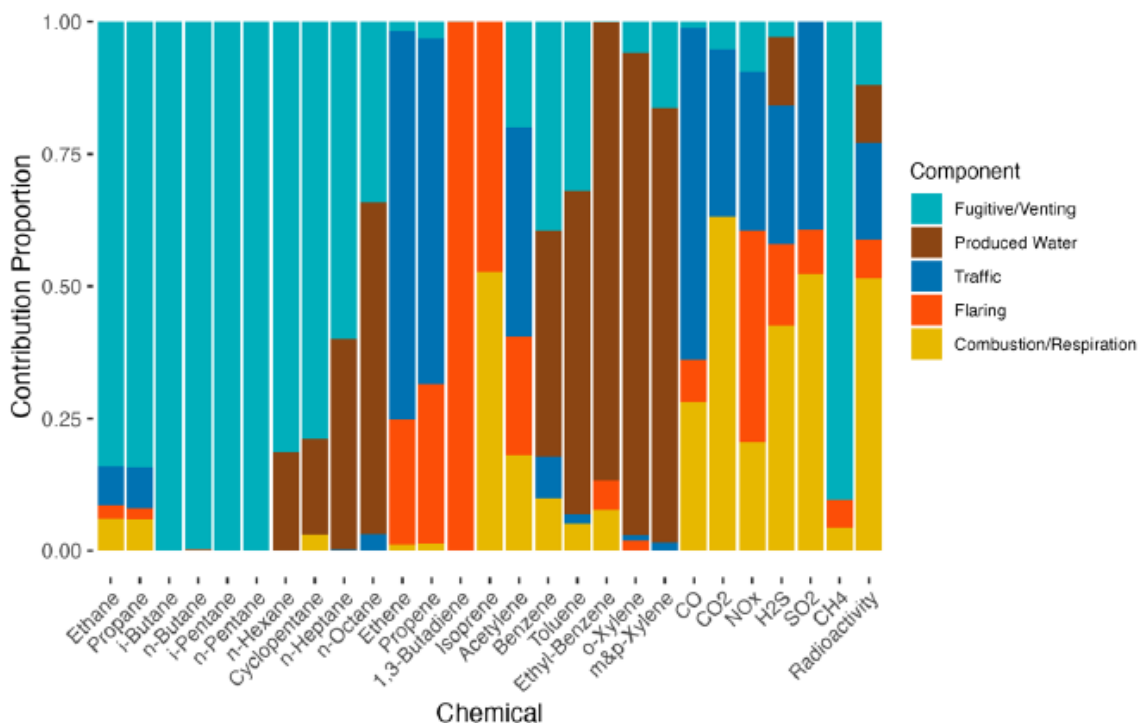


Figure 32. Contribution proportions of each compound to the five NMF-derived source factors at LNM.

Figure 7-19. Receptor modeling of observed VOC concentrations at the Loving, New Mexico to obtain VOC species-specific contributions due to five factors (Source: Franklin et al., 2025).

Therefore, given the limited time remaining it is recommended that the NMED Phase II study proceed with ozone source apportionment using the 2022v2 base-year and 2032 future-year emission inventories, while considering the Permian Basin O&G emissions shortfall in the analysis and interpretation of modeling results by recognizing that ozone contributions attributed to Permian Basin O&G sources are likely understated.

For 2032 future-year ozone design value (DVF) projections, one approach for accounting for understated Permian Basin O&G emissions is the method developed under the Coordinating Research Council (CRC) Project A-112 ([CRC A-122](#)). This approach decomposes the observed 2020–2024 base-year design value (DVB) into local and regional components and applies CAMx 2022v2 and 2032v2 ozone source apportionment results to separately project each component to the future year before recombining them to estimate the future-year ozone DVF (Dunker, Koo, and Yarwood, 2019).

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