EPA-454R26004

Technical Support Document (TSD): 2022 Regulatory Modeling Platform: Air Quality Modeling version 2

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Office of State Air Partnerships
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Acronyms

AERO7: 7th generation aerosol module

AMET: Atmospheric Model Evaluation Tool

AQS: Air Quality System

AWS: Amazon Web Services

BC: boundary condition

BEIS: Biogenic Emissions Inventory System

CAA: Clean Air Act

CAMS: Copernicus Atmosphere Monitoring Service

CAMx: Comprehensive Air Quality Model with Extensions

CASTNET: Clean Air Status and Trends Network

CB6r5: Carbon Bond 6 mechanism revision 5

CEDS: Community Emissions Data System

CMAQ: Community Multiscale Air Quality model

CONUS: CONtinental U.S.

CSN: Chemical Speciation Network

EC: elemental carbon

EPA: Environmental Protection Agency

EPIC: Environmental Policy Integrated Climate model

EQUATES: EPA's Air Quality Time Series Project

FINN: Fire Inventory from NCAR

GEOS-CF: Goddard Earth Observing System Composition Forecast Model

GEOS-Chem: Global Earth Observing System

GFDE: Global Fire Emissions Database

HAQAST: Health and Air Quality Applied Science Team

hPa: hectopascal

HTAP: Hemispheric Transport of Air Pollution

IC: Initial condition

IMPROVE: Interagency Monitoring of Protected Visual Environments

Kv: vertical eddy diffusivities

M3dry: Models-3 dry deposition

MB: mean bias

MCIP: Meteorology – Chemistry Interface Processor

MDA8 O_3: Maximum Daily Average 8-hour Ozone

ME: mean error

MEGAN: Model Emissions of Gases and Aerosols from Nature

MERRA2: Modern-Era Retrospective analysis for Research and Applications version 2

MJO: Multi-Jurisdictional Organization

NASA: National Aeronautics and Space Administration

NEI: National Emissions Inventory

NH_3: ammonia

NMB: Normalized Mean Bias

NME: Normalized Mean Error

NO_3^-: nitrates

NO: nitrogen oxide

NOx: nitrogen oxides

NOAA: National Oceanic and Atmospheric Administration

OC: organic carbon

OSAP: Office of State Air Partnerships

$PM_{2.5}$: particulate matter with diameters < 2.5 µm (also called fine particulate matter)

pNO_3^-: particulate-nitrate

POA: primary organic aerosol

QFED: Quick Fire Emissions Database

Rscale: a scaling factor used within chemistry parameter files to adjust surface resistance in CAMx

SCC: Source classification code

SLT: state, local, and Tribal agencies

SO_4^{2-}: sulfate

SOA: secondary organic aerosol

SMOKE: Sparse Matrix Operator Kernel Emissions

STAGE: Surface Tiled Aerosol and Gaseous Exchange

TSD: Technical Support Document

U.S.: United States

VGLVLS: vertical grid levels, vertical sigma-pressure layer edges or midpoints

VGTOP: pressure at the top of model domain

VOC: volatile organic compound

WBD: Wind-blown dust

WOUDC: World Ozone and Ultraviolet Radiation Data Centre

VPOP: Vehicle Population

WRF: Weather Research and Forecasting model

WWLLNs: scaled World-Wide Lightning Location Network data

1 Background

The U.S. Environmental Protection Agency (EPA) periodically develops an air quality modeling platform for criteria air pollutants to support regulatory and nonregulatory applications. The EPA's last modeling platform used a 2016 base year, was initially released in 2019, and has included multiple version updates. The 2016 platform has been used for various regulatory applications through the end of 2024. In 2023, EPA reviewed environmental conditions and emissions, and selected 2022 as the base year for next EPA modeling platform; the details can be found in 2022v1 Technical Support Document (TSD)[1]. This TSD documents improvements to the 2022 platform inputs and options that comprise the second version (2022v2).

The 2022v2 platform addresses issues identified during evaluation of 2022v1 and incorporates input from stakeholders. The model performance statistics for 2022v1 platform are generally within the range of those reported in previous applications[2,3] and suggest that the simulations are suitable for use of national scale applications. Overall, Community Multiscale Air Quality (CMAQ) and Comprehensive Air Quality Model with Extensions (CAMx) predictions for particulate matter with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) sulfate (SO_4^{2-}) and nitrate (NO_3^-) are in reasonable agreement with ambient air quality observations. However, for $PM_{2.5}$ organic carbon (OC), the CMAQ and CAMx predictions tend to be biased high compared to observations at Chemical Speciation Network (CSN) and Interagency Monitoring of Protected Visual Environments (IMPROVE) ambient air quality monitoring sites. These biases are related to the interaction among three factors: atmospheric mixing under stagnant conditions, direct PM emissions, and chemistry (e.g., volatility). The CMAQ and CAMx normalized mean biases (NMBs) of Maximum Daily Average 8-hour (MDA8) Ozone (O_3) predictions during the O_3 season are reasonable across the domain, except that some urban areas in the West and Southwest regions

[1] Technical Support Document (TSD): 2022 Regulatory Modeling Platform: Air Quality Modeling Version 1, EPA-454R26001, 2026. https://www.epa.gov/system/files/documents/2026-04/2022-v1-modeling-platform-aq-model-tsd_final_version.pdf

[2] https://doi.org/10.1016/j.atmosenv.2012.07.012

[3] https://doi.org/10.1016/j.atmosenv.2019.116872

show negative bias (models underpredicted the MDA8 O_3); and both models underpredicted MDA8 O_3 concentrations when the values were higher than 65 ppb. The MDA8 O_3 underprediction could be due to several factors: regional meteorological conditions, chemistry and emissions. After reviewing the 2022v1 model results and cooperating with Multi-jurisdictional Organizations (MJOs) and states, EPA worked on updating the emissions and boundary conditions (see below for detailed information).

Similar to the 2022v1 platform, the EPA's 2022v2 platform consists of input data (emissions, ancillary data, meteorological data, initial conditions, and boundary conditions), air quality model outputs, model performance evaluations, and potential applications of the platform (e.g. regulation analysis). The 2022 meteorological data from the Weather Research and Forecasting model (WRF) that are used for the 2022v1 platform are also used for 2022v2. Detailed WRF configuration options and model performance can be found in the 2022 WRF TSD[4].

The 2022v2 emissions data are based on the 2020 National Emissions Inventory (NEI) released in the spring of 2023 with updates to better represent the year 2022. Detailed information can be found in the TSD for the 2022 v2 North American Emissions Modeling Platform (EMP)[5]. The abbreviation for the modeling case name was "2022he", where 2022 is the year modeled, 'h' indicates that it was based on the 2020 NEI, and 'e' represents that it was the fifth version of a 2020 NEI-based platform.

The 2022v2 platform includes updates to one of the two air quality models used in the 2022v1 platform. Specifically, the CMAQ model was updated from version 5.4 to version 5.5[6] in 2022v2.

[4] U.S. EPA: Meteorological Model Performance Evaluation for Annual 2022 Simulation WRF v4.4.2, Office of Air Quality Planning and Standards, 454-R-24-001, 2024. https://www.epa.gov/system/files/documents/2024-03/wrf_2022_tsd.pdf

[5] https://www.epa.gov/system/files/documents/2024-10/2021_emismod_tsd_october2024.pdf

[6] CMAQ version 5.5: United States Environmental Protection Agency. (2024). CMAQ (Version 5.5) [Software]. Available from https://doi.org/10.5281/zenodo.7218076; https://www.epa.gov/cmaq. CMAQ v5.5 is also available from the Community Modeling and Analysis System (CMAS) at: http://www.cmascenter.org.

The CAMx version 7.20[7] was applied in both versions of the platform. CMAQ and CAMx are widely used by EPA, state, local, and Tribal agencies (SLTs), and MJOs for photochemical modeling applications. The update to version 5.5 of CMAQ ensures the latest available science is being applied.

EPA applied CMAQ and CAMx to two continental U.S. (CONUS) domains: a 36-km horizontal grid resolution domain (36US3) and a 12-km horizontal grid resolution domain (12US2) (see Figure 1). This TSD focuses on air quality model simulations with the 12US2 domain, including the model configuration sensitivity and model performance evaluations for 2022v2.

In this document, model predictions are evaluated against ambient measurements to examine the ability of the 2022v2 air quality modeling platform to represent the magnitude and variability of measured MDA8 O_3 concentrations, daily average $PM_{2.5}$ species concentrations, and daily average $PM_{2.5}$ total concentrations within the modeling domain.

2 Platform Developments

2.1 Model Domain

The CMAQ modeling analyses are performed for two domains covering the CONUS, as shown in Figure 1. The 36US3 domain uses 36-km by 36-km horizontal grid resolution and was applied for testing alternative boundary conditions (BC) and served as a buffering domain, balancing the desire for greater resolution over the U.S. and adjacent areas of Canada and Mexico with the need of shorter model runtime. The 12-km domain covers the entire CONUS and portions of Canada and Mexico using 12-km by 12-km horizontal grid spacing. In the 2022 platform, the 12-km domain uses a Lambert Conformal map projection centered at (-97, 40) with true latitudes at 33 and 45 degrees north. The 12-km CMAQ domain consists of 396 by 246 grid cells and 35 vertical layers extending up to 50 millibars (mb) with the layer closest to the surface being 20 m in depth. More details on the vertical grid structure are available in the 2022 WRF TSD. The

[7] https://www.camx.com/Files/CAMxUsersGuide_v7.20.pdf

larger 36-km domain includes international emission sources and some emissions in federal waters that are not within the 12-km domain. Model predictions from the 36US3 domain are used to provide boundary conditions for 12US2 modeling to balance the desire for greater resolution over the U.S. and adjacent areas of Canada and Mexico with a short model runtime.

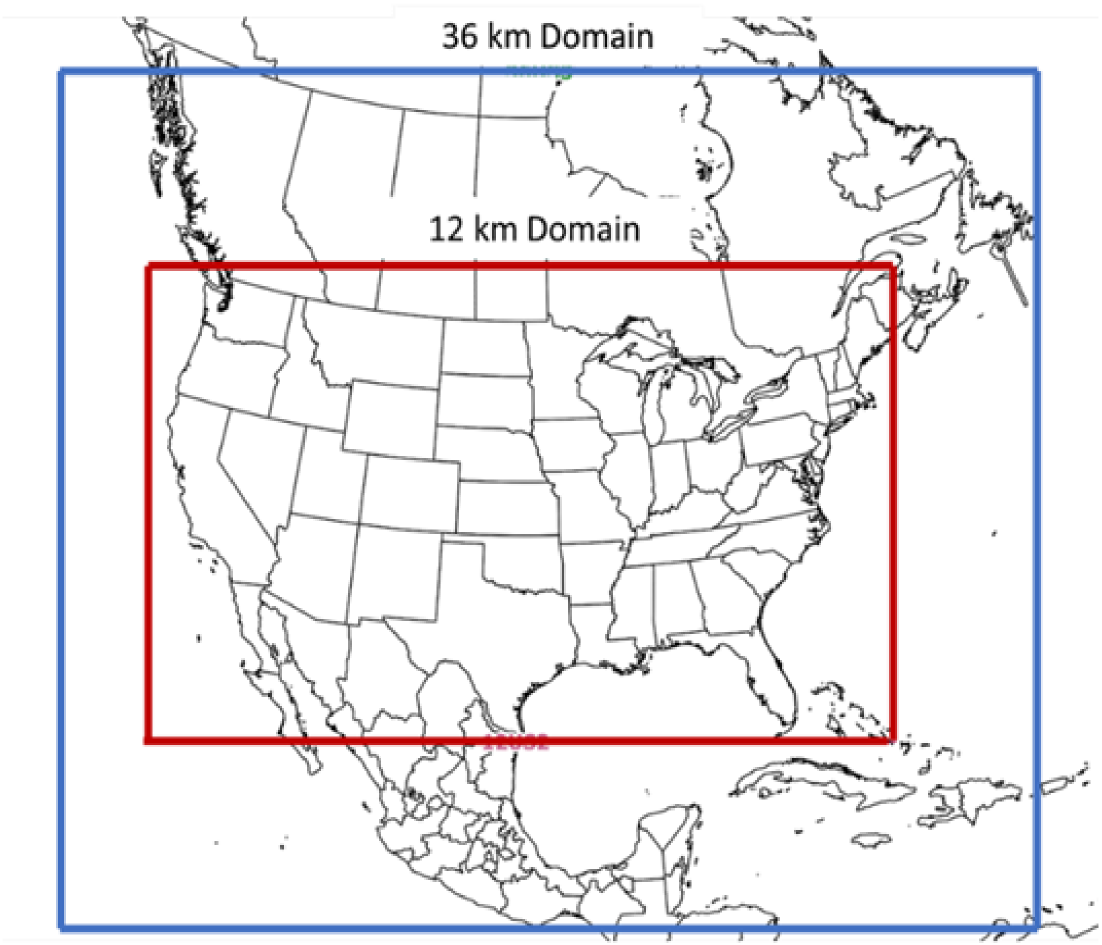

Figure 1 - Map of the 2022 CMAQ Modeling Domain. The blue box denotes the 36-km national modeling domain, and the red box denotes the 12-km domain.

2.2 2022 Meteorological Data

The 2022v2 platform uses the same meteorological data as the 2022v1 platform. WRF was applied for the entire year of 2022 to generate meteorological data to support emissions and photochemical modeling applications for the base year of the 2022 Modeling Platform. WRF was evaluated with observations to ensure that its predictions reasonably represent the actual meteorological conditions during the modeling period and to understand how meteorological modeling might influence the air quality modeling results. For more information on the WRF model setup and evaluation, please refer to the WRF modeling TSD for 2022.[8]

The meteorological data generated by the WRF simulations were processed using the wrfcamx v5.2 meteorological data processing program to create 35-layer gridded model-ready meteorological inputs to CAMx. During the wrfcamx processing, vertical eddy diffusivities (Kv) were calculated using the Yonsei University (YSU)[9] mixing scheme. A minimum Kv of 0.1 m^2/sec was used, except for urban grid cells where the minimum Kv was reset to 1.0 m^2/sec within the lowest 200 m of the atmosphere to enhance mixing associated with the nighttime “urban heat island” effect. The meteorological data generated by the WRF simulations were processed using Meteorology – Chemistry Interface Processor (MCIP) v5.4 to create 35-layer gridded model-ready meteorological inputs to CMAQ.

2.3 2022v2 Emissions

The 2022v2 emissions modeling platform includes point sources, nonpoint sources, onroad mobile sources, nonroad mobile sources, biogenic emissions, and fires for the U.S., Canada, and Mexico. Some platform categories use more disaggregated data than what is available in the NEI. The primary emissions modeling tool used to create the CMAQ model-ready emissions is the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system. SMOKE version 5.2.1 is utilized to generate CMAQ-ready emissions files for a 12-km grid covering the continental U.S. Biogenic VOC, soil NO, lightning NOx, and fertilizer ammonia (NH_3) emissions are calculated inline in CMAQ. All CMAQ-ready emissions files, biogenic VOC, soil NO, lightning NOx, and

[8] U.S. EPA: Meteorological Model Performance Evaluation for Annual 2022 Simulation WRF v4.4.2, Office of Air Quality Planning and Standards, 454-R-24-001, 2024. https://www.epa.gov/system/files/documents/2024-03/wrf_2022_tsd.pdf

[9] Hong et al., 2006 monthly Weather Review, 2318-2341, A New Vertical Diffusion Package with an Explicit Treatment of Entrainment Processes. 10.1175/MWR3199.1

fertilizer NH_3 emissions are then converted into CAMx format. Detailed information can be found in the 2022v2 EMP TSD.[10]

The major updates of emissions from 2022v1 to 2022v2 are:

1. MOVES5.0.0 was used to generate emissions estimates for onroad and nonroad emissions sources instead of MOVES4. This includes the addition of age IDs 31 to 40 years old in the age distributions. VPOP and age distribution were updated using new registration data obtained for the 2023 NEI from S&P Global Mobility. Finally, telematics data from StreetLight were incorporated into new speed distributions and new daily and day-of-week temporal VMT distributions unique to each county. Onroad NOx and VOC emissions increases for most states from 2022v1 (~8% increase in NO_x and ~14% increase in VOC).
2. Residential wood combustion emissions are calculated and allocated from the state-to-county level based on new methods developed for the 2023 NEI, which includes the use of many new source classification codes (SCCs). The updated allocation of residential wood combustion $PM_{2.5}$ emissions tends to shift emissions from urban to rural counties compared with 2022v1 emissions.
3. Incorporation of 30 state, local, and Tribal comments on the inventory and/or activity data as detailed in the 2022v2 EMP TSD.

2.4 2022v2 Initial and Boundary Conditions (IC/BCs)

To develop version 1 of the 2022 modeling platform, three global or hemispheric models were considered for the generation of initial and boundary conditions: GEOS-Chem, GEOS-CF-BC and HEMI-CMAQ-BC. Based on evaluation of the regional domain simulations for the 2022v1 platform, HEMI-CMAQ-BC was selected for 2022v2. The HEMI-CMAQ simulation used in 2022v2 is also updated from 2022v1 with the following changes:

[10] Technical Support Document (TSD): Preparation of Emissions Inventories for the 2022v2 North American Emissions Modeling Platform, EPA-454/B-25-002, December 2025. https://www.epa.gov/system/files/documents/2025-12/2022v2_emismod_tsd_base_december2025.pdf

- Increased spin-up length
- Correction to December formaldehyde emissions

The model's configuration, output data, and 12US2 IC/BCs are available on AWS OSAP 2022 Modeling Platform Bucket,[11] and its configuration is described in more detail in section 2.4.1. A more detailed description of the changes made is provided in section 2.4.2.

2.4.1 HEMI-CMAQ-BC

The hemispheric CMAQ simulation uses CMAQ v5.5 with aerosol nitrate photolysis. This version of CMAQ is described in more detail by Sarwar et al.[12] and augments the v5.5 Carbon Bond 6 chemistry with aerosol nitrate photolysis as proposed by Shah et al.[13] A summary of the configuration is provided below.

- **Meteorology and resolution**: Driven by WRFv4.4.2 meteorology at a 108-km resolution on a polar stereographic grid. Both WRF and CMAQ utilize 44 vertical layers extending up to a zero-flux top at 50 hPa. CMAQ is run offline using MCIPv5.3.3.
- **Chemistry and Parameters**: Carbon Bond 6 mechanism with full halogen chemistry and AERO7 aerosols. Stratospheric ozone fluxes, which are very important at hemispheric scales, are parameterized based on potential vorticity.
- **Emissions**: Natural emissions are consistent with those used in the EPA Air Quality Time Series (EQUATES) project.[14] The EQUATES hemispheric biogenic VOC and soil NOx emissions are developed from emission files from the Copernicus Atmosphere Monitoring Service (CAMS). Wildfire emissions are developed globally from the Fire

[11] https://epa-2022-modeling-platform.s3.amazonaws.com/index.html#global/

[12] https://doi.org/10.1016/j.scitotenv.2025.178968

[13] https://doi.org/10.5194/acp-23-1227-2023

[14] https://dataverse.unc.edu/dataset.xhtml?persistentId=doi:10.15139/S3/F2KJSK

Inventory from NCAR (FINN) v1.5.[15] Anthropogenic emissions derive from the Hemispheric Transport of Air Pollutants Task Force Phase 3 harmonized emissions.[16]

The hemispheric CMAQ results are archived at hourly resolution for all 44 layers over the whole domain for initial and boundary conditions. The standard CMAQ preprocessors ICON and BCON are used to extract initial and lateral boundary conditions for the 36US3 domain and vertically interpolate to the 35-layer vertical structure needed for the regional platform.

2.4.2 The Changes of HEMI-CMAQ-BC between 2022v1 and 2022v2

The HEMI-CMAQ configuration is consistent with 2022v1 but includes two updates that improve performance at the start of the simulation. The first is that the 2022v1 HEMI-CMAQ simulation was initialized on December 31, 2021, using predictions for December 31, 2020. This approach assumed that December 31, 2020, was consistent with December 31, 2021. However, the difference in model versions and options between the 2020 and 2022 simulations created a discontinuity. This is addressed by initializing the HEMI-CMAQ simulation for 2022v2 with the December 31 output from the 2022v1 simulation. There is less discontinuity between the conditions in December 2021 and January 2022 in the 2022v2 simulation. This influences concentrations for the first few months of 2022 in the 2022v2 results as compared to the 2022v1 results, but this effect tapers by the start of the ozone season. For example, Figure 2 illustrates the difference between 2022v1 (red) and 2022v2 (blue) in January and March of 2022.

[15] https://doi.org/10.5194/gmd-4-625-2011

[16] https://doi.org/10.5194/essd-15-2667-2023

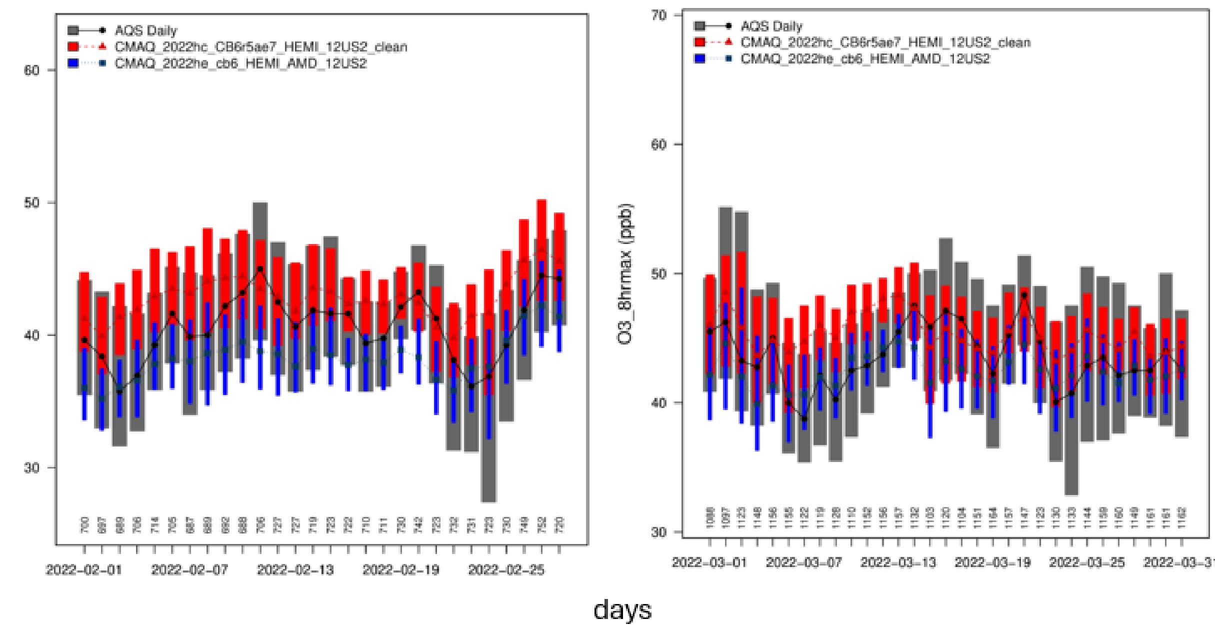

Figure 2 - Maximum daily 8-hour ozone concentrations for January (left) and March (right) of 2022 for each of the AQS monitors (gray) and the 2022 Modeling Platform versions 1 (red) and 2 (blue).

The second update is to correct an identified error in primary acetaldehyde emissions in December. This issue leads to large formaldehyde spikes in the 2022v1 modeling results that are specific to the day of the week. The cause of this error in the file is unclear. Correcting it improves performance related to atmospheric oxidation.

2.4.3 36US3 CMAQ simulations

In 2022v2, the updated Hemispheric CMAQ model outputs are used to generate ICs and BCs for the 36US3 CMAQ run, and outputs from the 36US3 run are used to generate ICs and BCs for the 12US2 model runs. Table 1 provides the model performance statistics and indicates that the 2022v2 MDA8 O_3 concentrations and daily $PM_{2.5}$ concentrations predicted by the Hemi-CMAQ-BC 36US3 modeling platform closely reflect the corresponding observed MDA8 O_3 and daily $PM_{2.5}$ concentrations at Air Quality System (AQS) U.S. monitoring sites. Model performance is analyzed in comparison to the range of performance statistics reported in recent state-of-the science regional CMAQ applications (Appel et al.[17]; Kelly et al.[18], Simon et al.[19]).

The overall performance of 2022v2 is incrementally better than 2022v1 for the 36US3 domain. For $PM_{2.5}$, both 2022v1 and 2022v2 have mean biases less than 1 µg/m^3 with improved correlations (r at IMPROVE sites in 2022v1: 0.35 and r in 2022v2: 0.54). For O_3, 2022v2 have mean biases less than 1 ppb compared with 1-to-2 ppb in v1. The slightly better performance combines with the known improvements in inputs support the use of 2022v2 for the 36US3 domain.

Table 1 – 2022v2 platform CMAQ Performance Statistics for $PM_{2.5}$ and MDA8 O_3 in 36km CONUS (unit of AvgObs, AvgMod, MB, ME for $PM_{2.5}$ is µg m^{-3} and for MDA8 O_3 is ppb, NMB and NME are %). N is the number of data points.

Network	species	N	AvgObs	AvgMod	NMB	MB	NME	ME	Correlation
36US3 Hemispheric CMAQ-BC simulations									
IMPROVE	$PM_{2.5}$	16798	3.97	4.17	5.1	0.20	54.4	2.16	0.54
CSN	$PM_{2.5}$	115708	8.23	7.40	-10.1	-0.83	39.2	3.22	0.52
AQS	$PM_{2.5}$	560598	7.54	6.54	-13.4	-1.01	43.1	3.25	0.38
AQS	MDA8 O_3	368243	42.0	43.0	2.4	0.99	13.4	5.64	0.76
CASTNET	MDA8 O_3	27870	42.5	42.5	0.1	0.04	12.1	5.12	0.75

[17] Appel, K. W., Bash, J. O., Fahey, K. M., Foley, K. M., Gilliam, R. C., Hogrefe, C., Hutzell, W. T., Kang, D., Mathur, R., Murphy, B. N., Napelenok, S. L., Nolte, C. G., Pleim, J. E., Pouliot, G. A., Pye, H. O. T., Ran, L., Roselle, S. J., Sarwar, G., Schwede, D. B., Sidi, F. I., Spero, T. L., and Wong, D. C.: The Community Multiscale Air Quality (CMAQ) model versions 5.3 and 5.3.1: system updates and evaluation, Geosci. Model Dev., 14, 2867–2897, https://doi.org/10.5194/gmd-14-2867-2021, 2021.

18 Kelly, J. T., Koplitz, S. N., Baker, K. R., Holder, A. L., Pye, H. O.T., Murphy, B. N., Bash, J. O., Henderson, B. H., Possiel, N. C., Simon, H., Eyth, A. M., Jang, C., Phillips, S., Timin B.,: Assessing PM2.5 model performance for the conterminous U.S. with comparison to model performance statistics from 2007-2015, Atmospheric Environment 214, https://doi.org/10.1016/j.atmosenv.2019.116872, 2019.

[19] Heather S., Kirk R. B., Sharon P. Compilation and interpretation of photochemical model performance statistics published between 2006 and 2012, Atmospheric Environment, 61,124-139, https://doi.org/10.1016/j.atmosenv.2012.07.012 , 2012.

2.5 12US2 CMAQ Configuration Tests

CMAQ version 5.5 is used in the 2022v2 platform to generate $PM_{2.5}$ and O_3 predictions for various model configurations. The EPA starts with a CMAQ configuration developed based on the 2022v1 platform, which included:

CB6r5 chemistry mechanism,
AERO7 aerosol module with non-volatile Primary Organic Aerosol (POA),
Surface Tiled Aerosol and Gaseous Exchange (STAGE),
NH3 bi-directional flux,
inline Biogenic Emission Inventory System (BEIS) biogenic emissions,
inline lightning NOx emissions (based on scaled World-Wide Lightning Location Network (WWLLN) data), and
the wind-blown dust option turned off.

The options used in base CMAQ runs for 2022v1 and 2022v2 are the same, but they are applied in different CMAQ versions. To understand the impact of various option selections on CMAQ predictions, we modify the options one-by-one from the initial CMAQ run. Table 2 provides a summary of the configuration options used in the sensitivity tests.

Table 2 – Description of CMAQ sensitivity tests

Configuration option	Starting configuration	Sensitivity test(s)
Biogenic emissions model	BEIS	Model Emissions of Gases and Aerosols from Nature (MEGAN)
Wind-blown dust (WBD)	None	WBD in CMAQv5.5+ WBD in CMAQv5.5+ with Brown Vegetation correction
Kzmin option	Kzmin on	Kzmin off (kzout = 1)
POA adjustment for gridded emissions	100% POA from gridded emissions files	50% POA from gridded emissions files
Emissions sensitivities	2022 platform emissions	25% of anthropogenic emissions reduction of direct $PM_{2.5}$, sulfur dioxide (SO_2), NO_x, NH_3, and VOCs
pNO3 photolysis	CONUS without pNO3 photolysis	CONUS with pNO3 photolysis
Alternative boundary conditions	12US2 BC from 36US3 model simulation	12US2 BC from 108-km HEMI-CMAQ model simulation

2.6 12US2 CAMx Configuration Tests

CAMx version 7.20 is used in the 2022 platform to generate $PM_{2.5}$ and O_3 predictions based on specified meteorological conditions and emissions. EPA startes with a CAMx configuration developed based on the 2022v1 platform, which included:

CB6r5_CF2E chemistry (coarse/fine (CF) with SOAP2 (2) and optional elements (E)),
ZHANG03 dry deposition model,
bi-directional flux,
BEIS biogenic emissions, and
NH3 Rscale = 0.

The options of base CAMx runs in 2022v1 and 2022v2 were the same. To understand the impact of biogenic emissions model on CAMx outputs, we tested an option used for the sensitivity run with MEGAN biogenic emissions.

Table 3 – Description of CAMx sensitivity tests

Configuration option	Starting configuration	Sensitivity test(s)
Biogenic emissions model	BEIS	MEGAN

3 Selected CMAQ and CAMx Configurations for v2

The EPA conducted 16 model configuration sensitivity simulations and evaluated the corresponding model performance at national, regional, and urban scales. EPA selected the 2022v2 configuration for the EPA 12US2 national model simulations, but different configurations may be selected in future model applications based on needs relevant to the specific application. In addition, SLTs performing model simulations for regional or local domains may find different configurations are more appropriate for their areas of interest. The 2022v2 configurations are selected by considering the following factors:

1. **State-of-the-Science**: Ensuring configurations are up to date with evolving scientific understanding.
2. **Consistency**: Maintaining alignment with previous platforms and model runs.
3. **Comparability**: Ability to compare against historical model simulations.
4. **Regulatory Relevance**: O_3 and $PM_{2.5}$ model performance relevant for policy applications.

In simulations using the 2022v2 base CMAQ configuration, the EPA employes CMAQ inline bi-directional NH_3 flux to generate fertilizer NH_3 emissions, inline BEIS to calculate biogenic VOC emissions and soil NO emissions, inline lightning NOx calculation based on WWLLN data. These emissions were converted into CAMx emission format and used in CAMx simulations.

EPA selects the BEIS for inline biogenic emissions and soil NO emissions based on several considerations:

1. **Model Specificity**: MEGAN is a global biogenic emission model, whereas BEIS provides a more detailed representation of biogenic emissions specific to North America. This makes BEIS more suitable for regional modeling within the U.S.
2. **Emission Levels and Uncertainty**: Recent versions of BEIS (v3.6) and MEGAN (v3) predicted similar amounts of biogenic VOC in the Great Lakes region (Baker et al., 2023). Previous versions of MEGAN (v2) systematically overpredicted isoprene and monoterpenes in areas of high emitting vegetation such as the Ozarks[20] and northern California.[21] Overall, these previous assessments[22] found closer agreement between BEIS than MEGAN with measurements of biogenic VOC in high emitting regions of the CONUS.

[20] Carlton, A.G., Baker, K.R., 2011. Photochemical Modeling of the Ozark Isoprene Volcano: MEGAN, BEIS, and Their Impacts on Air Quality Predictions. Environmental Science & Technology 45, 4438-4445.

[21] Bash, J.O., Baker, K.R., Beaver, M.R., 2016. Evaluation of improved land use and canopy representation in BEIS v3. 61 with biogenic VOC measurements in California. Geoscientific Model Development 9, 2191.

[22] Baker, K.R., Liljegren, J., Valin, L., Judd, L., Szykman, J., Millet, D.B., Czarnetzki, A., Whitehill, A., Murphy, B., Stanier, C., 2023. Photochemical model representation of ozone and precursors during the 2017 Lake Michigan ozone study (LMOS). J Atmospheric Environment 293, 119465.

CMAQ version 5.5 with CB6r5 chemistry and the AERO7 aerosol module with non-volatile POA is the model configuration for 2022 platform v2 (Table 2). The non-volatile POA approach was used in 2022v1 platform, previous modeling applications,[23,24] and remains a reliable modeling approach.

The STAGE dry deposition scheme in CMAQ version 5.5 is selected for the 2022v2 base configuration based on the state-of-science. STAGE is used to generate fertilizer NH_3 emissions based on Environmental Policy Integrated Climate model (EPIC) inputs about fertilizer application. This allows for more straightforward adjustment of these emissions (for example, by modifying the EPIC input data) for testing the sensitivity to fertilizer NH_3 emissions.

The 2022v2 CAMx configuration includes CB6r5_CF2E chemistry, ZHANG03 dry deposition model, bi-directional flux off, and NH_3 Rscale = 0 (Table 3). The bi-directional flux off and NH_3 Rscale = 0 options are selected due to following reasons:

1. **Performance:** This configuration shows better performance for total $PM_{2.5}$ and particulate nitrate.
2. **Consistency:** It is a consistent configuration with the 2022v1 and 2016 platforms.

[23] Bayesian Space-time Downscaling Fusion Model (Downscaler) - Derived Estimates of Air Quality for 2021, EPA-454/R-24-002

[24] Final Regulatory Impact Analysis for the Reconsideration of the National Ambient Air Quality Standards for Particulate Matter, EPA-452/R-24-006

Table 4 - Key options in EPA 2022v2 platform 12US2 CMAQ configuration

Options	Description
Initial and boundary conditions	36US3 CMAQ with HEMI-CMAQ BCs
Gas and aerosol chemistry	CB6r5 AERO 7 treatment of SOA standard cloud chemistry with nvPOA
Dry Deposition/Air-surface exchange	STAGE with CTM_STAGE_E20 option with bi-directional NH_3 flux on
Lightning NOx calculation	Hourly 3-D lightning NOx emissions were calculated inline using WWLLN data
Biogenic emission calculation	Hourly biogenic emissions were calculated inline using BEIS data
Kz/Kv	use Min Kz option determined by WRF landuse *

*CMAQ calculates a minimum Kz value based on the percent of landuse in a grid cell that is assigned to the urban category

Table 5 - Key options in EPA 2022v2 platform 12US2 CAMx configuration

Options	Description
Initial and boundary conditions	36US3 CMAQ with HEMI-CMAQ BC
Gas and aerosol chemistry	CB6r5_CF2E similar to nvPOA option in CMAQ
Dry Deposition/Air-surface exchange	ZHANG03 with bi-directional NH3 calculation off
Lightning NOx calculation	Hourly 3-D lightning NOx emissions calculated offline based on WWLLN data
Biogenic emission calculation	Hourly biogenic emissions calculated offline based on BEIS data
Kz/Kv	Kv of 0.1 m^2/sec except for urban grid cells where the minimum Kv was reset to 1.0 m^2/sec within the lowest 200 m of the surface to enhance mixing associated with the nighttime “urban heat island” effect

4 Model Performance Evaluation of Selected CMAQ and CAMx Configurations

4.1 Model Performance Evaluation Methods

Model performance statistics are created for the period 01/01/2022 to 12/31/2022 using the 2022v2 12US2 CMAQ and CAMx model configurations described in Table 4 and Table 5. The performance statistics include:

1. **Mean bias (MB):** The sum of the difference (predicted – observed) divided by the total number of samples (*n*). MB is given in either ppb or µg m^{-3} and is defined as:

   $$MB = \frac{1}{n}\sum_{1}^{n}(P - O)\ ,$$

   where *P* = predicted concentrations and *O* = observed concentrations
2. **Mean error (ME):** The sum of absolute value of the differences (predicted - observed) divided by the total number of samples (*n*). ME is given in either ppb or µg m^{-3} and is defined as:

   $$ME = \frac{1}{n}\sum_{1}^{n}|P - O|$$
3. **Normalized mean bias (NMB):** The sum of the difference (predicted - observed) over the sum of observed values. NMB is a useful model performance indicator because it avoids over inflating the observed range of values, especially at low concentrations. NMB is given in percentage units and is defined as:

   $$NMB = \frac{\sum_{1}^{n}(P-O)}{\sum_{1}^{n}(O)} * 100$$
4. **Normalized mean error (NME):** The sum of absolute value of the differences (predicted - observed) over the sum of observed values. NME is given in percentage units and is defined as:

   $$NME = \frac{\sum_{1}^{n}|P-O|}{\sum_{1}^{n}(O)} * 100$$
5. **Pearson Correlation coefficient (r):** Measures the strength and direction of a linear relationship between two continuous, normally distributed variables. r is defined as:

$$r = \frac{\sum_1^n (P_i - \bar{P})(O_i - \bar{O})}{\sqrt{\sum_1^n (P_i - \bar{P})^2 \sum_1^n (O_i - \bar{O})^2}}$$

6. **Root-Mean-Square Deviation (RMSE):** A standard metric used to measure the average magnitude of error in prediction models, calculated as the square root of the average of squared differences between predicted and observed values. RMSE is given in units of either ppb or µg m^{-3} and is defined as:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_i^n (P_i - O_i)^2}$$

The Atmospheric Model Evaluation Tool (AMET) v1.5[25] was used to calculate the model performance statistics in this document. AMET includes many additional statistical metrics used by the science community for model performance evaluation. For a robust evaluation, the principal evaluation statistics used to evaluate CMAQ and CAMx performance were MB, NMB, RMSE, and NME. Modeled $PM_{2.5}$ concentrations and ozone concentrations were compared with available observations from the EPA's AQS database (www.epa.gov/aqs, data pull date September 2025). In AMET, AQS data are passed through a filtering process to remove missing values and retain the particulate organic matter for individual observations. CASTNET data are passed through a filtering process that is documented in github.[26] Statistics were generated for each of the nine National Oceanic and Atmospheric Administration (NOAA) climate regions[27] of the 12US2 (Figure 3). The regions include the Northeast, Ohio Valley, Upper Midwest,

[25] https://github.com/USEPA/AMET/tree/1.5

[26] https://github.com/USEPA/CMAQ_Dev/pull/1376

[27] NOAA, National Centers for Environmental Information scientists have identified nine climatically consistent regions within the contiguous U.S., http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php.

Southeast, South, Southwest, Northern Rockies/Plains, Northwest, and West[28,29] as were originally identified in Karl and Koss.[30]

In addition to the performance statistics, CONUS maps of the MB and NMB were prepared for the ozone season, May through September, at individual monitoring sites as well as on an annual basis for $PM_{2.5}$ and its component species.

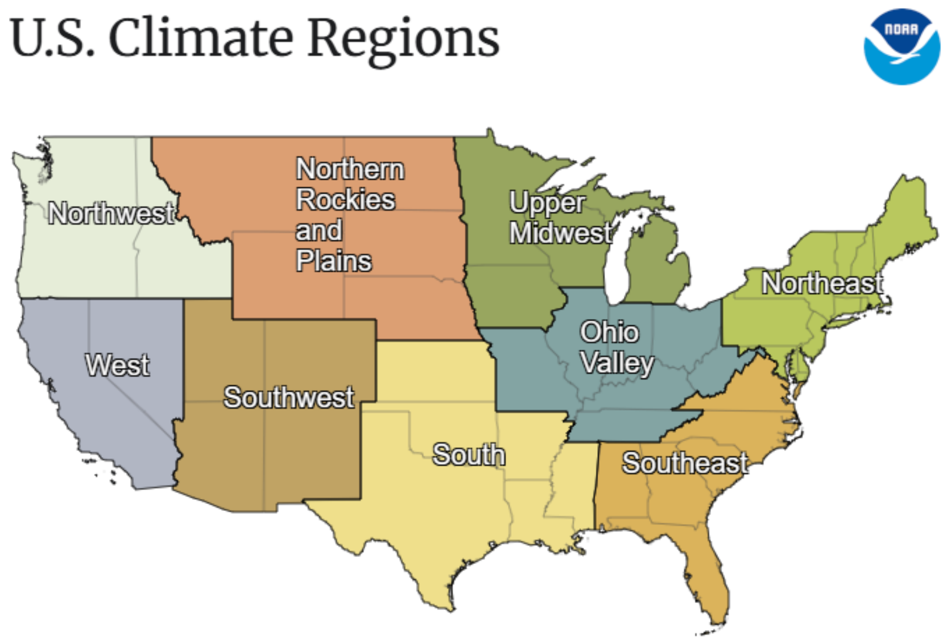

Figure 3 - NOAA climate regions (source: http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php)

[28] The nine climate regions are defined by States where: Northeast includes CT, DE, ME, MA, MD, NH, NJ, NY, PA, RI, and VT; Ohio Valley includes IL, IN, KY, MO, OH, TN, and WV; Upper Midwest includes IA, MI, MN, and WI; Southeast includes AL, FL, GA, NC, SC, and VA; South includes AR, KS, LA, MS, OK, and TX; Southwest includes AZ, CO, NM, and UT; Northern Rockies includes MT, NE, ND, SD, WY; Northwest includes ID, OR, and WA; and West includes CA and NV.

[29] Note most monitoring sites in the West region are located in California (see Figure 4-2), therefore statistics for the West will be mostly representative of California ozone air quality.

[30] Karl, T. R. and Koss, W. J., 1984: "Regional and National Monthly, Seasonal, and Annual Temperature Weighted by Area, 1895-1983." Historical Climatology Series 4-3, National Climatic Data Center, Asheville, NC, 38 pp.

4.2 CMAQ Results

This section summarizes the performance of CMAQ in predicting total $PM_{2.5}$, its constituent species, and the MDA-8hr O_3. The summary is organized by monitoring network (AQS, IMPROVE, CSN, CASTNet), season, and region, using the statistical metrics described in the previous section.

4.2.1 $PM_{2.5}$ and Corresponding Species: Sulfate (SO_4^{2-}), Nitrate (NO_3^-), Organic Carbon (OC), and Elemental carbon (EC)

The MB, NMB, RMSE, NME and Pearson correlation coefficient (r) of $PM_{2.5}$ used in evaluating model performance are reported in Table 6. The seasonal NMBs in $PM_{2.5}$ predictions are within ±30% for all regions except the Northeast (NMB: 32.1%) at AQS sites. Overpredictions of $PM_{2.5}$ concentrations in the Northeast could be attributed to OC species and associated with challenges in simulating the atmospheric mixing height. Correlation coefficients over the annual period for $PM_{2.5}$ were greater than 0.4 in all regions for AQS sites, indicating a moderate level of agreement between predictions and observations.

Model performance statistics for SO_4^{2-} by regions and seasons for sites in the Chemical Speciation Network (CSN) and IMPROVE networks are provided in Table 7 and 8. The seasonal NMBs in sulfate predictions are within ±30% for all regions at CSN sites and within ±30% for all regions except the Northwest (NMB: 44.5%) at IMPROVE sites. Spatially, SO_4^{2-} predictions tend to be biased slightly low in the southern and eastern parts of the domain and biased slightly high toward the Northwestern part of the domain (Figure 4). Modeled and measured SO_4^{2-} concentrations are relatively low in the Northwest (~0.50 μg m^{-3}) compared with the eastern U.S. (0.8 – 1.0 μg m^{-3}).

Model performance statistics for NO_3^- by region and season for sites in the CSN and IMPROVE networks are provided in Table 9 and 10. The annual NMBs in NO_3^- predictions are within ±65% for all regions at CSN sites and within ±65% for all regions except the Northeast (NMB: 82.7%) at IMPROVE sites. Spatially, NO_3^- predictions tend to be biased slightly low in the western and southwestern parts of the domain and biased slightly high toward the Northwest (Figure 4). Model NO_3^- performance is reasonable in the regions where ammonium nitrate (NH_4NO_3) is important, such as the Upper Midwest and Northern Rockies and Plains. In Figure 4, CMAQ biases of NO_3^- and SO_4^{2-} are in opposite directions at most sites, NO_3^- is underestimated and SO_4^{2-} is overpredicted in the western U.S. and NO_3^- is overestimated and SO_4^{2-} is underpredicted in the eastern U.S. This could be related to NH_4^+, NO_3^- and SO_4^{2-} chemistry.

Model performance statistics for OC by region and season for sites in the CSN and IMPROVE networks are provided in Table 11 and 12. The annual NMBs in OC predictions are relatively high for all regions at CSN and IMPROVE sites. However, organic carbon is particularly high bias in the Northeast (winter, spring, and fall), Ohio Valley (winter) and Upper Midwest (winter). The high NMBs of OC in these regions and seasons might be associated with residential wood combustion and, in some cases, these high biases are also related to low planetary boundary layer height. The high NMBs of organic carbon in the Northwest region in summer may be related to challenges in simulating the magnitude and spatial distribution of wildfire influence. Although OC predictions are biased high, overall, OC correlations are moderate in most regions and seasons. Spatially, OC predictions tend to be biased high across the 12US2 domain (Figure 4), and the high biases in wintertime in the Northeast region will be discussed in detail in section 5.3.

Model performance statistics for EC by region and season for sites in the CSN and IMPROVE networks are provided in Table 13 and 14. The annual NMBs in EC predictions are negative in eight of nine regions at CSN and IMPROVE sites. However, the annual NMBs in four of nine regions at CSN sites and seven of nine regions at IMPROVE sites are within ±40%. Overall, annual and regional average EC concentrations are low across the domain (0.05 – 0.49 µg m^{-3} in the CSN network and 0.01 – 0.12 µg m^{-3} in the IMPROVE network) and relatively high normalized biases correspond to small absolute biases. Spatially, EC predictions tend to be biased low across the 12US2 domain (Figure 4).

4.2.2 Daily Maximum 8-hour O_3 (MDA8 O_3)

In general, the model performance statistics indicate that the MDA8 O_3 concentrations predicted by the 2022 CMAQ simulation closely reflect the corresponding observed MDA8 O_3 concentrations in space and time in each subregion of the 12-km modeling domain, as indicated by the statistics in Table 15 and 16. Generally, MDA8 O_3 at the AQS and CASTNET sites is within ±15% for all climate regions (NMB ranging from -12.4 to 11.5 percent). A significant improvement in O_3 performance in winter from the 2022v1 to 2022v2 platform occurred due to the updated hemispheric-CMAQ data used for boundary conditions.

MBs of MDA8 O_3 during the O_3 season are within 0 – 6 ppb at most eastern U.S. sites (Figure 5); however, at most western U.S. sites, the biases are negative. NMBs of MDA8 O_3 during the O_3 season are within ±20% at most monitoring sites across the U.S. domain (Figure 6). In the eastern part of the domain, MDA8 O_3 tends to be overpredicted. MDA8 O_3 tends to be underpredicted in southern California and at urban sites in Arizona. Figure 7 shows that MDA8 O_3 was underpredicted at most AQS and CASTNET sites when observed MDA8 O_3 was greater than 65 ppb during O_3 season.

Table 6 - CMAQ Performance Statistics for $PM_{2.5}$ at AQS Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	94803	6.86	9.06	2.20	32.1	53.0	5.92	0.62
	Winter	22620	8.12	12.58	4.46	54.9	65.4	8.16	0.67
	Spring	24144	6.03	8.20	2.17	36.0	52.0	5.19	0.61
	Summer	24631	7.12	6.77	-0.35	-4.9	35.8	3.62	0.54
	Fall	23408	6.23	8.96	2.74	43.9	59.2	6.02	0.63
Southeast	All	73423	7.67	7.79	0.13	1.7	36.7	4.01	0.59
	Winter	17747	7.91	9.26	1.35	17.1	41.5	4.73	0.63
	Spring	18413	7.81	8.02	0.21	2.7	34.5	3.99	0.62
	Summer	18996	7.63	6.57	-1.06	-13.9	34.6	3.58	0.51
	Fall	18267	7.33	7.42	0.09	1.2	36.4	3.68	0.60
Ohio Valley	All	87586	8.24	9.45	1.21	14.7	36.8	4.38	0.64
	Winter	21179	8.85	11.25	2.40	27.1	41.0	4.98	0.69
	Spring	22061	7.32	8.63	1.31	17.9	37.7	3.82	0.70
	Summer	22341	8.66	8.24	-0.42	-4.9	30.7	3.99	0.48
	Fall	22005	8.15	9.77	1.62	19.9	38.1	4.65	0.69
Upper Midwest	All	50413	7.33	8.09	0.76	10.4	37.7	4.24	0.70
	Winter	12399	8.35	10.47	2.12	25.4	39.6	4.94	0.71
	Spring	12210	6.35	7.16	0.81	12.7	38.7	4.00	0.66
	Summer	12422	6.78	5.59	-1.19	-17.6	34.9	3.38	0.48
	Fall	13382	7.79	9.07	1.27	16.4	37.4	4.44	0.79
South	All	50911	8.62	7.65	-0.98	-11.3	41.1	5.42	0.40
	Winter	12261	7.40	8.16	0.76	10.3	42.4	4.95	0.50
	Spring	12861	9.06	8.28	-0.78	-8.6	37.5	5.14	0.51
	Summer	12952	9.54	5.73	-3.81	-39.9	49.8	7.03	0.25
	Fall	12837	8.43	8.46	0.03	0.3	34.0	4.07	0.58
Southwest	All	40373	6.42	6.20	-0.22	-3.5	54.0	5.45	0.37
	Winter	9912	8.01	7.81	-0.20	-2.5	59.6	7.38	0.38
	Spring	10299	5.96	6.72	0.76	12.8	53.0	4.83	0.31
	Summer	10111	5.89	4.08	-1.82	-30.9	50.1	4.33	0.15
	Fall	10051	5.87	6.22	0.35	6.0	51.2	4.77	0.45
Northern Rockies & Plains	All	25372	5.67	4.42	-1.25	-22.1	47.8	4.55	0.62
	Winter	6135	5.28	4.20	-1.08	-20.4	49.7	4.61	0.43
	Spring	6286	4.10	4.19	0.09	2.2	45.2	2.66	0.47
	Summer	6522	5.74	3.30	-2.44	-42.5	51.2	4.04	0.32
	Fall	6429	7.52	5.99	-1.53	-20.4	45.3	6.16	0.73
Northwest	All	52038	7.58	7.95	0.37	4.8	69.5	15.10	0.56
	Winter	12806	8.13	8.08	-0.05	-0.6	83.6	10.30	0.21
	Spring	13327	3.81	5.48	1.67	43.8	82.4	6.61	0.20
	Summer	13174	5.19	5.00	-0.19	-3.7	55.4	10.10	0.42
	Fall	12731	13.46	13.46	0.01	0.0	62.7	25.90	0.60
West	All	72477	8.00	7.10	-0.90	-11.3	45.5	7.16	0.53
	Winter	18018	9.34	8.65	-0.69	-7.4	50.3	7.48	0.60
	Spring	18145	6.93	6.95	0.01	0.2	42.9	4.72	0.42
	Summer	17956	7.14	5.21	-1.93	-27.1	42.1	7.34	0.46
	Fall	18358	8.58	7.57	-1.01	-11.8	45.4	8.51	0.55

Table 7 - CMAQ Performance Statistics for $PM_{2.5}$ SO_4^{2-} at CSN Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	3034	0.81	0.76	-0.05	-6.7	35.1	0.49	0.47
	Winter	732	0.83	0.78	-0.05	-6.2	35.0	0.46	0.40
	Spring	781	0.76	0.88	0.12	15.2	32.0	0.38	0.64
	Summer	784	0.99	0.68	-0.31	-31.1	37.3	0.66	0.56
	Fall	737	0.67	0.70	0.03	4.9	35.5	0.42	0.48
Southeast	All	1788	0.86	0.83	-0.04	-4.5	33.8	0.42	0.44
	Winter	444	0.81	0.85	0.04	5.5	34.9	0.38	0.49
	Spring	451	0.91	0.94	0.02	2.5	31.4	0.41	0.49
	Summer	461	0.97	0.70	-0.27	-27.4	35.7	0.52	0.40
	Fall	432	0.76	0.81	0.05	7.0	32.9	0.35	0.55
Ohio Valley	All	2117	1.04	0.92	-0.12	-11.7	33.2	0.55	0.58
	Winter	518	1.04	0.89	-0.15	-14.3	34.3	0.53	0.52
	Spring	550	1.01	1.03	0.03	2.6	31.7	0.51	0.63
	Summer	547	1.25	0.91	-0.35	-27.6	36.4	0.72	0.58
	Fall	502	0.87	0.85	-0.01	-1.4	28.8	0.36	0.72
Upper Midwest	All	1029	0.84	0.78	-0.06	-7.0	31.9	0.46	0.66
	Winter	250	0.92	0.82	-0.10	-10.7	30.1	0.42	0.63
	Spring	265	0.84	0.88	0.03	4.0	32.7	0.49	0.71
	Summer	266	0.87	0.66	-0.21	-24.2	34.3	0.56	0.64
	Fall	248	0.73	0.78	0.04	6.0	29.9	0.33	0.77
South	All	1032	1.15	1.03	-0.12	-10.2	40.7	0.73	0.49
	Winter	254	0.94	0.98	0.04	4.4	43.1	0.60	0.65
	Spring	275	1.32	1.16	-0.16	-12.4	38.6	0.89	0.62
	Summer	256	1.34	0.86	-0.48	-36.1	42.9	0.77	0.32
	Fall	247	0.95	1.11	0.16	16.4	38.4	0.59	0.46
Southwest	All	1083	0.52	0.56	0.04	7.0	42.2	0.30	0.39
	Winter	259	0.45	0.47	0.01	3.2	52.1	0.36	0.11
	Spring	267	0.49	0.69	0.20	41.6	49.4	0.28	0.73
	Summer	276	0.68	0.51	-0.17	-24.9	33.5	0.33	0.46
	Fall	281	0.45	0.55	0.10	22.1	38.8	0.23	0.58
Northern Rockies & Plains	All	520	0.54	0.55	0.01	2.7	42.0	0.37	0.62
	Winter	130	0.50	0.47	-0.03	-5.2	45.8	0.31	0.57
	Spring	125	0.52	0.64	0.12	23.2	47.5	0.39	0.64
	Summer	134	0.60	0.50	-0.10	-16.8	36.1	0.37	0.67
	Fall	131	0.54	0.61	0.07	13.1	40.3	0.40	0.66
Northwest	All	542	0.49	0.60	0.12	23.8	51.1	0.44	0.36
	Winter	143	0.40	0.52	0.12	28.5	59.8	0.32	0.32
	Spring	149	0.41	0.59	0.18	45.1	55.3	0.28	0.54
	Summer	133	0.63	0.67	0.04	7.0	51.8	0.74	0.16
	Fall	117	0.54	0.66	0.11	21.1	38.3	0.26	0.75
West	All	1868	0.91	0.78	-0.12	-13.6	42.9	0.71	0.50
	Winter	462	0.62	0.63	0.01	2.2	61.4	0.63	0.32
	Spring	466	0.86	0.84	-0.02	-2.8	40.5	0.51	0.58
	Summer	473	1.28	0.86	-0.42	-32.7	40.8	1.06	0.42
	Fall	467	0.85	0.79	-0.06	-6.8	35.2	0.48	0.67

Table 8 - CMAQ Performance Statistics for $PM_{2.5}$ SO_4^{2-} at IMPROVE Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	1952	0.58	0.54	-0.05	-7.8	33.8	0.30	0.70
	Winter	484	0.61	0.56	-0.05	-8.7	27.3	0.23	0.69
	Spring	486	0.53	0.63	0.10	18.1	32.1	0.23	0.78
	Summer	487	0.73	0.47	-0.26	-35.0	40.9	0.45	0.80
	Fall	495	0.46	0.49	0.03	6.3	33.1	0.21	0.77
Southeast	All	1619	0.81	0.70	-0.11	-13.1	34.8	0.40	0.52
	Winter	390	0.74	0.71	-0.03	-3.4	36.4	0.44	0.49
	Spring	408	0.84	0.83	-0.02	-2.1	30.8	0.36	0.57
	Summer	416	0.95	0.62	-0.33	-35.1	38.9	0.47	0.59
	Fall	405	0.69	0.65	-0.04	-5.3	32.3	0.30	0.60
Ohio Valley	All	939	0.88	0.77	-0.10	-11.8	33.2	0.41	0.67
	Winter	222	0.76	0.71	-0.05	-6.2	34.1	0.36	0.60
	Spring	239	0.81	0.84	0.02	3.0	31.8	0.41	0.66
	Summer	241	1.18	0.81	-0.37	-31.5	35.9	0.54	0.72
	Fall	237	0.75	0.74	-0.01	-1.5	29.5	0.30	0.75
Upper Midwest	All	938	0.57	0.55	-0.02	-4.4	33.0	0.31	0.77
	Winter	229	0.64	0.59	-0.05	-8.0	29.9	0.26	0.72
	Spring	232	0.57	0.59	0.02	2.9	36.0	0.43	0.71
	Summer	241	0.58	0.44	-0.14	-24.0	33.1	0.28	0.91
	Fall	236	0.50	0.58	0.08	15.1	33.4	0.22	0.85
South	All	1138	0.87	0.77	-0.10	-11.9	43.5	0.59	0.46
	Winter	275	0.59	0.67	0.08	12.8	47.5	0.52	0.57
	Spring	281	0.98	0.92	-0.06	-6.4	42.0	0.70	0.52
	Summer	292	1.17	0.68	-0.49	-41.8	45.4	0.70	0.38
	Fall	290	0.74	0.81	0.07	10.1	39.2	0.40	0.54
Southwest	All	3639	0.41	0.48	0.07	16.7	51.9	0.33	0.51
	Winter	891	0.29	0.35	0.06	19.4	69.7	0.39	0.25
	Spring	897	0.41	0.64	0.23	54.7	66.8	0.35	0.57
	Summer	927	0.58	0.46	-0.13	-21.4	34.4	0.29	0.70
	Fall	924	0.36	0.48	0.12	34.6	50.0	0.27	0.72
Northern Rockies & Plains	All	1858	0.35	0.40	0.05	12.8	47.9	0.25	0.64
	Winter	446	0.31	0.32	0.00	1.4	58.0	0.27	0.73
	Spring	462	0.35	0.49	0.13	37.7	57.6	0.26	0.58
	Summer	483	0.37	0.34	-0.03	-8.8	32.6	0.21	0.67
	Fall	467	0.37	0.45	0.08	21.0	46.3	0.28	0.68
Northwest	All	1926	0.26	0.38	0.12	44.5	66.1	0.27	0.48
	Winter	445	0.16	0.27	0.12	76.2	105.0	0.20	0.48
	Spring	495	0.23	0.40	0.17	75.6	84.9	0.24	0.57
	Summer	502	0.33	0.40	0.07	22.0	51.6	0.38	0.28
	Fall	484	0.33	0.43	0.11	32.0	51.0	0.22	0.69
West	All	2231	0.45	0.48	0.04	8.6	50.8	0.32	0.51
	Winter	539	0.26	0.32	0.07	25.5	80.6	0.36	0.49
	Spring	607	0.49	0.63	0.14	28.5	51.7	0.32	0.53
	Summer	565	0.61	0.51	-0.10	-16.9	42.6	0.35	0.35
	Fall	520	0.41	0.45	0.04	10.8	43.3	0.23	0.62

Table 9 - CMAQ Performance Statistics for $PM_{2.5}$ NO_3^- at CSN Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	3032	0.82	1.07	0.24	29.5	62.9	0.92	0.82
	Winter	731	1.63	2.60	0.96	58.9	69.8	1.64	0.74
	Spring	781	0.80	0.86	0.07	8.4	48.5	0.60	0.78
	Summer	783	0.30	0.12	-0.18	-59.8	78.6	0.34	0.19
	Fall	737	0.60	0.76	0.16	27.5	56.0	0.57	0.83
Southeast	All	1787	0.39	0.63	0.24	60.3	101.0	0.72	0.73
	Winter	444	0.73	1.51	0.79	108.0	123.0	1.25	0.66
	Spring	451	0.32	0.36	0.04	13.7	67.1	0.32	0.35
	Summer	460	0.21	0.14	-0.06	-30.1	74.6	0.22	0.29
	Fall	432	0.31	0.50	0.19	60.9	101.0	0.63	0.60
Ohio Valley	All	2117	1.14	1.23	0.09	8.2	45.4	0.83	0.86
	Winter	518	2.41	2.89	0.48	20.0	38.4	1.28	0.77
	Spring	550	0.94	0.92	-0.02	-1.9	46.1	0.66	0.82
	Summer	547	0.40	0.16	-0.24	-60.5	75.5	0.41	0.29
	Fall	502	0.85	1.04	0.18	21.1	49.5	0.76	0.89
Upper Midwest	All	1028	1.30	1.32	0.02	1.4	39.0	0.85	0.88
	Winter	250	2.54	2.98	0.43	17.1	32.5	1.23	0.82
	Spring	265	1.31	1.10	-0.21	-16.0	39.5	0.81	0.87
	Summer	265	0.42	0.18	-0.24	-57.3	73.5	0.46	0.29
	Fall	248	1.00	1.12	0.12	12.1	39.5	0.72	0.93
South	All	1031	0.62	0.60	-0.02	-3.5	59.1	0.58	0.73
	Winter	253	1.11	1.28	0.17	15.3	46.2	0.74	0.74
	Spring	275	0.60	0.44	-0.16	-27.2	54.3	0.46	0.74
	Summer	256	0.34	0.18	-0.16	-46.4	71.1	0.30	0.42
	Fall	247	0.45	0.53	0.08	17.6	89.4	0.70	0.53
Southwest	All	1083	1.11	0.53	-0.58	-52.2	67.7	1.84	0.67
	Winter	259	2.99	1.14	-1.86	-62.0	67.4	3.59	0.63
	Spring	267	0.53	0.44	-0.09	-16.5	56.9	0.48	0.39
	Summer	276	0.30	0.17	-0.13	-44.3	94.5	0.36	0.05
	Fall	281	0.74	0.42	-0.32	-43.1	65.4	0.91	0.69
Northern Rockies & Plains	All	519	0.60	0.46	-0.15	-24.0	55.0	0.63	0.71
	Winter	130	1.08	0.96	-0.12	-11.0	49.3	0.93	0.68
	Spring	125	0.54	0.42	-0.12	-22.6	49.2	0.45	0.75
	Summer	133	0.24	0.08	-0.15	-64.5	71.3	0.24	0.58
	Fall	131	0.57	0.38	-0.19	-33.0	64.1	0.68	0.52
Northwest	All	541	0.90	1.40	0.50	54.9	121.0	1.84	0.34
	Winter	143	1.64	2.04	0.40	24.3	105.0	2.48	0.17
	Spring	148	0.46	0.94	0.48	103.0	142.0	1.13	0.43
	Summer	133	0.27	1.13	0.86	315.0	344.0	1.59	0.54
	Fall	117	1.28	1.51	0.23	17.8	81.0	1.89	0.46
West	All	1867	1.94	0.81	-1.14	-58.5	67.3	2.54	0.61
	Winter	462	3.54	1.72	-1.82	-51.3	62.0	3.75	0.60
	Spring	465	1.35	0.67	-0.68	-50.2	66.4	1.46	0.30
	Summer	473	0.93	0.28	-0.65	-69.6	72.1	1.04	0.61
	Fall	467	1.98	0.56	-1.42	-71.7	75.0	2.95	0.56

Table 10 - CMAQ Performance Statistics for $PM_{2.5}$ NO_3^- at IMPROVE Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	1953	0.35	0.64	0.29	82.7	109.0	0.71	0.77
	Winter	486	0.68	1.53	0.85	125.0	128.0	1.24	0.74
	Spring	486	0.29	0.48	0.19	63.5	98.3	0.53	0.61
	Summer	486	0.16	0.16	0.00	-1.8	91.2	0.25	0.41
	Fall	495	0.28	0.41	0.14	48.8	81.2	0.39	0.78
Southeast	All	1619	0.31	0.45	0.14	45.1	96.4	0.56	0.72
	Winter	390	0.55	1.10	0.55	100.0	122.0	0.96	0.70
	Spring	408	0.29	0.31	0.02	7.1	65.9	0.28	0.50
	Summer	416	0.18	0.12	-0.07	-37.0	70.4	0.18	0.48
	Fall	405	0.23	0.31	0.08	34.5	97.5	0.49	0.58
Ohio Valley	All	939	0.59	0.78	0.19	32.2	70.1	0.75	0.79
	Winter	222	1.34	2.08	0.75	55.7	73.2	1.31	0.70
	Spring	239	0.42	0.47	0.04	10.4	61.7	0.45	0.73
	Summer	241	0.21	0.06	-0.15	-69.5	79.7	0.26	0.21
	Fall	237	0.45	0.62	0.16	35.7	64.7	0.57	0.88
Upper Midwest	All	936	0.58	0.66	0.08	13.9	50.2	0.57	0.87
	Winter	229	1.29	1.60	0.32	24.5	46.6	0.89	0.86
	Spring	231	0.49	0.45	-0.04	-8.1	51.5	0.50	0.71
	Summer	241	0.13	0.06	-0.06	-50.9	76.4	0.16	0.59
	Fall	235	0.44	0.56	0.12	27.3	51.3	0.48	0.93
South	All	1138	0.45	0.42	-0.03	-6.9	64.2	0.47	0.78
	Winter	275	0.75	0.94	0.18	24.4	55.6	0.63	0.81
	Spring	281	0.51	0.39	-0.12	-22.9	49.7	0.35	0.87
	Summer	292	0.26	0.04	-0.22	-83.5	87.5	0.30	0.19
	Fall	290	0.30	0.34	0.04	13.4	87.9	0.54	0.61
Southwest	All	3638	0.23	0.13	-0.10	-43.4	75.9	0.39	0.47
	Winter	891	0.37	0.18	-0.20	-52.6	73.9	0.68	0.54
	Spring	897	0.22	0.24	0.01	5.3	67.0	0.23	0.45
	Summer	927	0.17	0.03	-0.14	-81.9	89.2	0.20	0.17
	Fall	923	0.15	0.08	-0.07	-48.4	78.7	0.25	0.51
Northern Rockies & Plains	All	1858	0.22	0.22	0.00	-1.7	68.1	0.29	0.70
	Winter	446	0.33	0.40	0.06	19.5	68.4	0.41	0.67
	Spring	462	0.23	0.23	-0.01	-3.0	56.3	0.25	0.75
	Summer	482	0.10	0.03	-0.07	-70.4	78.6	0.13	0.62
	Fall	468	0.22	0.22	0.01	2.5	75.1	0.32	0.68
Northwest	All	1911	0.22	0.25	0.04	17.0	111.0	0.67	0.44
	Winter	440	0.34	0.40	0.06	16.7	111.0	0.86	0.40
	Spring	489	0.14	0.21	0.07	46.9	109.0	0.38	0.51
	Summer	498	0.10	0.15	0.05	50.5	180.0	0.58	0.56
	Fall	484	0.30	0.27	-0.03	-8.7	89.3	0.79	0.50
West	All	2230	0.45	0.21	-0.24	-53.8	69.8	0.88	0.78
	Winter	538	0.63	0.32	-0.31	-49.1	61.1	1.22	0.87
	Spring	607	0.44	0.29	-0.16	-34.9	64.9	0.53	0.45
	Summer	565	0.25	0.05	-0.20	-78.5	86.4	0.31	0.27
	Fall	520	0.48	0.16	-0.32	-66.5	77.4	1.14	0.77

Table 11 - CMAQ Performance Statistics for $PM_{2.5}$ OC at CSN Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	2951	1.61	3.16	1.56	96.8	106.0	2.82	0.39
	Winter	707	1.30	3.60	2.30	176.0	180.0	3.48	0.45
	Spring	760	1.35	3.00	1.64	121.0	127.0	2.79	0.46
	Summer	781	2.18	2.89	0.72	32.9	50.1	1.73	0.51
	Fall	703	1.56	3.20	1.65	106.0	111.0	3.07	0.46
Southeast	All	1724	2.25	3.18	0.92	41.0	61.0	1.98	0.53
	Winter	427	2.09	3.26	1.17	55.8	71.2	2.17	0.63
	Spring	423	2.29	3.26	0.97	42.4	61.0	2.08	0.54
	Summer	445	2.21	3.01	0.80	36.3	56.4	1.72	0.44
	Fall	429	2.42	3.19	0.76	31.5	56.6	1.93	0.46
Ohio Valley	All	2116	1.90	2.72	0.82	43.1	54.8	1.47	0.66
	Winter	535	1.49	2.85	1.36	91.8	98.0	1.90	0.56
	Spring	549	1.75	2.52	0.78	44.4	55.3	1.36	0.76
	Summer	525	2.37	2.82	0.45	18.8	32.6	1.04	0.72
	Fall	507	2.01	2.69	0.68	33.6	47.8	1.43	0.72
Upper Midwest	All	1162	1.61	2.52	0.90	55.9	73.2	1.88	0.47
	Winter	289	1.25	3.29	2.04	163.0	164.0	2.76	0.59
	Spring	288	1.27	2.13	0.86	67.8	78.7	1.55	0.57
	Summer	303	1.98	1.95	-0.03	-1.5	33.0	0.88	0.51
	Fall	282	1.95	2.74	0.78	40.1	54.2	1.85	0.64
South	All	936	2.18	2.56	0.37	17.1	48.6	2.83	0.29
	Winter	223	1.96	2.75	0.80	40.6	60.2	1.82	0.52
	Spring	233	1.81	2.22	0.41	22.7	46.4	1.36	0.67
	Summer	250	1.89	2.10	0.21	11.0	45.1	1.30	0.51
	Fall	230	3.10	3.20	0.11	3.4	45.2	5.05	0.19
Southwest	All	1110	1.68	2.49	0.81	48.5	74.0	2.05	0.39
	Winter	282	2.36	3.72	1.37	58.0	88.4	3.06	0.25
	Spring	280	1.14	1.95	0.81	71.7	81.8	1.44	0.40
	Summer	276	1.40	1.57	0.17	12.3	47.4	0.85	0.32
	Fall	272	1.81	2.70	0.89	49.1	70.4	2.13	0.33
Northern Rockies & Plains	All	488	1.46	1.17	-0.29	-19.9	57.5	1.83	0.66
	Winter	116	1.12	1.02	-0.10	-8.5	82.4	2.07	0.14
	Spring	113	0.68	0.79	0.11	16.4	57.9	0.59	0.53
	Summer	129	1.61	0.91	-0.69	-43.1	51.5	1.14	0.30
	Fall	130	2.29	1.88	-0.41	-18.1	50.7	2.67	0.79
Northwest	All	530	2.21	5.36	3.16	143.0	162.0	5.01	0.46
	Winter	143	1.92	5.73	3.81	199.0	207.0	5.00	0.50
	Spring	148	1.13	4.64	3.51	311.0	312.0	5.12	0.55
	Summer	134	1.67	4.46	2.80	168.0	178.0	4.10	0.44
	Fall	105	4.80	7.03	2.23	46.5	80.7	5.84	0.55
West	All	1232	2.75	3.48	0.73	26.6	52.2	2.98	0.49
	Winter	309	3.78	5.38	1.60	42.4	58.9	3.34	0.65
	Spring	306	1.81	2.56	0.75	41.2	54.1	1.46	0.60
	Summer	312	1.95	1.94	-0.02	-0.9	37.5	1.03	0.40
	Fall	305	3.46	4.05	0.59	17.2	52.2	4.63	0.38

Table 12 - CMAQ Performance Statistics for $PM_{2.5}$ OC at IMPROVE Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	1830	0.86	1.71	0.86	100.0	118.0	3.15	0.33
	Winter	458	0.67	2.08	1.41	212.0	215.0	2.08	0.74
	Spring	451	0.65	1.81	1.16	178.0	184.0	5.76	0.28
	Summer	458	1.26	1.34	0.08	6.0	43.3	0.81	0.73
	Fall	463	0.84	1.63	0.79	94.3	105.0	1.43	0.79
Southeast	All	1727	1.31	1.87	0.56	42.7	62.6	2.06	0.58
	Winter	420	1.24	2.07	0.83	67.2	81.4	2.22	0.61
	Spring	437	1.35	2.12	0.77	57.2	74.8	3.16	0.48
	Summer	438	1.31	1.69	0.38	29.0	51.0	1.08	0.77
	Fall	432	1.34	1.61	0.27	19.7	44.8	0.97	0.80
Ohio Valley	All	930	1.23	1.92	0.69	56.3	67.3	1.39	0.71
	Winter	221	0.92	1.76	0.85	91.9	96.6	1.46	0.63
	Spring	236	1.19	1.92	0.73	61.5	72.2	1.73	0.79
	Summer	236	1.50	2.15	0.65	43.6	54.9	1.24	0.71
	Fall	237	1.29	1.84	0.55	42.6	57.6	1.07	0.73
Upper Midwest	All	1036	0.89	1.25	0.36	40.9	66.8	0.92	0.67
	Winter	253	0.63	1.45	0.82	131.0	133.0	1.19	0.85
	Spring	253	0.64	1.00	0.35	55.0	68.3	0.72	0.80
	Summer	266	1.23	1.07	-0.16	-13.1	40.1	0.63	0.58
	Fall	264	1.02	1.48	0.46	44.7	59.5	1.05	0.76
South	All	1142	1.08	1.38	0.30	27.4	53.5	1.24	0.69
	Winter	274	0.75	1.21	0.47	62.6	73.8	1.20	0.68
	Spring	290	1.23	1.65	0.42	34.1	58.6	1.87	0.77
	Summer	293	1.18	1.16	-0.02	-1.8	40.8	0.75	0.62
	Fall	285	1.16	1.49	0.33	28.8	48.8	0.81	0.74
Southwest	All	3637	0.66	0.65	-0.01	-2.1	52.2	0.70	0.66
	Winter	886	0.67	0.66	-0.01	-2.1	60.9	1.00	0.65
	Spring	894	0.58	0.77	0.19	32.5	56.7	0.68	0.78
	Summer	932	0.74	0.50	-0.24	-32.0	46.9	0.52	0.58
	Fall	925	0.65	0.67	0.01	1.9	45.5	0.51	0.70
Northern Rockies & Plains	All	1935	1.06	0.92	-0.15	-13.7	60.9	3.37	0.46
	Winter	462	0.31	0.53	0.22	71.7	93.4	0.90	0.25
	Spring	474	0.34	0.52	0.17	51.2	81.2	0.80	0.26
	Summer	504	1.16	0.69	-0.47	-40.2	57.6	1.60	0.23
	Fall	495	2.36	1.89	-0.47	-19.8	55.7	6.35	0.47
Northwest	All	1877	1.39	1.66	0.27	19.6	80.7	3.48	0.68
	Winter	430	0.51	1.01	0.51	99.4	146.0	1.85	0.46
	Spring	470	0.33	0.79	0.45	135.0	158.0	1.65	0.62
	Summer	500	1.09	1.20	0.11	9.7	74.1	1.75	0.45
	Fall	477	3.52	3.58	0.06	1.6	67.0	6.21	0.68
West	All	2185	1.02	1.03	0.01	1.1	60.5	2.77	0.42
	Winter	526	0.74	0.79	0.04	6.0	57.4	0.86	0.79
	Spring	584	0.68	0.74	0.06	8.9	46.6	0.51	0.63
	Summer	552	1.30	1.23	-0.06	-5.0	67.6	4.75	0.37
	Fall	523	1.38	1.38	0.00	0.3	62.9	2.70	0.59

Table 13 - CMAQ Performance Statistics for $PM_{2.5}$ EC at CSN Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	2952	0.58	0.41	-0.17	-29.3	44.5	0.44	0.47
	Winter	707	0.60	0.51	-0.09	-14.9	40.4	0.47	0.48
	Spring	761	0.53	0.38	-0.15	-27.7	42.6	0.42	0.52
	Summer	781	0.57	0.31	-0.26	-45.5	50.5	0.43	0.35
	Fall	703	0.62	0.44	-0.18	-28.3	44.4	0.44	0.52
Southeast	All	1725	0.76	0.35	-0.40	-53.1	60.7	0.69	0.39
	Winter	428	0.85	0.42	-0.42	-50.1	57.1	0.75	0.43
	Spring	423	0.77	0.35	-0.42	-54.8	59.9	0.69	0.48
	Summer	445	0.56	0.27	-0.29	-51.3	61.2	0.52	0.08
	Fall	429	0.85	0.38	-0.47	-55.7	64.5	0.78	0.30
Ohio Valley	All	2116	0.70	0.35	-0.34	-49.3	52.2	0.51	0.55
	Winter	535	0.64	0.42	-0.21	-33.6	42.7	0.45	0.42
	Spring	549	0.68	0.32	-0.36	-52.6	54.5	0.53	0.64
	Summer	525	0.71	0.29	-0.42	-58.9	59.3	0.54	0.48
	Fall	507	0.76	0.37	-0.39	-50.8	51.6	0.50	0.75
Upper Midwest	All	1164	0.50	0.34	-0.16	-31.6	48.0	0.34	0.50
	Winter	290	0.46	0.47	0.01	1.4	43.5	0.32	0.45
	Spring	289	0.40	0.29	-0.11	-26.8	44.0	0.25	0.56
	Summer	303	0.49	0.24	-0.26	-52.0	55.2	0.34	0.40
	Fall	282	0.64	0.37	-0.27	-42.3	47.8	0.43	0.65
South	All	936	0.68	0.39	-0.29	-42.2	48.3	1.29	0.25
	Winter	223	0.84	0.49	-0.34	-41.0	45.0	0.57	0.70
	Spring	233	0.52	0.32	-0.20	-38.1	42.0	0.33	0.73
	Summer	250	0.41	0.29	-0.12	-28.5	47.5	0.26	0.47
	Fall	230	0.98	0.47	-0.51	-51.7	54.9	2.50	0.09
Southwest	All	1110	0.63	0.40	-0.23	-36.3	47.5	0.56	0.56
	Winter	282	1.13	0.61	-0.53	-46.5	54.4	0.97	0.39
	Spring	280	0.36	0.31	-0.05	-13.8	38.1	0.21	0.61
	Summer	276	0.33	0.26	-0.07	-21.0	36.9	0.16	0.54
	Fall	272	0.71	0.44	-0.27	-38.5	46.0	0.49	0.49
Northern Rockies & Plains	All	488	0.40	0.16	-0.24	-59.2	65.5	0.70	0.32
	Winter	116	0.49	0.17	-0.32	-65.7	75.9	1.14	0.06
	Spring	113	0.20	0.12	-0.08	-40.8	51.2	0.19	0.45
	Summer	129	0.35	0.11	-0.24	-68.0	68.2	0.30	0.22
	Fall	130	0.55	0.25	-0.30	-54.3	60.0	0.72	0.53
Northwest	All	530	0.71	0.76	0.05	6.7	61.5	0.68	0.47
	Winter	143	0.86	0.76	-0.10	-11.7	49.3	0.58	0.50
	Spring	148	0.47	0.63	0.16	34.7	74.0	0.52	0.47
	Summer	134	0.47	0.74	0.27	56.9	87.7	0.56	0.57
	Fall	105	1.15	0.96	-0.19	-16.7	53.2	1.05	0.45
West	All	1232	0.98	0.48	-0.49	-50.5	52.8	0.86	0.75
	Winter	309	1.68	0.75	-0.93	-55.3	56.5	1.22	0.71
	Spring	306	0.61	0.37	-0.24	-39.7	45.2	0.39	0.71
	Summer	312	0.49	0.29	-0.20	-41.3	45.0	0.36	0.42
	Fall	305	1.14	0.54	-0.61	-53.1	54.7	1.09	0.66

Table 14 - CMAQ Performance Statistics for $PM_{2.5}$ EC at IMPROVE Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	1823	0.18	0.19	0.01	4.8	47.3	0.15	0.70
	Winter	455	0.19	0.26	0.08	41.6	58.9	0.18	0.72
	Spring	449	0.15	0.19	0.03	22.3	50.8	0.16	0.67
	Summer	458	0.20	0.12	-0.08	-39.3	43.3	0.12	0.79
	Fall	461	0.20	0.20	0.00	1.5	37.9	0.12	0.82
Southeast	All	1724	0.29	0.17	-0.12	-41.0	48.4	0.24	0.78
	Winter	420	0.32	0.22	-0.09	-29.3	40.9	0.21	0.80
	Spring	437	0.30	0.18	-0.12	-39.1	48.9	0.29	0.74
	Summer	435	0.23	0.11	-0.11	-49.5	54.4	0.19	0.76
	Fall	432	0.32	0.16	-0.15	-48.3	51.0	0.26	0.83
Ohio Valley	All	930	0.25	0.16	-0.09	-34.4	42.5	0.14	0.67
	Winter	221	0.24	0.20	-0.04	-14.7	34.6	0.12	0.59
	Spring	236	0.24	0.16	-0.08	-32.6	40.5	0.13	0.76
	Summer	236	0.24	0.11	-0.13	-53.0	54.8	0.16	0.64
	Fall	237	0.28	0.18	-0.10	-36.1	40.1	0.15	0.77
Upper Midwest	All	1033	0.20	0.13	-0.06	-32.5	47.5	0.14	0.71
	Winter	252	0.18	0.18	0.01	4.4	35.8	0.10	0.81
	Spring	253	0.16	0.11	-0.05	-29.2	42.8	0.11	0.79
	Summer	266	0.21	0.08	-0.13	-60.1	61.6	0.17	0.76
	Fall	262	0.25	0.16	-0.09	-36.2	46.3	0.18	0.75
South	All	1135	0.20	0.13	-0.07	-37.2	49.5	0.21	0.47
	Winter	274	0.19	0.13	-0.05	-28.7	39.4	0.12	0.73
	Spring	290	0.22	0.17	-0.05	-24.7	53.5	0.29	0.61
	Summer	286	0.16	0.07	-0.09	-54.1	56.5	0.12	0.48
	Fall	285	0.23	0.13	-0.10	-44.4	48.7	0.24	0.34
Southwest	All	3606	0.16	0.09	-0.07	-45.6	57.3	0.26	0.67
	Winter	876	0.24	0.10	-0.14	-57.6	63.9	0.46	0.72
	Spring	878	0.12	0.10	-0.02	-17.9	50.5	0.14	0.73
	Summer	928	0.11	0.06	-0.05	-44.9	55.9	0.09	0.66
	Fall	924	0.17	0.09	-0.08	-48.8	54.2	0.22	0.68
Northern Rockies & Plains	All	1913	0.14	0.11	-0.03	-21.7	61.8	0.29	0.50
	Winter	450	0.07	0.07	-0.01	-10.3	63.2	0.15	0.20
	Spring	470	0.06	0.06	0.00	0.6	65.6	0.13	0.18
	Summer	498	0.13	0.07	-0.06	-47.9	69.1	0.21	0.15
	Fall	495	0.27	0.22	-0.05	-17.3	57.1	0.50	0.52
Northwest	All	1855	0.20	0.18	-0.02	-9.3	69.1	0.68	0.48
	Winter	415	0.13	0.13	0.00	1.8	75.3	0.19	0.70
	Spring	472	0.07	0.10	0.03	34.3	85.7	0.20	0.58
	Summer	494	0.14	0.14	0.00	2.2	78.7	0.24	0.68
	Fall	474	0.44	0.34	-0.10	-23.3	61.6	1.30	0.50
West	All	2145	0.17	0.11	-0.07	-38.2	57.3	0.28	0.68
	Winter	512	0.20	0.10	-0.10	-48.6	63.0	0.27	0.80
	Spring	573	0.10	0.09	-0.02	-18.3	46.0	0.09	0.69
	Summer	537	0.16	0.10	-0.06	-36.3	55.8	0.28	0.61
	Fall	523	0.24	0.14	-0.10	-40.8	59.2	0.41	0.69

Table 15 - CMAQ Performance Statistics MDA8 O_3 at AQS Sites in 2022

Region	Season	N	AvgObs (ppb)	AvgMod (ppb)	MB	NMB	NME	RMSE	r
Northeast	All	52703	39.8	40.9	1.1	2.8	11.7	6.02	0.81
	Winter	7926	33.9	34.3	0.3	1.0	10.9	4.95	0.71
	Spring	16165	42.5	43.3	0.8	2.0	10.4	5.64	0.69
	Summer	16222	44.8	45.7	0.9	2.0	11.2	6.52	0.79
	Fall	12390	33.5	35.7	2.3	6.8	15.2	6.44	0.74
Southeast	All	48275	39.4	40.8	1.3	3.3	13.0	6.56	0.77
	Winter	6842	36.7	35.5	-1.2	-3.1	12.8	5.89	0.69
	Spring	15220	43.9	42.7	-1.2	-2.8	10.5	5.89	0.79
	Summer	14520	37.9	42.0	4.2	11.1	16.2	7.65	0.80
	Fall	11693	37.2	39.6	2.5	6.6	13.0	6.32	0.77
Ohio Valley	All	60934	41.6	43.7	2.2	5.2	13.0	6.88	0.78
	Winter	5499	30.9	32.9	2.0	6.5	14.7	5.65	0.77
	Spring	20427	42.7	44.4	1.7	4.0	11.7	6.40	0.64
	Summer	20107	46.4	49.1	2.7	5.8	12.6	7.36	0.74
	Fall	14901	37.4	39.6	2.1	5.7	15.1	7.25	0.71
Upper Midwest	All	24294	40.2	42.1	1.9	4.7	12.3	6.30	0.80
	Winter	1492	33.3	35.4	2.2	6.5	10.3	4.50	0.80
	Spring	8201	42.0	44.7	2.7	6.4	11.4	6.02	0.71
	Summer	8620	43.4	44.3	0.9	2.1	11.4	6.40	0.80
	Fall	5981	34.8	36.8	2.1	5.9	15.9	6.89	0.74
South	All	45543	40.5	40.6	0.1	0.3	14.0	7.22	0.81
	Winter	9623	33.7	32.8	-0.9	-2.6	15.2	6.39	0.74
	Spring	12336	44.3	43.6	-0.7	-1.6	12.5	7.13	0.73
	Summer	12064	41.3	43.2	1.9	4.7	15.7	8.13	0.82
	Fall	11520	41.5	41.4	-0.1	-0.3	13.1	6.97	0.83
Southwest	All	46026	48.0	46.6	-1.4	-2.9	11.0	7.03	0.76
	Winter	10447	39.2	37.8	-1.5	-3.7	12.8	6.70	0.62
	Spring	11922	51.1	50.2	-0.9	-1.8	9.2	6.22	0.60
	Summer	12266	55.8	52.9	-2.9	-5.3	11.9	8.67	0.50
	Fall	11391	44.3	44.0	-0.3	-0.6	10.7	6.08	0.72
Northern Rockies & Plains	All	16891	42.1	43.5	1.4	3.3	10.3	5.68	0.76
	Winter	4042	38.0	39.1	1.2	3.0	9.9	5.08	0.70
	Spring	4278	44.6	46.2	1.6	3.7	8.7	5.17	0.65
	Summer	4335	47.1	48.0	0.9	1.9	10.4	6.23	0.67
	Fall	4236	38.3	40.3	1.9	5.1	12.4	6.10	0.73
Northwest	All	6337	37.7	38.3	0.6	1.7	13.7	6.95	0.77
	Winter	803	32.3	34.8	2.5	7.9	18.2	7.66	0.72
	Spring	1672	39.1	40.5	1.5	3.7	10.7	5.47	0.71
	Summer	2521	39.1	38.3	-0.7	-1.9	13.6	7.30	0.80
	Fall	1341	36.5	37.6	1.0	2.8	15.7	7.45	0.73
West	All	60629	44.5	42.1	-2.4	-5.4	13.5	7.91	0.82
	Winter	13437	34.9	34.7	-0.3	-0.7	15.5	6.95	0.64
	Spring	15970	47.4	44.9	-2.5	-5.4	11.2	7.02	0.73
	Summer	16392	49.8	45.7	-4.1	-8.3	14.6	9.40	0.84
	Fall	14830	44.2	41.9	-2.3	-5.1	13.3	7.84	0.80

Table 16 - CMAQ Performance Statistics for MDA8 O_3 at CASTNET Sites in 2022

Region	Season	N	AvgObs (ppb)	AvgMod (ppb)	MB	NMB	NME	RMSE	r
Northeast	All	4265	39.9	40.3	0.4	1.1	10.5	5.55	0.79
	Winter	1113	35.4	35.3	-0.1	-0.3	9.3	4.44	0.72
	Spring	1183	43.9	44.2	0.3	0.6	9.4	5.35	0.67
	Summer	978	45.1	45.7	0.5	1.2	10.7	6.48	0.72
	Fall	991	35.1	36.2	1.1	3.2	13.2	5.89	0.70
Southeast	All	4006	39.7	39.7	0.0	0.0	12.5	6.37	0.74
	Winter	982	37.1	35.1	-2.0	-5.4	13.8	6.45	0.67
	Spring	1067	45.4	43.2	-2.3	-5.0	10.4	5.88	0.77
	Summer	971	38.1	41.7	3.6	9.4	15.0	7.32	0.78
	Fall	986	37.7	38.6	0.9	2.3	11.6	5.75	0.72
Ohio Valley	All	5596	40.1	41.1	1.0	2.4	12.6	6.39	0.77
	Winter	1407	33.7	34.2	0.5	1.3	13.4	5.80	0.70
	Spring	1550	44.5	44.7	0.2	0.3	10.8	6.16	0.61
	Summer	1307	44.6	47.0	2.4	5.3	12.8	6.91	0.76
	Fall	1332	37.3	38.4	1.0	2.8	14.1	6.71	0.69
Upper Midwest	All	1765	38.2	39.5	1.4	3.6	11.5	5.75	0.81
	Winter	436	34.7	36.3	1.6	4.7	8.3	3.88	0.80
	Spring	454	42.9	44.9	2.0	4.8	10.3	5.51	0.71
	Summer	442	40.9	41.2	0.3	0.8	11.8	6.31	0.82
	Fall	433	33.9	35.4	1.5	4.5	16.3	6.86	0.69
South	All	2034	41.4	40.8	-0.6	-1.4	13.3	6.90	0.77
	Winter	517	36.0	34.5	-1.6	-4.3	15.3	6.76	0.71
	Spring	536	45.9	44.7	-1.3	-2.8	10.8	6.31	0.75
	Summer	501	42.3	43.9	1.6	3.8	15.1	7.98	0.78
	Fall	480	41.1	40.2	-0.9	-2.2	12.8	6.46	0.79
Southwest	All	4235	48.8	47.5	-1.3	-2.7	9.0	5.63	0.75
	Winter	1060	43.7	40.6	-3.1	-7.1	10.2	5.41	0.66
	Spring	1075	52.3	51.3	-1.0	-1.9	7.5	5.07	0.65
	Summer	1056	54.3	52.9	-1.4	-2.6	9.7	6.81	0.48
	Fall	1044	44.7	45.0	0.3	0.6	8.8	5.04	0.70
Northern Rockies & Plains	All	2476	44.2	46.2	2.1	4.6	10.1	6.02	0.72
	Winter	609	40.8	41.4	0.7	1.7	10.8	6.15	0.60
	Spring	634	47.1	48.5	1.4	3.0	7.4	4.48	0.71
	Summer	624	47.8	50.9	3.1	6.4	10.2	6.15	0.73
	Fall	609	40.9	43.9	3.0	7.4	12.5	7.07	0.66
Northwest	All	1050	40.4	43.0	2.7	6.6	11.8	6.49	0.69
	Winter	256	36.6	40.8	4.2	11.5	16.4	8.25	0.34
	Spring	268	42.4	45.0	2.7	6.3	9.2	5.00	0.75
	Summer	267	44.0	44.6	0.6	1.4	8.9	5.15	0.79
	Fall	259	38.2	41.4	3.2	8.4	14.0	7.10	0.65
West	All	2443	49.4	45.4	-4.0	-8.2	12.6	8.26	0.73
	Winter	597	41.7	40.0	-1.7	-4.0	11.3	5.85	0.52
	Spring	607	50.9	47.5	-3.4	-6.6	10.9	6.99	0.67
	Summer	630	56.7	49.6	-7.1	-12.4	15.4	11.10	0.66
	Fall	609	48.1	44.2	-3.9	-8.2	12.1	8.03	0.67

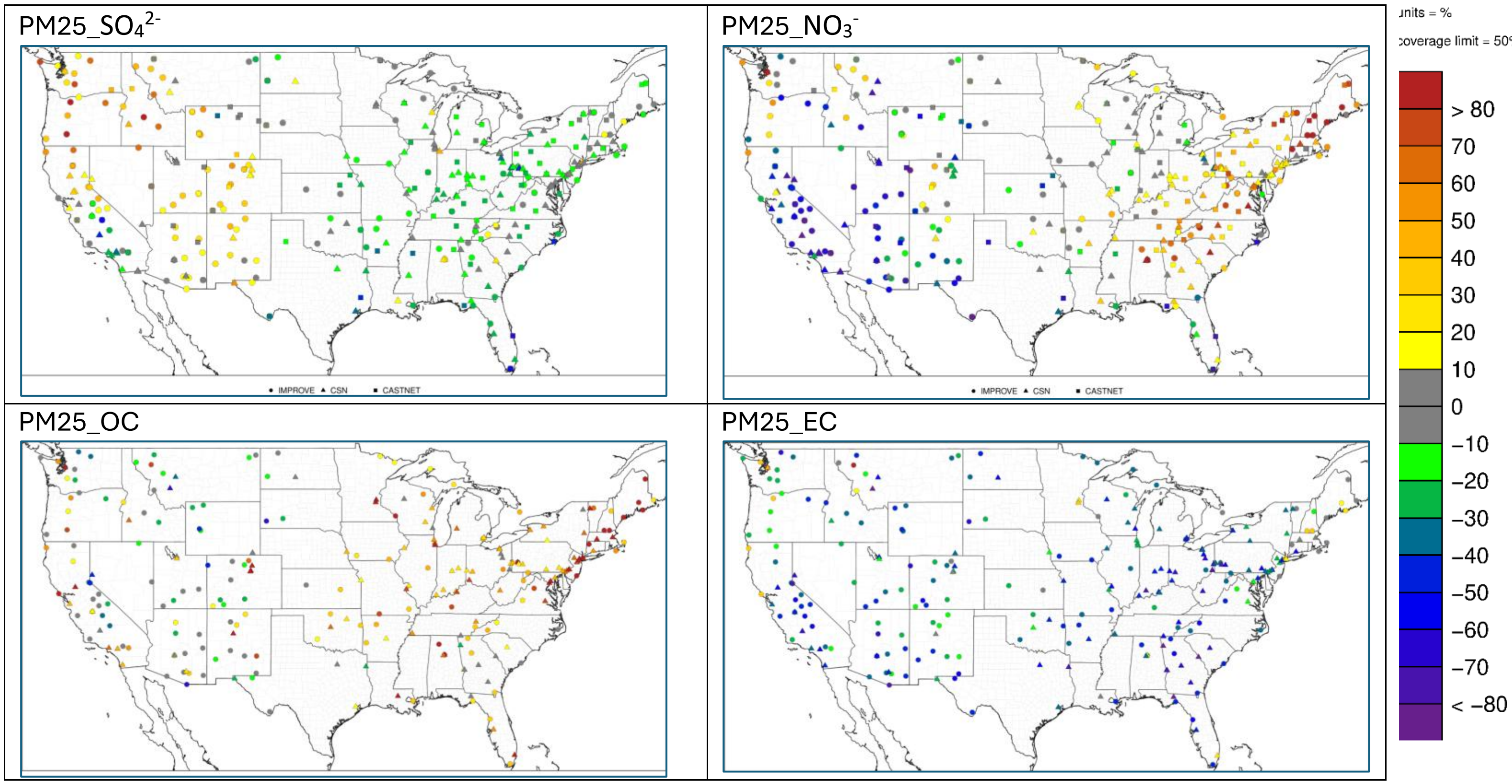

Figure 4 - NMB in 2022 CMAQ Predictions of $PM_{2.5}$ Components at CSN and IMPROVE Sites

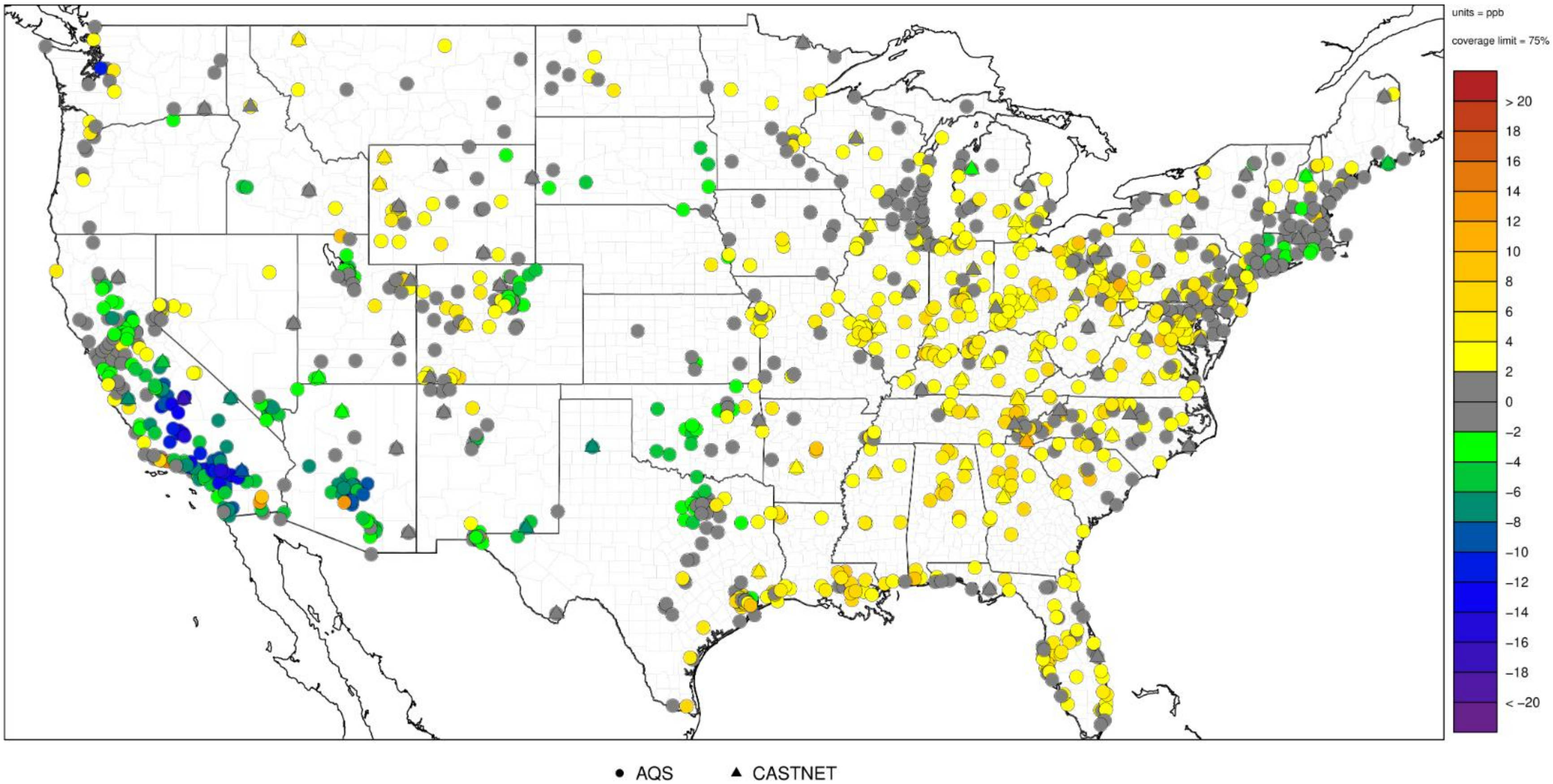

Figure 5 - MB in 2022 CMAQ Predictions of MDA8 O_3 at AQS and CASTNET sites during O_3 season (05/01/2022-09/30/2022)

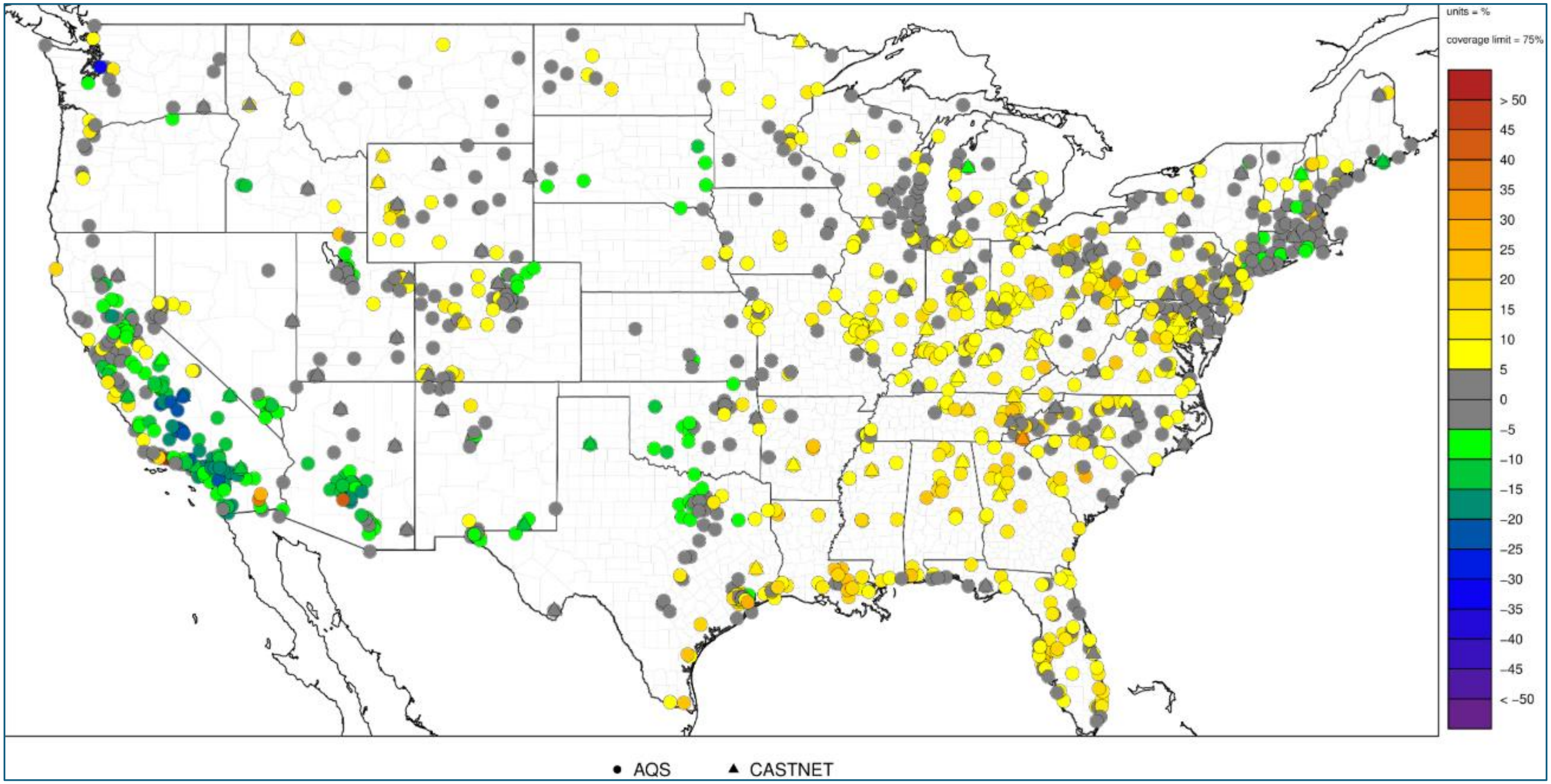

Figure 6 - NMB in 2022 CMAQ Predictions of MDA8 O_3 at AQS and CASTNET sites during O_3 season (05/01/2022-09/30/2022)

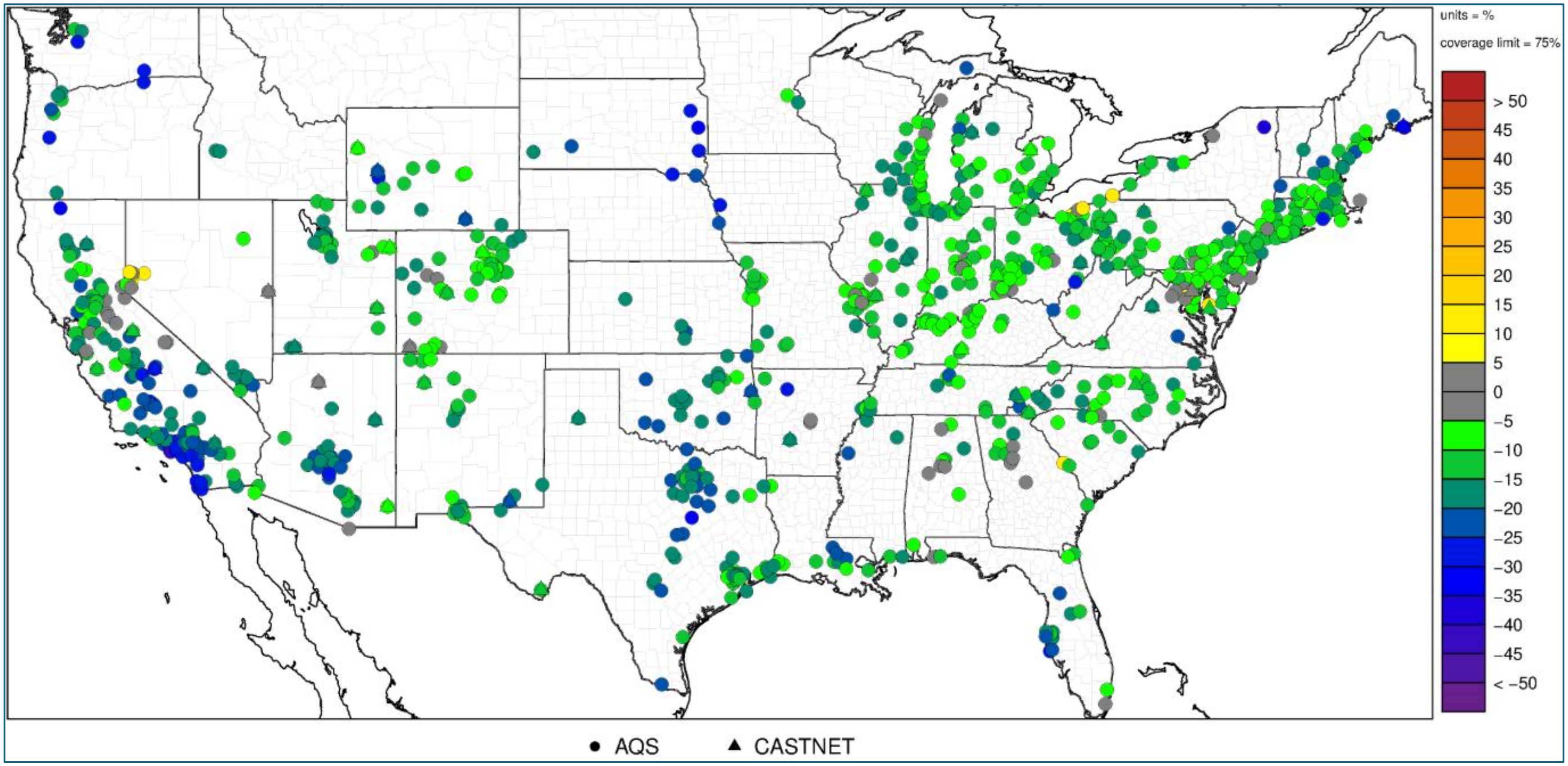

Figure 7 - NMB in 2022 CMAQ predictions of MDA8 O_3 at AQS and CASTNET sites when observation MDA8O3 > 65 ppb during O_3 season (2022/05/01-2022/09/30)

4.3 CAMx Results

This section summarizes the performance of CAMx in predicting total $PM_{2.5}$, its constituent species, and the MDA-8hr O_3. The summary is organized by monitoring network (AQS, IMPROVE, CSN, CASTNET), season, and region, using the statistical metrics described in the previous section.

4.3.1 $PM_{2.5}$ and Corresponding Species: SO_4^{2-}, NO_3^-, OC, and EC

The MB, NMB, RSME, NME and r of $PM_{2.5}$ used in evaluating model performance are shown in Table 17. The CAMx annual NMBs in $PM_{2.5}$ predictions are within ±30% for all regions except the Northern Rockies & Plains (NMB: -38.6%) at AQS sites. Correlation coefficients over the annual period for $PM_{2.5}$ predictions and observations were greater than 0.4 in seven of nine regions for AQS sites. As described above, performance statistics for this application are generally within the range of model performance statistics reported in previous applications and suggest that the simulations are suitable for use in national scale applications. Overall, $PM_{2.5}$ model performance of CAMx is similar to the $PM_{2.5}$ model performance of CMAQ in this platform.

CAMx model performance statistics for SO_4^{2-} by region and season for sites in the CSN and IMPROVE networks are provided in Table 18 and 19. The annual NMBs in SO_4^{2-} predictions are within ±30% for all regions except the Northwest (NMB: 37.3 and 83.0 %) at CSN and IMPROVE sites. Spatially, SO_4^{2-} predictions tend to be biased slightly high toward the Eastern and Northwestern part of the domain (Figure 7).

CAMx model performance statistics for NO_3^- by regions and seasons for sites in the CSN and IMPROVE networks are provided in Table 20 and 21. The annual NMBs in NO_3^- predictions are within ±65% for all regions except the Southeast (NMB: 93.0 and 85.2%) at CSN sites and IMPROVE sites. Model NO_3^- performance is reasonable in the regions where NH_4NO_3 concentrations are relatively high, such as Upper Midwest and Northern Rockies and Plains. Spatially, NO_3^- predictions tend to be biased slightly low in the western and southwestern parts of the domain and biased slightly high toward the northwestern and eastern parts of the domain (Figure 7).

CAMx model performance statistics for OC by region and season for sites in the CSN and IMPROVE networks are provided in Table 22 and 23. The annual NMBs in OC predictions are relatively high for all regions at CSN and IMPROVE sites. The OC overprediction issues for CAMx are similar to those for CMAQ in the Northeast (winter, spring, and fall), Ohio Valley (winter) and Upper Midwest (winter). Spatially, OC predictions tend to be biased high across the 12US2 domain (Figure 7).

CAMx model performance statistics for EC by region and season for sites in the CSN and IMPROVE networks are provided in Table 24 and 25. The annual NMBs in EC predictions are negative in most regions at CSN and IMPROVE sites. However, the annual NMB in three of nine regions at CSN sites and four of nine regions at IMPROVE sites are within ±40%. Spatially, EC predictions tend to be biased low across the 12US2 domain (Figure 7).

4.3.2 Daily Maximum 8-hour O_3 (MDA8 O_3)

In general, the model performance statistics indicate that the MDA8 O_3 concentrations predicted by the 2022 CAMx simulation closely reflect the corresponding observed MDA8 O_3 concentrations in space and time in each subregion of the 12-km modeling domain, as indicated by the statistics in Table 26 and 27. Generally, MDA8 O_3 at the AQS and CASTNET sites during the O_3 season (spring, summer and fall) is within ±15% at all climate regions (NMB ranging from -18.1 to 14.6 percent).

MBs of MDA8 O_3 during O_3 season are within 0 – 6 ppb at most eastern U.S. sites (Figure 9); however, in most western U.S. sites, the biases are negative. NMBs of MDA8 O_3 during the O_3 season are within ±20% at most monitoring sites across the U.S. domain (Figure 10). Figure 11 shows that MDA8 O_3 was underpredicted at most AQS and CASTNET sites. Overall, MDA8 O_3 model performance of CAMx is similar to the MDA8 O_3 model performance of CMAQ in this platform.

Table 17 - CAMx Performance Statistics for $PM_{2.5}$ at AQS Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	94803	6.86	8.18	1.31	19.1	43.6	5.01	0.58
	Winter	22620	8.12	10.13	2.00	24.7	45.5	5.97	0.63
	Spring	24144	6.03	7.55	1.52	25.2	43.5	4.48	0.61
	Summer	24631	7.12	6.68	-0.44	-6.1	33.9	3.56	0.50
	Fall	23408	6.23	8.50	2.28	36.6	53.2	5.76	0.54
Southeast	All	73423	7.67	7.23	-0.44	-5.8	32.9	3.55	0.57
	Winter	17747	7.91	8.46	0.55	7.0	34.5	3.90	0.64
	Spring	18413	7.81	7.18	-0.63	-8.0	30.6	3.49	0.61
	Summer	18996	7.63	6.43	-1.19	-15.7	34.2	3.60	0.43
	Fall	18267	7.33	6.89	-0.44	-6.0	32.1	3.21	0.58
Ohio Valley	All	87586	8.24	8.16	-0.08	-1.0	30.8	3.82	0.63
	Winter	21179	8.85	9.29	0.44	5.0	32.6	4.14	0.69
	Spring	22061	7.32	7.50	0.18	2.4	28.5	2.90	0.73
	Summer	22341	8.66	7.48	-1.18	-13.6	30.7	4.14	0.38
	Fall	22005	8.15	8.42	0.28	3.4	31.2	3.96	0.68
Upper Midwest	All	50413	7.33	6.74	-0.59	-8.0	32.9	3.58	0.71
	Winter	12399	8.35	8.06	-0.29	-3.5	31.7	3.90	0.72
	Spring	12210	6.35	6.10	-0.24	-3.9	34.1	3.42	0.68
	Summer	12422	6.78	5.23	-1.55	-22.8	36.6	3.54	0.43
	Fall	13382	7.79	7.51	-0.28	-3.6	30.3	3.46	0.80
South	All	50911	8.62	6.67	-1.95	-22.6	41.4	5.39	0.38
	Winter	12261	7.40	7.15	-0.25	-3.4	38.9	4.49	0.50
	Spring	12861	9.06	7.11	-1.95	-21.5	38.2	4.98	0.50
	Summer	12952	9.54	5.12	-4.42	-46.3	53.4	7.44	0.17
	Fall	12837	8.43	7.34	-1.09	-12.9	33.2	3.89	0.56
Southwest	All	40373	6.42	4.65	-1.78	-27.6	49.3	5.16	0.38
	Winter	9912	8.01	5.62	-2.39	-29.8	55.0	7.15	0.38
	Spring	10299	5.96	5.05	-0.91	-15.3	43.5	4.28	0.32
	Summer	10111	5.89	3.27	-2.62	-44.5	52.0	4.45	0.16
	Fall	10051	5.87	4.67	-1.20	-20.5	45.0	4.21	0.47
Northern Rockies & Plains	All	25372	5.67	3.48	-2.19	-38.6	51.1	4.84	0.63
	Winter	6135	5.28	3.03	-2.25	-42.7	54.8	4.89	0.42
	Spring	6286	4.10	3.34	-0.76	-18.5	42.6	2.57	0.49
	Summer	6522	5.74	2.88	-2.86	-49.8	55.6	4.29	0.29
	Fall	6429	7.52	4.67	-2.86	-38.0	49.6	6.68	0.74
Northwest	All	52038	7.58	6.97	-0.62	-8.1	63.3	13.50	0.57
	Winter	12806	8.13	6.76	-1.36	-16.8	75.2	8.80	0.16
	Spring	13327	3.81	4.87	1.06	27.8	70.7	5.73	0.19
	Summer	13174	5.19	4.62	-0.57	-10.9	50.1	7.51	0.49
	Fall	12731	13.46	11.79	-1.67	-12.4	59.0	24.10	0.60
West	All	72477	8.00	5.79	-2.21	-27.6	46.0	6.98	0.54
	Winter	18018	9.34	6.91	-2.43	-26.0	48.2	7.22	0.58
	Spring	18145	6.93	5.66	-1.28	-18.4	40.0	4.59	0.42
	Summer	17956	7.14	4.46	-2.68	-37.5	48.2	6.90	0.50
	Fall	18358	8.58	6.12	-2.46	-28.7	46.7	8.60	0.57

Table 18 - CAMx Performance Statistics for $PM_{2.5}$ SO_4^{2-} at CSN Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	3034	0.81	0.88	0.06	7.8	38.3	0.55	0.45
	Winter	732	0.83	0.85	0.02	2.3	39.2	0.54	0.36
	Spring	781	0.76	0.95	0.18	23.9	37.9	0.46	0.60
	Summer	784	0.99	0.85	-0.14	-14.0	31.7	0.63	0.54
	Fall	737	0.67	0.86	0.20	29.3	47.9	0.56	0.44
Southeast	All	1788	0.86	0.97	0.11	12.8	38.0	0.47	0.45
	Winter	444	0.81	1.04	0.23	28.0	41.1	0.47	0.59
	Spring	451	0.91	1.02	0.11	11.7	33.6	0.44	0.46
	Summer	461	0.97	0.84	-0.12	-12.7	32.8	0.50	0.39
	Fall	432	0.76	1.00	0.24	32.1	47.1	0.48	0.53
Ohio Valley	All	2117	1.04	1.03	-0.01	-1.4	33.6	0.59	0.59
	Winter	518	1.04	1.05	0.01	0.8	40.1	0.73	0.54
	Spring	550	1.01	1.04	0.03	3.1	28.8	0.49	0.68
	Summer	547	1.25	1.06	-0.19	-15.2	32.4	0.66	0.60
	Fall	502	0.87	0.97	0.10	12.0	33.3	0.44	0.74
Upper Midwest	All	1029	0.84	0.83	-0.01	-1.3	31.9	0.47	0.66
	Winter	250	0.92	0.83	-0.08	-8.9	32.2	0.48	0.59
	Spring	265	0.84	0.91	0.07	8.3	32.9	0.50	0.72
	Summer	266	0.87	0.77	-0.10	-11.4	32.3	0.53	0.62
	Fall	248	0.73	0.80	0.07	9.5	29.7	0.36	0.74
South	All	1032	1.15	1.10	-0.04	-3.6	40.4	0.76	0.47
	Winter	254	0.94	1.06	0.12	12.3	41.0	0.55	0.74
	Spring	275	1.32	1.18	-0.15	-11.1	38.0	0.89	0.60
	Summer	256	1.34	0.92	-0.42	-31.6	40.1	0.74	0.33
	Fall	247	0.95	1.27	0.31	32.6	43.8	0.79	0.46
Southwest	All	1083	0.52	0.54	0.02	4.3	40.3	0.29	0.39
	Winter	259	0.45	0.46	0.01	1.2	51.3	0.36	0.11
	Spring	267	0.49	0.65	0.16	33.5	42.1	0.24	0.76
	Summer	276	0.68	0.50	-0.18	-26.3	34.2	0.33	0.45
	Fall	281	0.45	0.55	0.10	22.4	37.4	0.23	0.64
Northern Rockies & Plains	All	520	0.54	0.54	0.00	0.4	40.5	0.36	0.63
	Winter	130	0.50	0.45	-0.04	-9.0	47.5	0.33	0.50
	Spring	125	0.52	0.60	0.08	15.2	39.5	0.35	0.72
	Summer	134	0.60	0.52	-0.08	-13.0	36.6	0.37	0.66
	Fall	131	0.54	0.60	0.06	10.6	39.5	0.40	0.64
Northwest	All	542	0.49	0.67	0.18	37.3	58.8	0.48	0.35
	Winter	143	0.40	0.57	0.16	40.5	69.3	0.38	0.28
	Spring	149	0.41	0.64	0.24	57.8	63.1	0.32	0.60
	Summer	133	0.63	0.79	0.17	26.8	63.1	0.78	0.15
	Fall	117	0.54	0.70	0.16	28.8	39.5	0.28	0.75
West	All	1868	0.91	0.81	-0.09	-10.4	43.4	0.71	0.48
	Winter	462	0.62	0.63	0.01	2.1	61.7	0.64	0.30
	Spring	466	0.86	0.86	0.00	-0.3	41.0	0.50	0.59
	Summer	473	1.28	0.94	-0.34	-26.2	40.2	1.04	0.39
	Fall	467	0.85	0.80	-0.05	-5.8	37.7	0.51	0.60

Table 19 - CAMx Performance Statistics for $PM_{2.5}$ SO_4^{2-} at IMPROVE Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	1952	0.58	0.65	0.07	11.4	37.0	0.31	0.71
	Winter	484	0.61	0.64	0.03	5.2	34.0	0.29	0.57
	Spring	486	0.53	0.70	0.16	30.4	39.5	0.29	0.76
	Summer	487	0.73	0.64	-0.09	-11.8	32.1	0.39	0.77
	Fall	495	0.46	0.61	0.16	33.8	45.7	0.28	0.75
Southeast	All	1619	0.81	0.85	0.04	4.9	37.3	0.42	0.52
	Winter	390	0.74	0.90	0.16	22.1	43.7	0.48	0.55
	Spring	408	0.84	0.90	0.05	6.1	32.0	0.36	0.57
	Summer	416	0.95	0.76	-0.19	-20.3	33.7	0.44	0.57
	Fall	405	0.69	0.83	0.15	21.3	42.1	0.39	0.56
Ohio Valley	All	939	0.88	0.93	0.05	6.3	34.9	0.49	0.63
	Winter	222	0.76	0.94	0.19	24.5	48.7	0.66	0.56
	Spring	239	0.81	0.87	0.06	7.4	29.7	0.38	0.72
	Summer	241	1.18	1.03	-0.15	-12.9	29.7	0.48	0.72
	Fall	237	0.75	0.89	0.14	18.2	35.9	0.41	0.71
Upper Midwest	All	938	0.57	0.61	0.03	5.5	33.9	0.32	0.75
	Winter	229	0.64	0.62	-0.03	-4.0	33.0	0.33	0.66
	Spring	232	0.57	0.64	0.07	12.4	40.0	0.44	0.69
	Summer	241	0.58	0.55	-0.03	-5.0	28.7	0.25	0.88
	Fall	236	0.50	0.61	0.11	21.9	34.3	0.22	0.88
South	All	1138	0.87	0.83	-0.05	-5.3	43.8	0.61	0.45
	Winter	275	0.59	0.71	0.12	20.0	53.9	0.57	0.53
	Spring	281	0.98	0.93	-0.05	-5.6	39.2	0.67	0.59
	Summer	292	1.17	0.75	-0.42	-35.8	41.7	0.66	0.39
	Fall	290	0.74	0.92	0.18	24.8	45.5	0.52	0.51
Southwest	All	3639	0.41	0.49	0.07	17.9	51.6	0.32	0.51
	Winter	891	0.29	0.36	0.07	25.1	74.2	0.40	0.24
	Spring	897	0.41	0.60	0.19	46.6	58.2	0.32	0.63
	Summer	927	0.58	0.47	-0.11	-19.5	35.6	0.29	0.66
	Fall	924	0.36	0.51	0.15	41.3	52.9	0.28	0.73
Northern Rockies & Plains	All	1858	0.35	0.42	0.07	19.1	50.8	0.26	0.64
	Winter	446	0.31	0.34	0.03	10.5	62.7	0.28	0.67
	Spring	462	0.35	0.49	0.14	38.2	58.3	0.26	0.56
	Summer	483	0.37	0.37	-0.01	-1.4	36.6	0.22	0.61
	Fall	467	0.37	0.48	0.11	29.2	49.0	0.26	0.74
Northwest	All	1926	0.26	0.48	0.22	83.0	95.5	0.35	0.44
	Winter	445	0.16	0.34	0.19	120.0	141.0	0.27	0.39
	Spring	495	0.23	0.47	0.25	108.0	113.0	0.31	0.56
	Summer	502	0.33	0.56	0.24	71.6	88.4	0.49	0.21
	Fall	484	0.33	0.53	0.20	60.9	70.9	0.29	0.66
West	All	2231	0.45	0.53	0.08	18.3	55.2	0.34	0.48
	Winter	539	0.26	0.35	0.09	36.5	87.8	0.36	0.50
	Spring	607	0.49	0.66	0.17	34.5	54.0	0.32	0.55
	Summer	565	0.61	0.58	-0.03	-4.4	47.1	0.41	0.22
	Fall	520	0.41	0.49	0.08	20.6	48.8	0.27	0.54

Table 20 - CAMx Performance Statistics for $PM_{2.5}$ NO_3^- at CSN Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	3032	0.82	1.09	0.26	32.0	59.1	0.99	0.72
	Winter	731	1.63	1.87	0.24	14.6	43.8	1.13	0.71
	Spring	781	0.80	1.04	0.24	30.7	51.3	0.77	0.81
	Summer	783	0.30	0.32	0.01	4.1	58.8	0.30	0.38
	Fall	737	0.60	1.17	0.58	96.1	112.0	1.42	0.56
Southeast	All	1787	0.39	0.75	0.36	93.0	110.0	0.79	0.62
	Winter	444	0.73	1.47	0.74	101.0	112.0	1.24	0.52
	Spring	451	0.32	0.59	0.27	83.5	99.3	0.56	0.18
	Summer	460	0.21	0.24	0.03	14.4	57.6	0.18	0.20
	Fall	432	0.31	0.74	0.43	140.0	156.0	0.79	0.55
Ohio Valley	All	2117	1.14	1.21	0.07	5.8	51.5	1.10	0.74
	Winter	518	2.41	2.29	-0.11	-4.6	44.6	1.67	0.64
	Spring	550	0.94	0.97	0.03	2.7	47.8	0.68	0.77
	Summer	547	0.40	0.39	-0.01	-2.3	63.2	0.40	0.22
	Fall	502	0.85	1.23	0.38	44.0	70.2	1.24	0.76
Upper Midwest	All	1028	1.30	1.16	-0.14	-10.8	37.2	0.83	0.86
	Winter	250	2.54	2.10	-0.44	-17.4	31.9	1.18	0.82
	Spring	265	1.31	1.14	-0.17	-13.2	37.7	0.82	0.86
	Summer	265	0.42	0.35	-0.07	-17.6	54.1	0.39	0.42
	Fall	248	1.00	1.12	0.13	12.6	42.5	0.76	0.86
South	All	1031	0.62	0.70	0.08	12.7	62.2	0.67	0.58
	Winter	253	1.11	1.17	0.06	5.4	50.2	0.77	0.62
	Spring	275	0.60	0.60	0.00	0.1	53.2	0.54	0.57
	Summer	256	0.34	0.26	-0.07	-21.5	60.1	0.30	0.17
	Fall	247	0.45	0.79	0.34	76.6	108.0	0.93	0.43
Southwest	All	1083	1.11	0.42	-0.69	-62.1	69.5	2.05	0.68
	Winter	259	2.99	0.75	-2.24	-75.0	75.8	4.02	0.63
	Spring	267	0.53	0.41	-0.12	-22.0	53.7	0.48	0.31
	Summer	276	0.30	0.20	-0.10	-34.2	56.5	0.24	0.15
	Fall	281	0.74	0.35	-0.39	-52.3	62.2	1.01	0.71
Northern Rockies & Plains	All	519	0.60	0.40	-0.20	-33.6	54.1	0.67	0.63
	Winter	130	1.08	0.63	-0.45	-41.4	52.0	1.01	0.64
	Spring	125	0.54	0.43	-0.11	-20.1	49.7	0.48	0.69
	Summer	133	0.24	0.18	-0.05	-21.7	51.7	0.22	0.46
	Fall	131	0.57	0.36	-0.21	-36.2	63.3	0.70	0.41
Northwest	All	541	0.90	0.98	0.08	8.4	83.0	1.42	0.37
	Winter	143	1.64	1.40	-0.24	-14.7	83.0	2.26	0.10
	Spring	148	0.46	0.70	0.24	52.6	90.1	0.63	0.46
	Summer	133	0.27	0.61	0.34	124.0	140.0	0.55	0.65
	Fall	117	1.28	1.23	-0.05	-3.8	66.0	1.51	0.51
West	All	1867	1.94	0.86	-1.09	-55.9	63.7	2.51	0.62
	Winter	462	3.54	1.69	-1.85	-52.2	62.4	3.78	0.60
	Spring	465	1.35	0.69	-0.66	-49.0	56.7	1.27	0.59
	Summer	473	0.93	0.40	-0.53	-57.1	64.5	0.93	0.64
	Fall	467	1.98	0.66	-1.32	-66.7	70.6	2.91	0.54

Table 21 - CAMx Performance Statistics for $PM_{2.5}$ NO_3^- at IMPROVE Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	1953	0.35	0.63	0.28	78.2	96.7	0.64	0.70
	Winter	486	0.68	1.11	0.43	62.5	79.3	0.87	0.69
	Spring	486	0.29	0.56	0.26	90.1	104.0	0.60	0.62
	Summer	486	0.16	0.24	0.08	51.2	89.2	0.26	0.48
	Fall	495	0.28	0.61	0.33	119.0	135.0	0.66	0.62
Southeast	All	1619	0.31	0.57	0.25	81.8	106.0	0.59	0.60
	Winter	390	0.55	1.10	0.55	100.0	116.0	0.96	0.54
	Spring	408	0.29	0.47	0.18	61.0	81.6	0.38	0.33
	Summer	416	0.18	0.20	0.02	10.9	65.7	0.17	0.28
	Fall	405	0.23	0.51	0.28	125.0	147.0	0.57	0.48
Ohio Valley	All	939	0.59	0.82	0.23	37.9	71.7	0.80	0.72
	Winter	222	1.34	1.70	0.36	27.3	63.9	1.31	0.63
	Spring	239	0.42	0.58	0.16	37.4	68.1	0.45	0.60
	Summer	241	0.21	0.27	0.06	30.4	81.5	0.28	0.20
	Fall	237	0.45	0.78	0.32	71.4	92.0	0.79	0.71
Upper Midwest	All	936	0.58	0.60	0.02	2.8	49.4	0.59	0.82
	Winter	229	1.29	1.05	-0.24	-18.2	36.4	0.90	0.85
	Spring	231	0.49	0.49	0.00	0.1	53.0	0.51	0.69
	Summer	241	0.13	0.22	0.09	68.5	88.6	0.23	0.71
	Fall	235	0.44	0.65	0.20	46.4	70.7	0.55	0.83
South	All	1138	0.45	0.46	0.01	1.9	60.3	0.50	0.66
	Winter	275	0.75	0.77	0.02	2.0	50.9	0.64	0.70
	Spring	281	0.51	0.49	-0.02	-3.9	47.0	0.38	0.79
	Summer	292	0.26	0.15	-0.12	-44.4	67.5	0.25	-0.02
	Fall	290	0.30	0.46	0.16	52.5	98.3	0.63	0.49
Southwest	All	3638	0.23	0.16	-0.07	-31.7	62.7	0.37	0.55
	Winter	891	0.37	0.16	-0.21	-56.7	66.9	0.65	0.66
	Spring	897	0.22	0.29	0.06	28.9	57.2	0.19	0.50
	Summer	927	0.17	0.08	-0.09	-54.7	63.3	0.16	0.42
	Fall	923	0.15	0.10	-0.05	-34.1	60.1	0.23	0.56
Northern Rockies & Plains	All	1858	0.22	0.21	-0.01	-6.0	64.0	0.29	0.64
	Winter	446	0.33	0.27	-0.06	-18.0	61.6	0.39	0.63
	Spring	462	0.23	0.26	0.03	12.6	69.4	0.28	0.69
	Summer	482	0.10	0.10	-0.01	-7.8	60.3	0.11	0.54
	Fall	468	0.22	0.20	-0.02	-7.4	63.5	0.33	0.58
Northwest	All	1911	0.22	0.26	0.04	20.8	100.0	0.52	0.44
	Winter	440	0.34	0.34	0.00	0.8	108.0	0.77	0.30
	Spring	489	0.14	0.26	0.12	82.4	116.0	0.27	0.57
	Summer	498	0.10	0.15	0.05	53.2	100.0	0.22	0.64
	Fall	484	0.30	0.30	0.00	1.2	84.6	0.65	0.52
West	All	2230	0.45	0.26	-0.19	-41.4	66.5	0.88	0.77
	Winter	538	0.63	0.38	-0.25	-39.9	62.4	1.21	0.86
	Spring	607	0.44	0.35	-0.09	-19.8	57.8	0.46	0.54
	Summer	565	0.25	0.11	-0.14	-57.1	73.5	0.28	0.22
	Fall	520	0.48	0.20	-0.28	-57.5	77.2	1.21	0.69

Table 22 - CAMx Performance Statistics for $PM_{2.5}$ OC at CSN Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	2951	1.61	2.70	1.10	68.2	81.2	2.25	0.38
	Winter	707	1.30	2.96	1.65	127.0	131.0	2.72	0.42
	Spring	760	1.35	2.55	1.19	88.3	96.0	2.15	0.50
	Summer	781	2.18	2.53	0.35	16.0	41.0	1.42	0.46
	Fall	703	1.56	2.82	1.26	80.9	87.7	2.57	0.40
Southeast	All	1724	2.25	2.78	0.53	23.6	48.5	1.59	0.51
	Winter	427	2.09	2.81	0.72	34.4	56.2	1.82	0.61
	Spring	423	2.29	2.81	0.52	22.8	47.5	1.63	0.55
	Summer	445	2.21	2.88	0.68	30.6	48.3	1.44	0.41
	Fall	429	2.42	2.63	0.21	8.5	43.1	1.43	0.44
Ohio Valley	All	2116	1.90	2.23	0.34	17.6	40.1	1.08	0.62
	Winter	535	1.49	2.36	0.87	58.7	66.3	1.38	0.59
	Spring	549	1.75	2.16	0.41	23.4	38.5	0.97	0.76
	Summer	525	2.37	2.28	-0.09	-3.9	30.2	0.91	0.56
	Fall	507	2.01	2.14	0.13	6.4	33.2	0.99	0.70
Upper Midwest	All	1162	1.61	2.08	0.46	28.7	57.4	1.46	0.42
	Winter	289	1.25	2.71	1.46	117.0	118.0	2.17	0.59
	Spring	288	1.27	1.81	0.54	42.8	60.9	1.21	0.56
	Summer	303	1.98	1.69	-0.29	-14.5	34.4	0.88	0.40
	Fall	282	1.95	2.12	0.16	8.4	40.3	1.28	0.60
South	All	936	2.18	2.10	-0.09	-4.0	42.1	2.70	0.28
	Winter	223	1.96	2.25	0.29	14.8	47.6	1.51	0.46
	Spring	233	1.81	1.83	0.02	1.1	39.6	1.11	0.68
	Summer	250	1.89	1.81	-0.09	-4.5	42.5	1.19	0.46
	Fall	230	3.10	2.54	-0.56	-18.1	40.0	4.96	0.20
Southwest	All	1110	1.68	1.73	0.06	3.5	51.9	1.41	0.40
	Winter	282	2.36	2.66	0.30	12.8	64.5	2.19	0.23
	Spring	280	1.14	1.26	0.12	10.5	50.7	0.90	0.37
	Summer	276	1.40	1.12	-0.28	-20.1	39.2	0.71	0.34
	Fall	272	1.81	1.90	0.09	4.9	45.5	1.33	0.36
Northern Rockies & Plains	All	488	1.46	0.88	-0.58	-39.9	54.9	1.83	0.73
	Winter	116	1.12	0.73	-0.39	-35.2	71.4	2.04	0.16
	Spring	113	0.68	0.52	-0.16	-23.4	48.0	0.51	0.59
	Summer	129	1.61	0.74	-0.87	-54.2	57.4	1.19	0.36
	Fall	130	2.29	1.46	-0.83	-36.2	47.7	2.69	0.85
Northwest	All	530	2.21	3.62	1.42	64.2	94.6	3.26	0.50
	Winter	143	1.92	4.19	2.27	119.0	131.0	3.10	0.51
	Spring	148	1.13	3.20	2.07	183.0	188.0	2.78	0.57
	Summer	134	1.67	2.50	0.83	49.6	71.9	1.51	0.51
	Fall	105	4.80	4.88	0.08	1.6	54.1	5.18	0.55
West	All	1232	2.75	2.46	-0.28	-10.3	40.4	2.51	0.52
	Winter	309	3.78	3.77	-0.01	-0.3	42.8	2.24	0.57
	Spring	306	1.81	1.72	-0.09	-5.2	38.0	0.95	0.54
	Summer	312	1.95	1.45	-0.50	-25.6	37.2	1.05	0.38
	Fall	305	3.46	2.93	-0.53	-15.3	40.9	4.29	0.50

Table 23 - CAMx Performance Statistics for $PM_{2.5}$ OC at IMPROVE Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	1830	0.86	1.48	0.62	72.5	87.8	2.55	0.34
	Winter	458	0.67	1.66	0.99	149.0	151.0	1.44	0.76
	Spring	451	0.65	1.52	0.87	133.0	141.0	4.79	0.30
	Summer	458	1.26	1.29	0.03	2.4	33.2	0.60	0.74
	Fall	463	0.84	1.43	0.59	70.9	78.7	0.99	0.80
Southeast	All	1727	1.31	1.71	0.39	30.0	52.4	1.68	0.59
	Winter	420	1.24	1.86	0.63	50.6	68.3	2.04	0.61
	Spring	437	1.35	1.82	0.47	34.5	55.8	2.38	0.51
	Summer	438	1.31	1.71	0.40	30.4	50.7	1.00	0.73
	Fall	432	1.34	1.43	0.09	6.5	36.3	0.72	0.78
Ohio Valley	All	930	1.23	1.67	0.44	36.0	46.4	0.99	0.71
	Winter	221	0.92	1.48	0.56	60.8	62.9	0.99	0.72
	Spring	236	1.19	1.70	0.52	43.3	51.5	1.33	0.82
	Summer	236	1.50	1.97	0.47	31.6	41.5	0.87	0.62
	Fall	237	1.29	1.52	0.23	17.7	36.3	0.67	0.73
Upper Midwest	All	1036	0.89	0.99	0.10	11.5	43.3	0.62	0.71
	Winter	253	0.63	1.05	0.42	66.8	73.1	0.76	0.87
	Spring	253	0.64	0.81	0.17	25.9	48.2	0.53	0.81
	Summer	266	1.23	0.99	-0.24	-19.3	34.3	0.56	0.53
	Fall	264	1.02	1.10	0.08	7.5	33.8	0.60	0.78
South	All	1142	1.08	1.14	0.06	5.2	45.0	1.03	0.69
	Winter	274	0.75	0.97	0.22	29.7	55.4	1.04	0.67
	Spring	290	1.23	1.42	0.19	15.3	52.9	1.51	0.79
	Summer	293	1.18	1.01	-0.17	-14.5	39.6	0.69	0.57
	Fall	285	1.16	1.16	0.00	-0.1	35.8	0.62	0.71
Southwest	All	3637	0.66	0.43	-0.23	-35.4	50.5	0.70	0.67
	Winter	886	0.67	0.44	-0.23	-34.3	56.1	1.03	0.66
	Spring	894	0.58	0.42	-0.17	-28.4	50.8	0.65	0.77
	Summer	932	0.74	0.39	-0.35	-47.0	52.0	0.52	0.68
	Fall	925	0.65	0.46	-0.19	-29.2	43.2	0.48	0.72
Northern Rockies & Plains	All	1935	1.06	0.73	-0.33	-31.5	58.4	3.26	0.50
	Winter	462	0.31	0.36	0.05	15.1	69.8	0.75	0.25
	Spring	474	0.34	0.32	-0.02	-7.2	67.3	0.76	0.24
	Summer	504	1.16	0.61	-0.55	-47.6	62.5	1.36	0.29
	Fall	495	2.36	1.59	-0.77	-32.5	53.7	6.22	0.51
Northwest	All	1877	1.39	1.43	0.04	3.2	69.7	3.12	0.72
	Winter	430	0.51	0.80	0.29	56.8	120.0	1.39	0.43
	Spring	470	0.33	0.54	0.20	60.2	109.0	0.94	0.62
	Summer	500	1.09	0.96	-0.13	-12.2	56.4	1.07	0.56
	Fall	477	3.52	3.38	-0.15	-4.1	63.8	5.87	0.71
West	All	2185	1.02	0.77	-0.25	-24.2	58.3	2.31	0.48
	Winter	526	0.74	0.55	-0.19	-26.0	55.1	0.77	0.76
	Spring	584	0.68	0.41	-0.27	-39.6	49.1	0.52	0.63
	Summer	552	1.30	1.02	-0.28	-21.5	68.9	3.80	0.40
	Fall	523	1.38	1.14	-0.24	-17.4	54.7	2.49	0.69

Table 24 - CAMx Performance Statistics for $PM_{2.5}$ EC at CSN Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	2952	0.58	0.40	-0.17	-30.1	45.6	0.45	0.44
	Winter	707	0.60	0.49	-0.11	-18.6	41.9	0.48	0.46
	Spring	761	0.53	0.38	-0.15	-28.7	42.9	0.43	0.51
	Summer	781	0.57	0.31	-0.26	-45.2	50.9	0.43	0.32
	Fall	703	0.62	0.45	-0.17	-27.3	46.4	0.46	0.45
Southeast	All	1725	0.76	0.34	-0.41	-54.4	61.1	0.70	0.36
	Winter	428	0.85	0.40	-0.44	-52.3	58.4	0.76	0.42
	Spring	423	0.77	0.34	-0.43	-55.9	60.8	0.70	0.45
	Summer	445	0.56	0.28	-0.28	-50.1	59.6	0.52	0.05
	Fall	429	0.85	0.36	-0.49	-58.1	65.1	0.79	0.28
Ohio Valley	All	2116	0.70	0.33	-0.36	-52.1	54.4	0.52	0.53
	Winter	535	0.64	0.40	-0.24	-37.4	44.0	0.45	0.46
	Spring	549	0.68	0.31	-0.37	-54.1	55.8	0.54	0.62
	Summer	525	0.71	0.28	-0.43	-61.0	61.4	0.56	0.40
	Fall	507	0.76	0.34	-0.42	-54.7	55.2	0.53	0.74
Upper Midwest	All	1164	0.50	0.32	-0.18	-36.2	49.2	0.35	0.49
	Winter	290	0.46	0.43	-0.03	-6.4	42.4	0.30	0.49
	Spring	289	0.40	0.28	-0.12	-29.3	44.7	0.24	0.57
	Summer	303	0.49	0.23	-0.27	-53.8	56.1	0.35	0.38
	Fall	282	0.64	0.33	-0.31	-48.2	51.6	0.46	0.64
South	All	936	0.68	0.37	-0.31	-45.4	50.7	1.30	0.24
	Winter	223	0.84	0.46	-0.38	-45.4	48.7	0.61	0.67
	Spring	233	0.52	0.31	-0.21	-40.9	43.3	0.34	0.72
	Summer	250	0.41	0.28	-0.12	-29.9	49.6	0.28	0.42
	Fall	230	0.98	0.44	-0.54	-54.7	56.9	2.51	0.08
Southwest	All	1110	0.63	0.34	-0.30	-46.8	52.2	0.60	0.57
	Winter	282	1.13	0.50	-0.63	-55.7	59.8	1.03	0.38
	Spring	280	0.36	0.26	-0.10	-27.0	39.6	0.22	0.62
	Summer	276	0.33	0.22	-0.11	-32.6	40.1	0.18	0.54
	Fall	272	0.71	0.36	-0.35	-49.1	52.0	0.53	0.49
Northern Rockies & Plains	All	488	0.40	0.15	-0.26	-63.6	67.5	0.70	0.33
	Winter	116	0.49	0.14	-0.35	-70.6	76.9	1.15	0.06
	Spring	113	0.20	0.11	-0.10	-46.8	53.6	0.20	0.46
	Summer	129	0.35	0.10	-0.24	-70.0	70.0	0.31	0.25
	Fall	130	0.55	0.22	-0.33	-59.4	62.8	0.73	0.54
Northwest	All	530	0.71	0.57	-0.14	-19.8	50.4	0.63	0.53
	Winter	143	0.86	0.62	-0.24	-28.1	47.4	0.58	0.55
	Spring	148	0.47	0.50	0.03	7.4	58.1	0.39	0.46
	Summer	134	0.47	0.48	0.01	1.8	47.2	0.28	0.58
	Fall	105	1.15	0.72	-0.44	-38.0	50.6	1.10	0.52
West	All	1232	0.98	0.40	-0.57	-58.7	60.1	0.95	0.73
	Winter	309	1.68	0.60	-1.08	-64.3	65.0	1.39	0.64
	Spring	306	0.61	0.31	-0.30	-48.9	52.2	0.45	0.67
	Summer	312	0.49	0.25	-0.23	-47.7	50.0	0.38	0.41
	Fall	305	1.14	0.45	-0.69	-60.3	61.4	1.16	0.67

Table 25 - CAMx Performance Statistics for $PM_{2.5}$ EC at IMPROVE Sites in 2022

Region	Season	N	AvgObs (µg m-3)	AvgMod (µg m-3)	MB	NMB	NME	RMSE	r
Northeast	All	1823	0.18	0.19	0.00	0.8	42.4	0.12	0.73
	Winter	455	0.19	0.24	0.05	29.3	49.1	0.14	0.76
	Spring	449	0.15	0.18	0.03	16.7	45.9	0.14	0.70
	Summer	458	0.20	0.13	-0.07	-36.9	40.9	0.11	0.79
	Fall	461	0.20	0.20	0.00	-0.1	35.0	0.11	0.84
Southeast	All	1724	0.29	0.17	-0.12	-41.1	48.3	0.25	0.77
	Winter	420	0.32	0.22	-0.10	-30.8	42.0	0.21	0.80
	Spring	437	0.30	0.18	-0.12	-40.4	49.2	0.30	0.72
	Summer	435	0.23	0.12	-0.11	-45.9	51.5	0.19	0.75
	Fall	432	0.32	0.16	-0.15	-48.3	51.4	0.27	0.82
Ohio Valley	All	930	0.25	0.16	-0.09	-36.0	41.6	0.14	0.70
	Winter	221	0.24	0.19	-0.05	-19.7	32.9	0.11	0.69
	Spring	236	0.24	0.16	-0.08	-33.1	38.6	0.12	0.79
	Summer	236	0.24	0.12	-0.12	-50.7	52.2	0.15	0.67
	Fall	237	0.28	0.17	-0.11	-39.3	42.3	0.16	0.76
Upper Midwest	All	1033	0.20	0.12	-0.07	-37.8	47.1	0.15	0.75
	Winter	252	0.18	0.16	-0.02	-8.7	33.3	0.08	0.86
	Spring	253	0.16	0.11	-0.05	-30.4	42.3	0.11	0.80
	Summer	266	0.21	0.08	-0.12	-59.4	60.3	0.17	0.78
	Fall	262	0.25	0.14	-0.11	-43.7	48.3	0.19	0.79
South	All	1135	0.20	0.12	-0.08	-40.5	50.5	0.20	0.48
	Winter	274	0.19	0.12	-0.07	-36.9	42.1	0.12	0.77
	Spring	290	0.22	0.16	-0.06	-25.6	52.5	0.26	0.62
	Summer	286	0.16	0.07	-0.08	-53.8	56.2	0.12	0.48
	Fall	285	0.23	0.12	-0.11	-48.4	51.3	0.25	0.36
Southwest	All	3606	0.16	0.08	-0.08	-51.3	59.6	0.28	0.65
	Winter	876	0.24	0.09	-0.15	-63.7	67.2	0.48	0.73
	Spring	878	0.12	0.09	-0.03	-24.9	50.8	0.14	0.72
	Summer	928	0.11	0.06	-0.05	-48.3	55.6	0.09	0.70
	Fall	924	0.17	0.08	-0.09	-54.6	58.1	0.23	0.69
Northern Rockies & Plains	All	1913	0.14	0.10	-0.04	-26.0	60.0	0.27	0.53
	Winter	450	0.07	0.06	-0.02	-20.4	61.6	0.14	0.21
	Spring	470	0.06	0.06	0.00	-4.6	63.6	0.13	0.18
	Summer	498	0.13	0.07	-0.06	-46.2	67.9	0.19	0.18
	Fall	495	0.27	0.21	-0.06	-22.8	55.0	0.47	0.56
Northwest	All	1855	0.20	0.17	-0.03	-15.1	61.8	0.68	0.50
	Winter	415	0.13	0.12	-0.01	-7.3	69.4	0.16	0.68
	Spring	472	0.07	0.09	0.02	24.1	72.3	0.14	0.58
	Summer	494	0.14	0.12	-0.02	-15.0	55.2	0.13	0.71
	Fall	474	0.44	0.34	-0.11	-23.7	60.2	1.31	0.48
West	All	2145	0.17	0.10	-0.07	-42.3	58.9	0.29	0.71
	Winter	512	0.20	0.09	-0.11	-55.4	66.6	0.30	0.77
	Spring	573	0.10	0.08	-0.02	-23.6	46.4	0.09	0.69
	Summer	537	0.16	0.10	-0.06	-37.6	56.5	0.27	0.64
	Fall	523	0.24	0.13	-0.10	-44.1	60.3	0.40	0.77

Table 26 - CAMx Performance Statistics MDA8 O_3 at AQS Sites in 2022

Region	Season	N	AvgObs (ppb)	AvgMod (ppb)	MB	NMB	NME	RMSE	r
Northeast	All	52703	39.8	40.6	0.8	2.1	12.3	6.25	0.82
	Winter	7926	33.9	30.1	-3.8	-11.3	14.3	5.95	0.77
	Spring	16165	42.5	41.5	-1.0	-2.4	10.3	5.54	0.74
	Summer	16222	44.8	48.2	3.4	7.6	11.9	6.88	0.84
	Fall	12390	33.5	36.3	2.8	8.4	15.3	6.46	0.78
Southeast	All	48275	39.4	41.3	1.9	4.8	13.2	6.70	0.79
	Winter	6842	36.7	34.8	-1.9	-5.1	12.1	5.40	0.77
	Spring	15220	43.9	43.4	-0.6	-1.3	9.8	5.52	0.82
	Summer	14520	37.9	42.7	4.9	12.9	17.6	8.37	0.81
	Fall	11693	37.2	40.7	3.5	9.5	13.6	6.46	0.82
Ohio Valley	All	60934	41.6	43.2	1.7	4.0	12.2	6.55	0.82
	Winter	5499	30.9	29.2	-1.7	-5.6	12.0	4.76	0.85
	Spring	20427	42.7	42.7	0.0	-0.1	10.0	5.62	0.76
	Summer	20107	46.4	50.2	3.8	8.1	13.3	7.74	0.76
	Fall	14901	37.4	39.9	2.5	6.6	13.8	6.55	0.80
Upper Midwest	All	24294	40.2	40.0	-0.2	-0.5	11.3	5.83	0.81
	Winter	1492	33.3	29.8	-3.5	-10.4	13.0	5.13	0.82
	Spring	8201	42.0	40.3	-1.7	-4.1	9.5	5.09	0.80
	Summer	8620	43.4	44.1	0.7	1.7	11.4	6.34	0.80
	Fall	5981	34.8	36.2	1.4	4.0	13.9	6.17	0.79
South	All	45543	40.5	40.0	-0.6	-1.4	14.0	7.27	0.81
	Winter	9623	33.7	30.8	-2.9	-8.5	14.4	6.03	0.83
	Spring	12336	44.2	43.3	-1.0	-2.2	12.5	7.11	0.74
	Summer	12064	41.3	42.6	1.3	3.2	16.7	8.65	0.78
	Fall	11520	41.5	41.3	-0.2	-0.5	12.8	6.80	0.84
Southwest	All	46026	48.0	45.3	-2.7	-5.6	12.1	7.49	0.77
	Winter	10447	39.2	34.4	-4.9	-12.4	16.1	7.98	0.65
	Spring	11922	51.1	48.7	-2.3	-4.6	10.6	6.93	0.61
	Summer	12266	55.8	52.9	-2.9	-5.2	12.0	8.74	0.52
	Fall	11391	44.3	43.4	-0.8	-1.9	10.7	6.01	0.76
Northern Rockies & Plains	All	16891	42.1	39.2	-2.9	-6.8	12.6	6.65	0.75
	Winter	4042	38.0	32.0	-6.0	-15.7	17.2	7.68	0.71
	Spring	4278	44.6	41.6	-3.0	-6.7	10.3	5.87	0.66
	Summer	4335	47.1	45.9	-1.1	-2.4	11.9	7.06	0.64
	Fall	4236	38.3	36.8	-1.5	-3.9	12.0	5.87	0.75
Northwest	All	6337	37.7	37.7	0.1	0.2	14.0	6.92	0.77
	Winter	803	32.3	29.1	-3.2	-9.8	20.6	8.06	0.71
	Spring	1672	39.1	39.0	-0.1	-0.1	11.4	5.75	0.62
	Summer	2521	39.1	39.6	0.5	1.3	13.5	7.11	0.81
	Fall	1341	36.5	37.9	1.4	3.7	15.1	7.15	0.76
West	All	60629	44.5	42.7	-1.8	-4.1	13.3	7.74	0.82
	Winter	13437	34.9	34.0	-0.9	-2.7	16.5	7.26	0.60
	Spring	15970	47.4	45.2	-2.2	-4.6	10.9	6.75	0.74
	Summer	16392	49.8	47.2	-2.6	-5.3	14.0	9.05	0.83
	Fall	14830	44.2	42.8	-1.4	-3.1	12.8	7.58	0.79

Table 27 - CAMx Performance Statistics for MDA8 O_3 at CASTNET Sites in 2022

Region	Season	N	AvgObs (ppb)	AvgMod (ppb)	MB	NMB	NME	RMSE	r
Northeast	All	4265	39.9	39.2	-0.7	-1.9	12.0	5.99	0.80
	Winter	1113	35.4	30.8	-4.6	-12.9	14.6	5.99	0.79
	Spring	1183	43.9	41.7	-2.2	-5.0	9.9	5.31	0.77
	Summer	978	45.1	48.3	3.2	7.1	11.8	6.95	0.79
	Fall	991	35.1	36.4	1.4	4.0	12.5	5.73	0.77
Southeast	All	4006	39.7	40.1	0.4	1.0	13.7	6.93	0.72
	Winter	982	37.1	33.1	-4.1	-10.9	15.6	6.84	0.75
	Spring	1067	45.4	43.6	-1.8	-4.0	10.2	5.81	0.77
	Summer	971	38.1	43.6	5.6	14.6	17.9	8.72	0.78
	Fall	986	37.7	39.8	2.1	5.5	12.1	6.09	0.75
Ohio Valley	All	5596	40.1	40.5	0.3	0.9	12.2	6.27	0.80
	Winter	1407	33.7	30.8	-2.9	-8.6	13.2	5.50	0.83
	Spring	1550	44.5	43.5	-1.0	-2.2	9.5	5.45	0.75
	Summer	1307	44.6	48.8	4.2	9.5	14.6	8.03	0.73
	Fall	1332	37.3	38.8	1.5	3.9	12.4	5.97	0.79
Upper Midwest	All	1765	38.1	36.8	-1.3	-3.4	11.7	5.60	0.82
	Winter	436	34.7	30.6	-4.0	-11.6	13.0	5.17	0.86
	Spring	454	42.9	40.1	-2.8	-6.5	9.6	5.17	0.81
	Summer	442	40.9	42.1	1.2	2.9	11.5	6.12	0.84
	Fall	433	33.9	34.3	0.4	1.3	13.2	5.88	0.77
South	All	2034	41.4	40.3	-1.1	-2.6	14.6	7.48	0.73
	Winter	517	36.0	32.3	-3.7	-10.3	15.4	6.60	0.83
	Spring	536	45.9	44.5	-1.4	-3.1	12.2	6.95	0.69
	Summer	501	42.3	44.3	2.0	4.8	18.4	9.49	0.64
	Fall	480	41.1	40.0	-1.1	-2.7	12.6	6.48	0.77
Southwest	All	4235	48.8	45.4	-3.4	-7.0	11.8	7.19	0.72
	Winter	1060	43.7	36.5	-7.2	-16.5	17.2	8.79	0.56
	Spring	1075	52.3	48.8	-3.5	-6.7	10.9	7.03	0.56
	Summer	1056	54.3	52.2	-2.1	-3.9	10.0	6.96	0.53
	Fall	1044	44.7	43.8	-0.8	-1.9	9.9	5.59	0.71
Northern Rockies & Plains	All	2476	44.2	41.7	-2.5	-5.6	13.4	7.24	0.68
	Winter	609	40.8	33.4	-7.4	-18.1	19.8	9.04	0.72
	Spring	634	47.1	42.8	-4.3	-9.2	11.0	6.49	0.65
	Summer	624	47.8	49.9	2.0	4.3	11.3	6.69	0.66
	Fall	609	40.8	40.5	-0.4	-0.9	12.3	6.48	0.69
Northwest	All	1050	40.3	39.0	-1.3	-3.3	12.1	6.17	0.72
	Winter	256	36.6	31.8	-4.8	-13.2	19.8	8.24	0.47
	Spring	268	42.4	40.5	-1.9	-4.4	9.7	5.21	0.68
	Summer	267	44.0	44.4	0.4	0.9	9.1	5.13	0.81
	Fall	259	38.2	39.1	0.9	2.4	11.4	5.68	0.75
West	All	2443	49.4	44.2	-5.2	-10.6	13.5	8.52	0.77
	Winter	597	41.7	36.6	-5.0	-12.1	15.5	7.45	0.53
	Spring	607	50.9	45.7	-5.2	-10.2	11.9	7.37	0.77
	Summer	630	56.7	50.3	-6.4	-11.3	14.5	10.70	0.66
	Fall	609	48.1	43.8	-4.3	-8.9	12.2	8.00	0.71

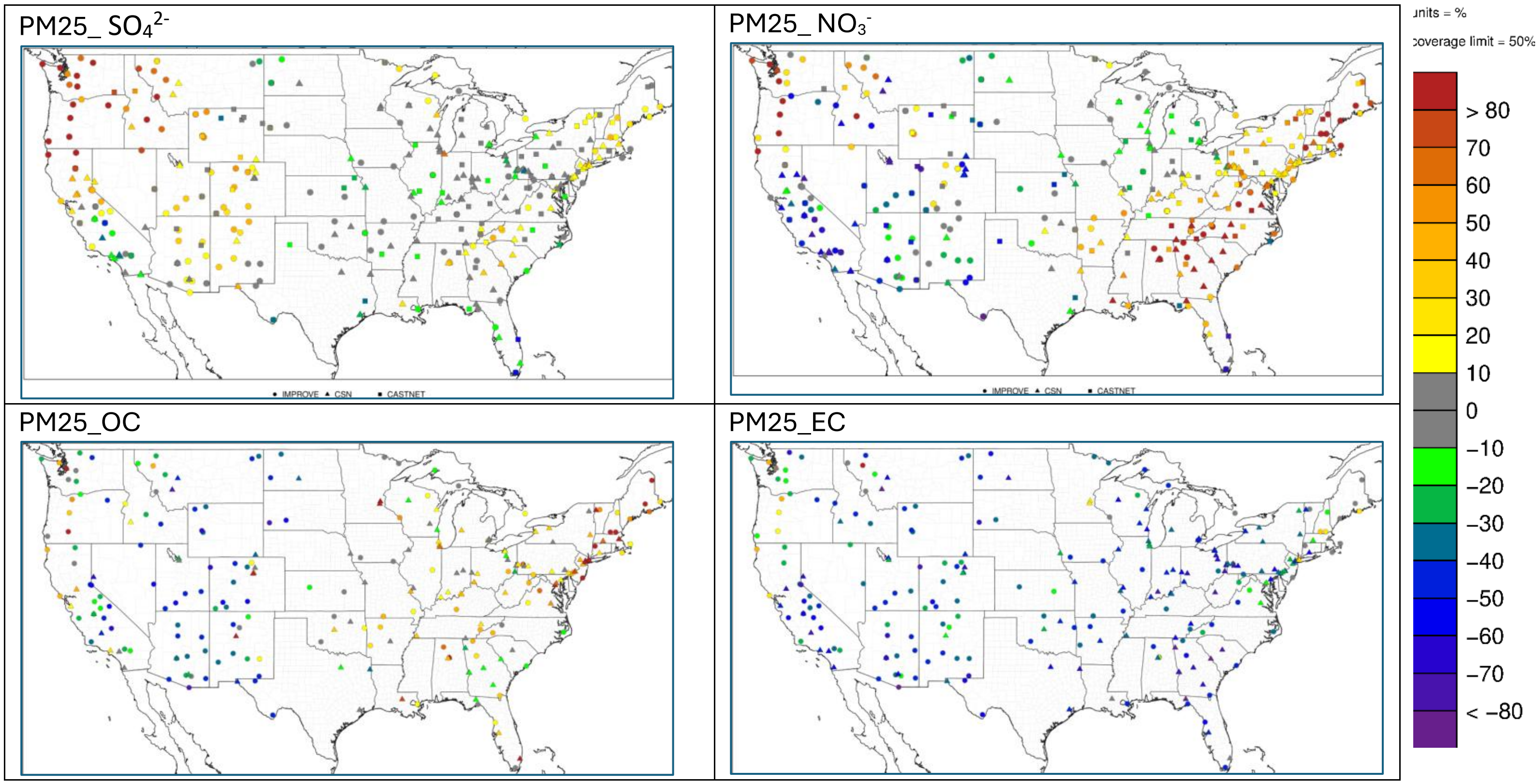

Figure 8 - NMB in 2022 CAMx Predictions of $PM_{2.5}$ Components at CSN and IMPROVE Sites

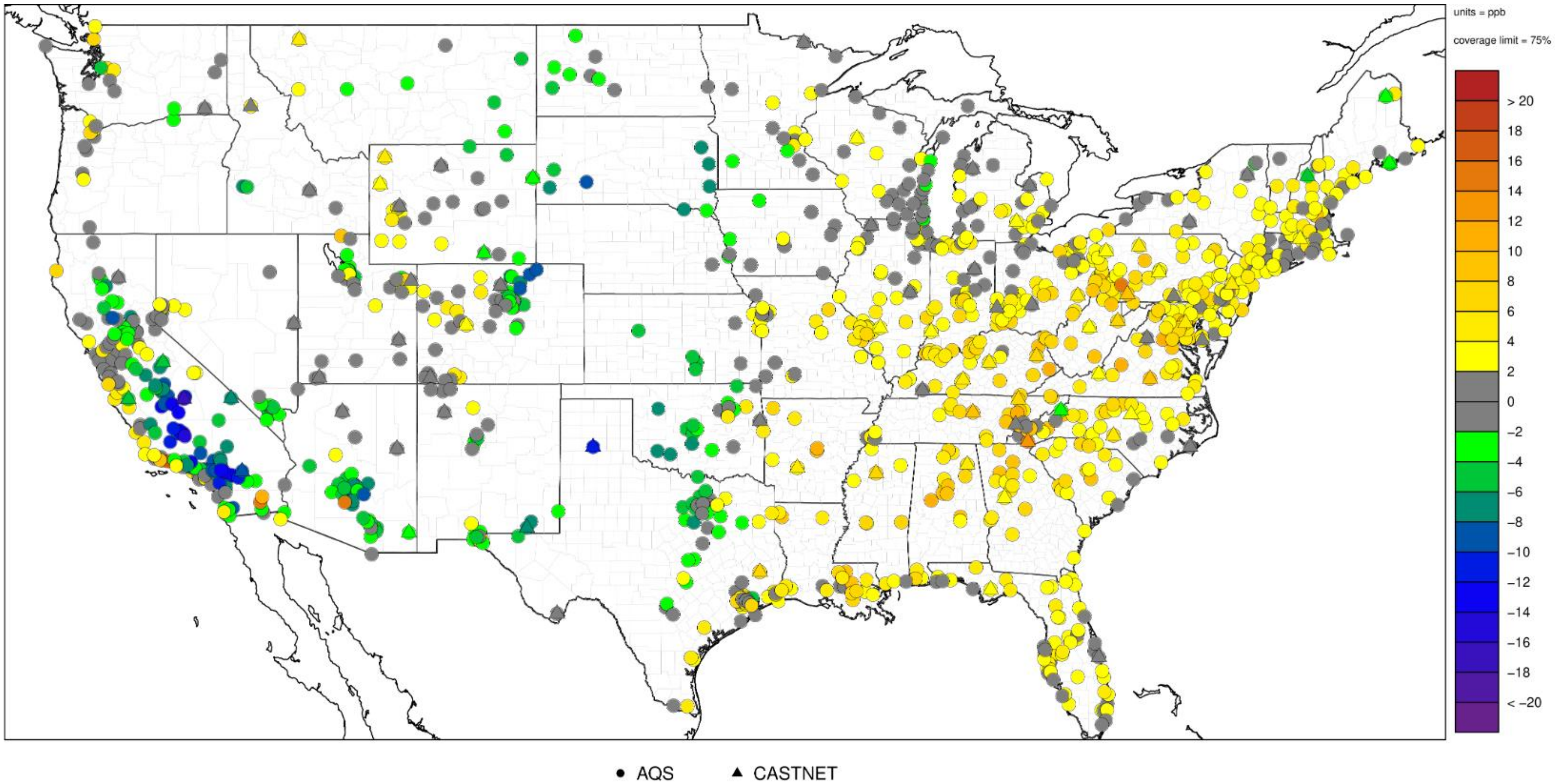

Figure 9 - MB in 2022 CAMx Predictions of MDA8 O_3 at AQS and CASTNET sites during O_3 season (05/01/2022-09/30/2022)

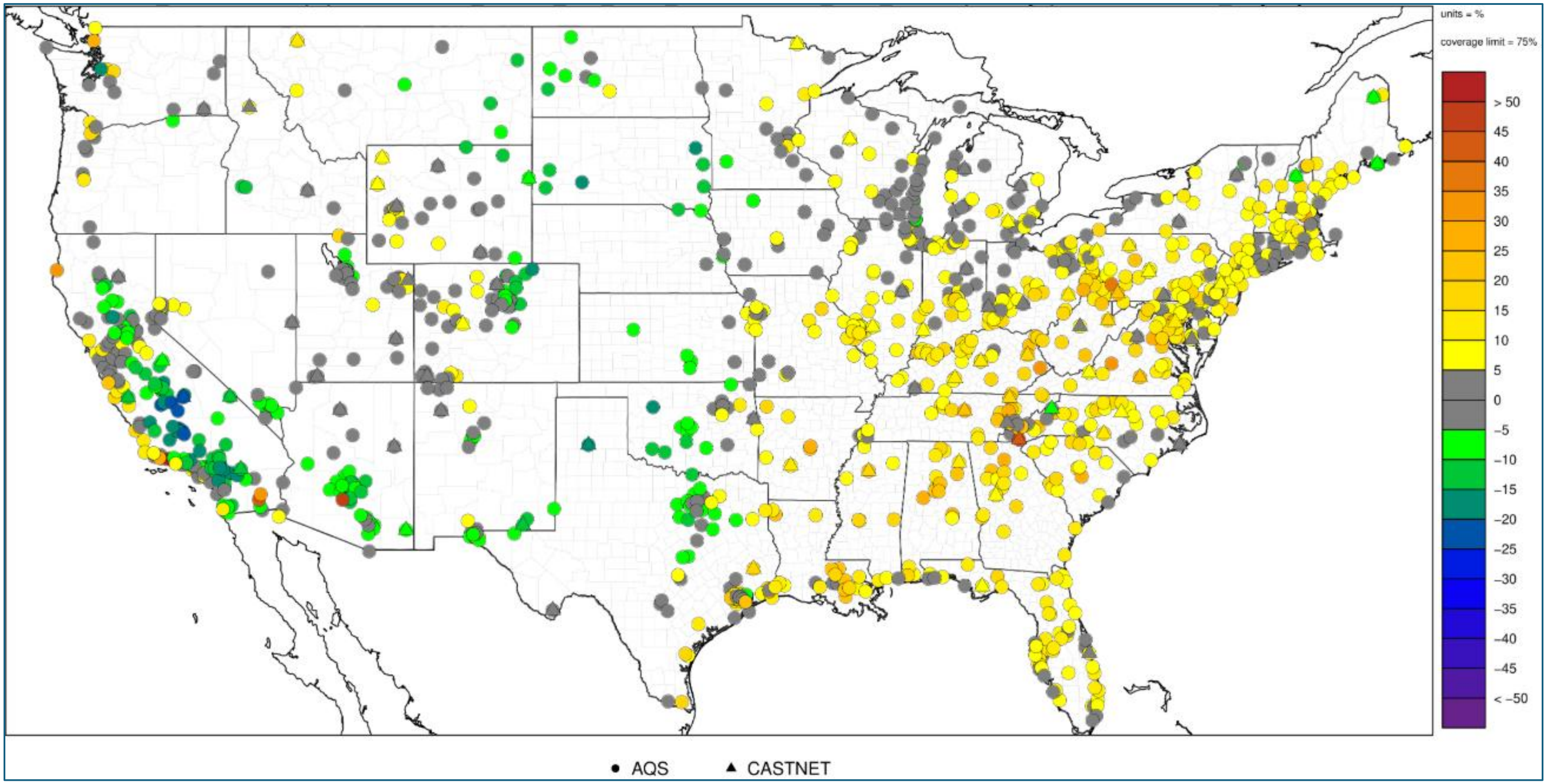

Figure 10 - NMB in 2022 CAMx Predictions of MDA8 O_3 at AQS and CASTNET sites during O_3 season (05/01/2022-09/30/2022)

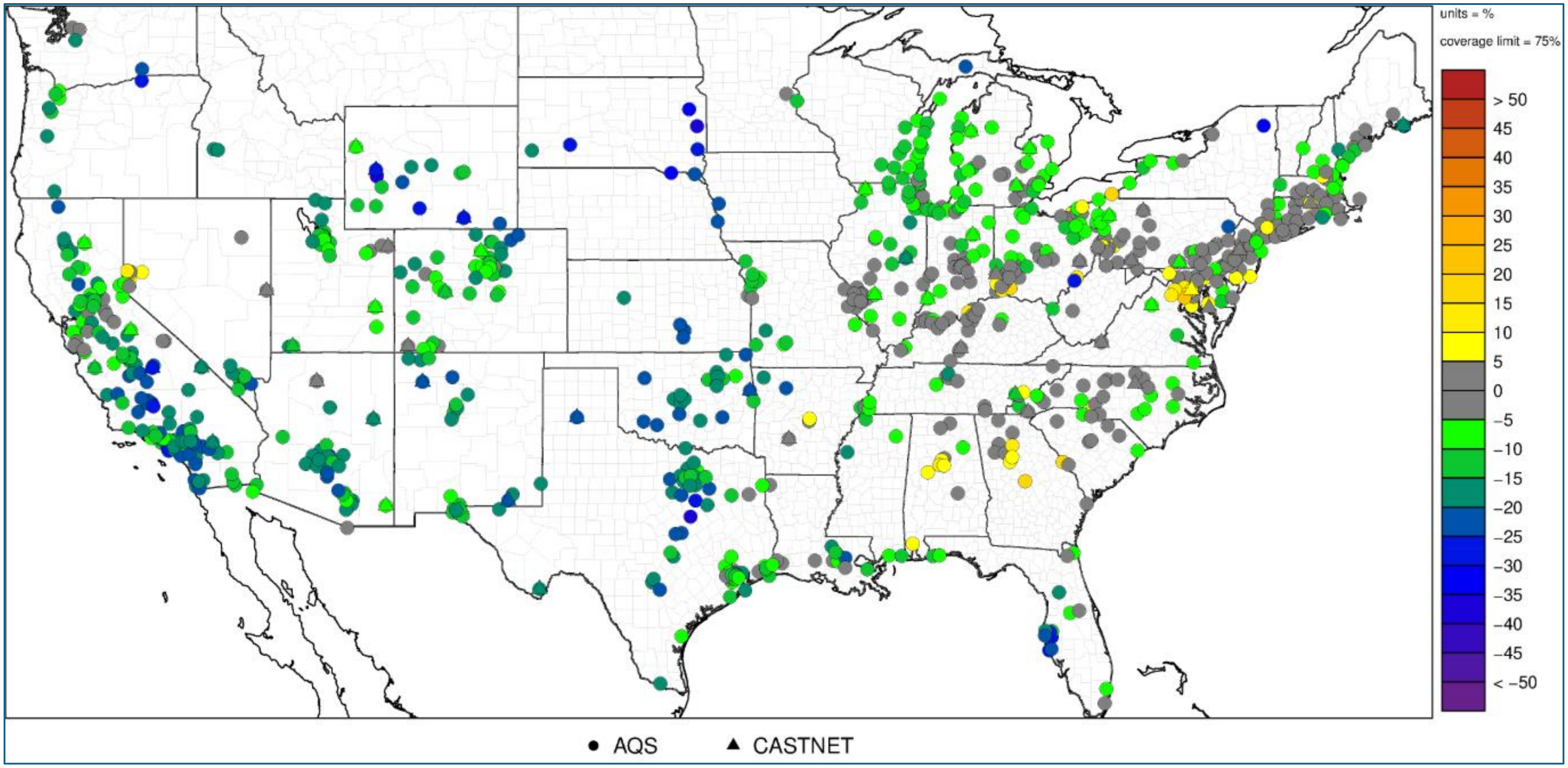

Figure 11 - NMB in 2022 CAMx predictions of MDA8 O3 at AQS and CASTNET sites when observation MDA8 O_3 > 65 ppb during O_3 season (05/01/2022-09/30/2022)

4.4 Comparison Between 2022v1 and 2022v2

Overall, the overestimation of MDA8hr O_3 in winter and early spring in 2022v1 CMAQ base simulation (NMB: 10 to 20%) is significantly improved in 2022v2 CMAQ base simulation (NMB: -5 to 5%) because of the boundary conditions updates (see section 2.4.2). However, the high O_3 events (MDA8hr O_3 > 65 ppb) were underpredicted by CMAQ in both the 2022v1 and 2022v2 platforms. Using updated boundary conditions increases ozone and improves the bias (negative) of O_3 in winter for CAMx, and the CAMx O_3 performances is similar in other seasons between 2022v1 and 2022v2. Similar to CMAQ, CAMx also underestimates O_3 during high O_3 events (MDA8hr O_3 > 65ppb). However, sites with lower NMBs (gray color with abs(NMB) < 5%) were more common in the CAMx simulation than the CMAQ simulation. CMAQ and CAMx total $PM_{2.5}$ and individual $PM_{2.5}$ species performance is similar between 2022v1 and 2022v2.

5 Discussion

As described above, the model performance statistics for 2022v2 platform are generally within the range of those reported in previous applications[31] [32] and suggest that the simulations are suitable for use in national-scale applications. Detailed CMAQ and CAMx site comparison files are available on Amazon Web Services (AWS, https://registry.opendata.aws/epa-2022-modeling-platform/). In this section, we discuss the implications of results from key sensitivity simulations using alternative model options or inputs.

5.1 Boundary Conditions of 12US2 Prepared from Two Different Processes

In the base CMAQ and CAMx simulations, outputs from the 36US3 CMAQ run were used to generate BCs for the 12US2 domain, a choice that balances higher resolution over the U.S. and adjacent areas of Canada and Mexico with model runtime. We also conducted a CMAQ sensitivity run in which 12US2 BCs were taken directly from a hemispheric CMAQ simulation. Relative to the base run, MDA8 O_3 bias differences range from -5 to +5 ppb (mostly < 2 ppb), with an overall increase in the Northeast when hemispheric BCs are used directly. $PM_{2.5}$ bias

[31] https://doi.org/10.1016/j.atmosenv.2012.07.012

[32] https://doi.org/10.1016/j.atmosenv.2019.116872

differences range from -2 to +2 μg/m^3 (mostly <0.5 μg/m^3), with mixed changes in performance. Overall, both MDA8 O_3 and $PM_{2.5}$ performance with hemispheric BCs are broadly consistent with the base run. The absence of significant Canadian wildfires in 2022 likely contributed to the small differences between the two BC approaches, since large wildfires lead to extreme ambient concentrations that are challenging to replicate with air quality models.

5.2 Continental pNO_3^- Photolysis Scheme

Recently, the particle NO_3^- photolysis parameterization has been added to a copy of CMAQ version 5.5.[33] In the 2022 platform base configuration, CMAQ v5.5 with pNO_3^- photolysis (v5.5np; available upon request) was used for the hemispheric simulation without including pNO_3^- photolysis in the CONUS simulation.[34] A sensitivity simulation was also performed to test the influence of using the pNO_3^- parameterization in both the CONUS and hemispheric simulations. MDA8 O_3 performance improved in the Southwest and West regions in spring and part of the summer (1-3 ppb in spring and 1-2 ppb in summer) when using the pNO_3^- treatment in both simulations. However, this configuration increased the MDA8 O_3 bias in eastern U.S. (~1 ppb in spring, and up to 6 ppb in the Southeast during summer). Most of the ozone increase from pNO_3^- photolysis occurs at the hemispheric-scale and is transported into the CONUS domain, and so we used the standard CMAQ v5.5 model (without pNO_3^- photolysis) as the base model for the CONUS simulation in the 2022 platform.

5.3 High Bias of $PM_{2.5}$ OC in Winter

In both the 2022v1 and 2022v2 platforms, CMAQ had a particularly high OC bias in the Northeast, Ohio valley, and Upper Middle West regions in winter. To better understand the OC high bias in CMAQ, we investigated two potential sources of bias: (1) POA emissions from nonpoint sources (including commercial cooking and residential wood combustion) and (2) the urban vertical mixing parameterization.

[33] https://doi.org/10.1016/j.scitotenv.2025.178968

[34] Technical Support Document (TSD): 2022 Regulatory Modeling Platform: Air Quality Modeling Version 1, EPA-454R26001, 2026. https://www.epa.gov/system/files/documents/2026-04/2022-v1-modeling-platform-aq-model-tsd_final_version.pdf

We anticipate that nonpoint source POA emissions will decrease in future modeling due to updates planned for the 2023 NEI. We tested the potential for these updates to improve CMAQ OC predictions using a sensitivity simulation for the 2022v2 platform that approximately reflects the updated 2023 NEI methods. The OC NMB is significntly reduced (from 180% to 110%) in winter at the Northeast CSN sites.

A sensitivity simulation related to the vertical mixing parameterization was also conducted due to the correlation of the high OC biases with low modeled planetary boundary layer heights and previous reports of $PM_{2.5}$ overpredictions due to challenges in simulating the stable wintertime boundary layer.[35] In this sensitivity simulation, CMAQ's kzmin option was turned off to apply a uniform kzmin value of 1 m^2/s and allow more vertical mixing in winter. Disabling the default kzmin parameterization along with the nonpoint POA emission updates improves model performance for OC prediction (NMB from 110% with the emissions change to 80% with both changes) in winter at Northeast CSN sites. These results confirm the importance of the vertical mixing parameterization for wintertime OC predictions. Additional analyses to understand the differences between CMAQ and CAMx and the impacts of urban vertical mixing on winter $PM_{2.5}$ are ongoing.

5.4 MEGAN Biogenic Emissions

The Biogenic Emission Inventory System (BEIS) inline scheme is the default option for biogenic VOCs and soil NO emission calculations in CMAQ. An alternative scheme is also available in CMAQ to use MEGAN for VOCs and the Berkeley-Dalhousie Soil Nitric Oxide Parameterization module (BDSNP) for soil NO emissions. This scheme recently has been used in modeling applications by some state air agencies. Sensitivity simulations using MEGAN with the BDSNP scheme (inline for CMAQ and offline for CAMx) were performed with the 2022v2 and 2022v1 platforms.

[35] Lu, W., Zhu, B., Yan, S., et al., Improving $PM_{2.5}$ simulation in the stable boundary layer over eastern China through parameterized minimum eddy diffusivity, J. of Env. Sci. 158, 254-264 (2025). https://doi.org/10.1016/j.jes.2025.01.012

Compared with the base configuration, BDSNP soil NO increases MDA8 O_3 concentrations in April to September significantly (> 5ppb) in major and minor crop areas (e.g. California, Kansas, Nebraska, Illinois, and Iowa). MEGAN VOC emissions have mixed impacts on MDA8 O_3 concentrations (-1 to 1 ppb in most areas, with decreases of ~3 ppb in Los Angeles). Overall, switching CMAQ inline biogenic VOC and soil NO emissions from BEIS to MEGAN significantly increases MDA8 O_3 concentrations except in the Los Angels Basin. However, while reviewing MEGAN-related input data, we found that MEGAN's growth-form categories (from the Community Earth System Model's Community Land Model, CESM-CLM) were not representative of vegetation fractions in a subset of urban areas and that the hemispheric total soil NO emissions from CMAQ's implementation of BDSNP were high compared with global estimates from previous literature.[36] To better consider these options in future applications, EPA plans to revise the MEGAN and BDSNP inline schemes by exploring other vegetation input datasets and developing a new parameterization for estimating soil NO emissions.

5.5 General Emission Sensitivities

CMAQ emissions sensitivity simulations were conducted using 25% reductions in anthropogenic sources of NOx, VOC, SO_2, NH_3, and primary $PM_{2.5}$. The NOx and VOC sensitivities are useful for understanding the influence of the controlling precursors for O_3. All the precursor and direct $PM_{2.5}$ sensitivities are useful for understanding the influence of controlling emissions for $PM_{2.5}$.

Figure 12 shows a 2022v2 top 10-day O_3 (10-top highest ozone days based on grid cells) spatial variation, and these spatial patterns are reasonable and consistent with previous modeling and analysis. NOx and VOC reductions reveal broad NOx sensitivity of modeled O_3; however, in select areas and times showing VOC sensitivity. Season average MDA8 O_3 concentrations are controlled by NOx-limited processes in most grid-cells in the CONUS domain, but some locations are sensitive to VOC emissions, specifically portions of Los Angeles, San Fransico, New York, Chicago, Seattle, Denver, and the Permian Basin (Figure 13-14). However, those figures just show the chemical regimes based on average values. The chemical regime changes day-to-

[36] Weng, H., Lin, J., Martin, R. *et al.* Global high-resolution emissions of soil NO_x, sea salt aerosols, and biogenic volatile organic compounds. *Sci Data* **7**, 148 (2020). https://doi.org/10.1038/s41597-020-0488-5

day and by hour-of-day based on the emission temporal variation and meteorological conditions (such as PBL height and solar radiation levels). Detailed O_3 chemistry requires specific investigations for different time periods and non-attainment areas.

Figure 15 shows a 2022v2 platform annual average $PM_{2.5}$ spatial variation. In the East, broad areas with moderate annual average $PM_{2.5}$ levels are predicted, with relatively high levels in urban areas. In the West, broad areas with low annual average $PM_{2.5}$ levels are predicted, with moderate-to-high levels in urban areas, California air basins, and the Northwest (mountain-valley $PM_{2.5}$ and fires). Modeled $PM_{2.5}$ shows moderate sensitivity to precursors and larger sensitivity to direct $PM_{2.5}$ emissions. With 25% reduction of all anthropogenic $PM_{2.5}$ precursors other than $PM_{2.5}$ (i.e., NOx, SO_2, VOC, and NH_3), modeled $PM_{2.5}$ decreased up to 1 µg m^{-3}, and the major impacted areas are central valley of California and Ohio River Valley (Figure 16). The majority of the predicted $PM_{2.5}$ reduction is from the NOx and NH_3 emissions reductions. Modeled $PM_{2.5}$ reduction from the SO_2 emissions cut was relatively small and located in Ohio River Valley and South region of the U.S. However, the 25% reduction in direct $PM_{2.5}$ emissions significantly reduced modeled $PM_{2.5}$ predictions (> 2 µg m^{-3}) in most high-$PM_{2.5}$ areas (Figure 17).

6 Summary

Overall, CMAQ and CAMx predictions for total O_3, total $PM_{2.5}$, and key $PM_{2.5}$ component species are in reasonable agreement with observations in most areas. The performance for O_3 and $PM_{2.5}$ are discussed separately because of their distinct regional and seasonal patterns.

Despite the reasonable agreement between CMAQ and CAMx predictions and observations for total $PM_{2.5}$, $PM_{2.5}$ SO_4 and $PM_{2.5}$ NO_3, predictions of $PM_{2.5}$ OC tend to be biased high compared to observations at CSN and IMPROVE sites. Large positive biases for $PM_{2.5}$ OC predictions are evident in the Northeast (winter, spring, and fall), Ohio Valley (winter) and Upper Midwest (winter). Overpredictions of $PM_{2.5}$ OC during wintertime in the Northeast have occurred in previous modeling platforms. These biases are related to the interaction among three factors: the ability to model atmospheric mixing under stagnant conditions, direct PM emissions estimates, and the modeled representations of atmospheric chemistry (e.g., volatility). The EPA is investigating the role of these factors during periods with degraded model performance. $PM_{2.5}$ EC is underpredicted across the domain in the CMAQ and CAMx simulations; however, mean biases are generally small due to the low ambient EC concentrations. In the 2022 platform (v1 and v2), the WBD option is disabled due to large overpredictions of soil when WBD is enabled in CMAQ v5.5. EPA is continuing to refine the WBD process for future CMAQ releases.

NMBs for CMAQ and CAMx predictions of MDA8 O_3 during the O_3 season are reasonable across the domain, except that some urban areas in the West and Southwest regions show negative bias (models underpredicted the MDA8 O_3). Also, both models underpredicted MDA8 O_3 concentrations when the observed values were higher than 60 ppb (NMBs: -10 to -20 %).

The MDA8 O_3 underprediction could be due to several factors. Recently, Sawar et al.[37] demonstrated that adding particulate nitrate ($pNO3^-$) photolysis to CMAQ improves O_3 underestimation in the western U.S., especially during spring months. In this modeling platform, EPA included $pNO3^-$ photolysis in the HEMI-CMAQ model runs. However, negative O_3 bias in the southwestern and western U.S. in the CMAQ and CAMx 12US2 runs occurred despite the influence of $pNO3^-$ photolysis through the boundary conditions. EPA also tested the influence of $pNO3^-$ photolysis in the 36US3 and 12US2 CMAQ runs, and the model performance improved slightly for O_3 in the southwestern and western U.S., but O_3 was overpredicted elsewhere. Another potential cause of the O_3 underpredictions is emissions uncertainty (e.g., underprediction of NOx emissions from emerging source categories or changes in activity not captured in current inventories). EPA is continuing to investigate causes of O_3 model underpredictions in the Western US.

In summary, CMAQ and CAMx generally perform well for total $PM_{2.5}$, key $PM_{2.5}$ components, and MDA8 O_3 across most of the domain, although persistent regional biases remain for $PM_{2.5}$ OC and western U.S. O_3, highlighting the need for continued improvements in emissions

[37] https://doi.org/10.1016/j.scitotenv.2025.178968

characterization, chemical treatment, and vertical mixing process representation in future modeling platforms.

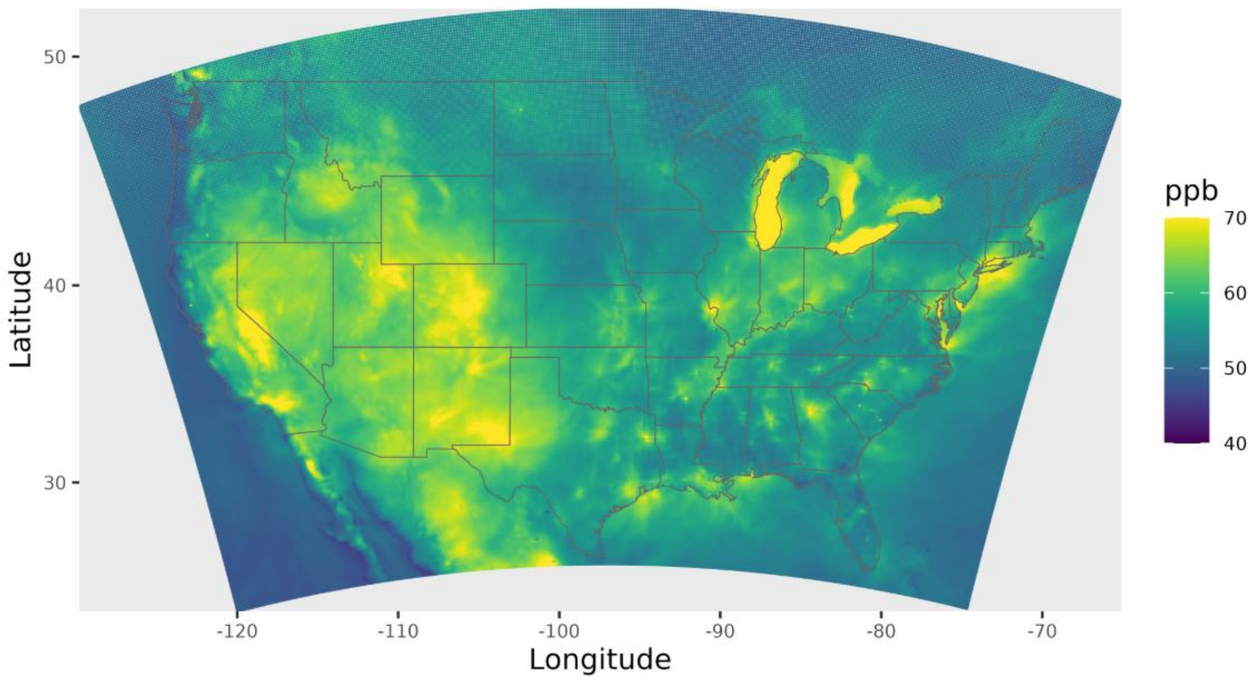

Figure 12 - 2022v2 CMAQ predictions of top 10-day MDA8 O3 average

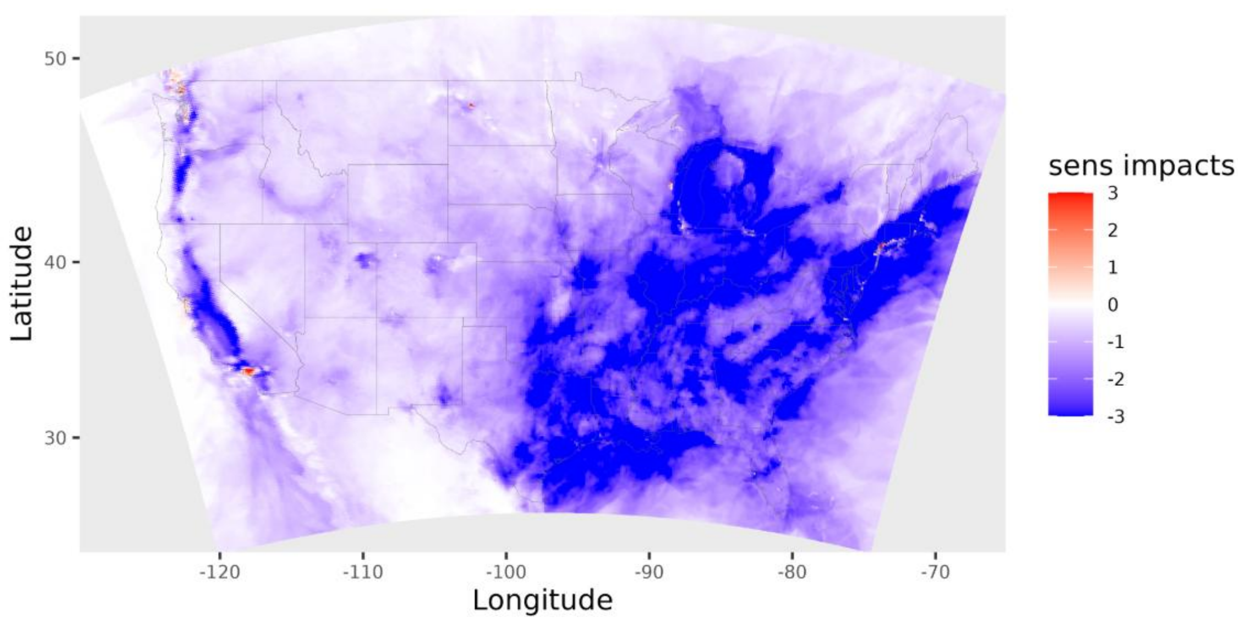

Figure 13 - 2022v2 CMAQ impacts of top 10-day MDA8 O_3 average from NOx 25% reduction (sens impacts = sensitivity – base simulation).

Red color indicates that top 10-day O3 increases while NOx emission decreases, the red grid cells mainly located in large urban areas (e.g. Los Angeles, New York, Chicago). Blue color indicates that top 10-day MDA8 O3 decreases while NOx emission decreases.

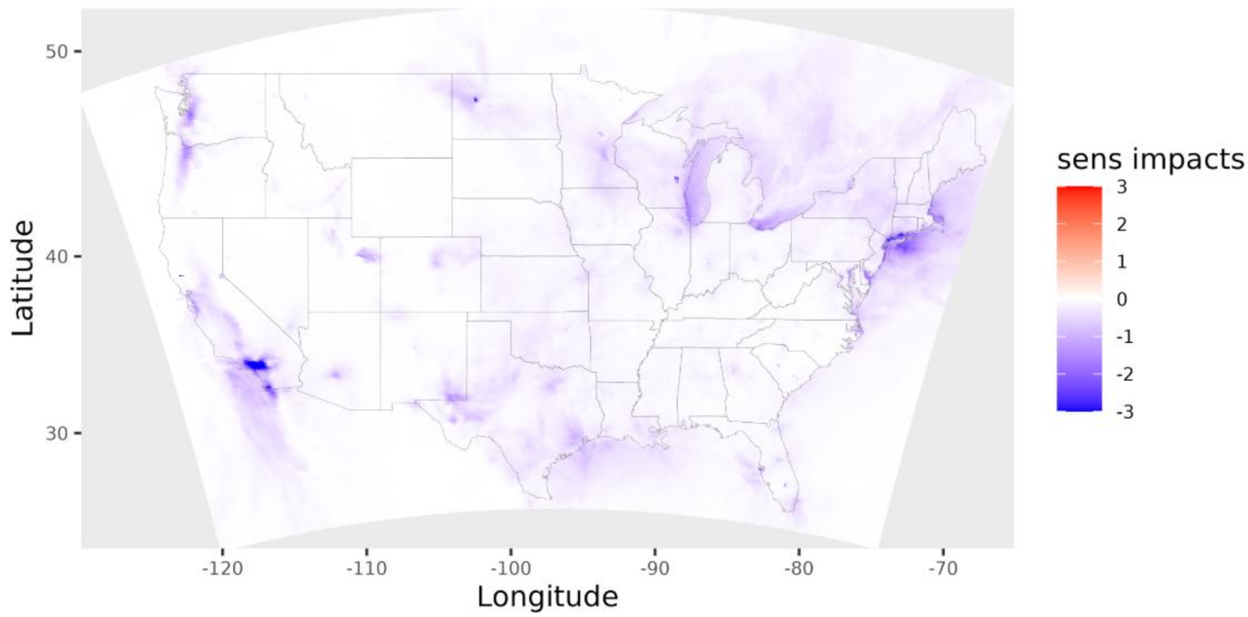

Figure 14 - 2022v2 CMAQ impacts of top 10-day MDA8 O_3 average from VOCs 25% reduction (sens impacts = sensitivity – base simulation).

Red color indicates that top 10-day MDA8 O_3 increases while VOC emission decreases. Blue color indicates that top 10-day MDA8 O_3 decreases while VOCs emissions decreases (e.g. urban areas).

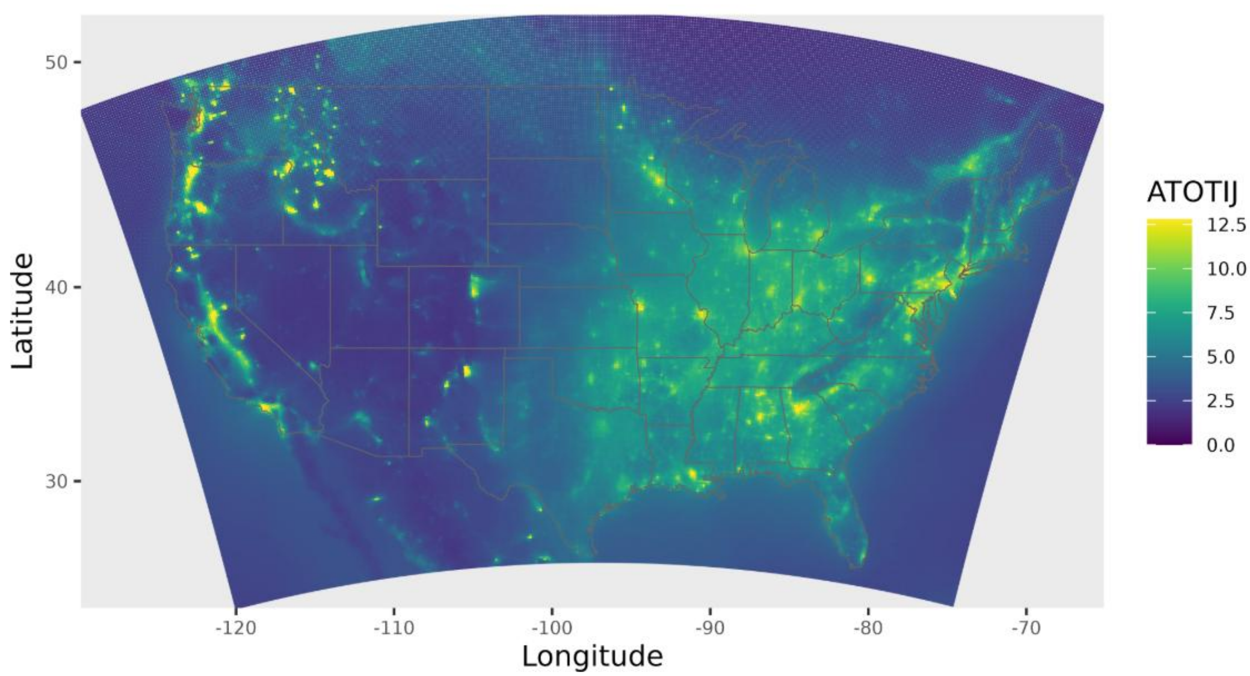

Figure 15 - 2022v2 CMAQ predictions of annual $PM_{2.5}$ average

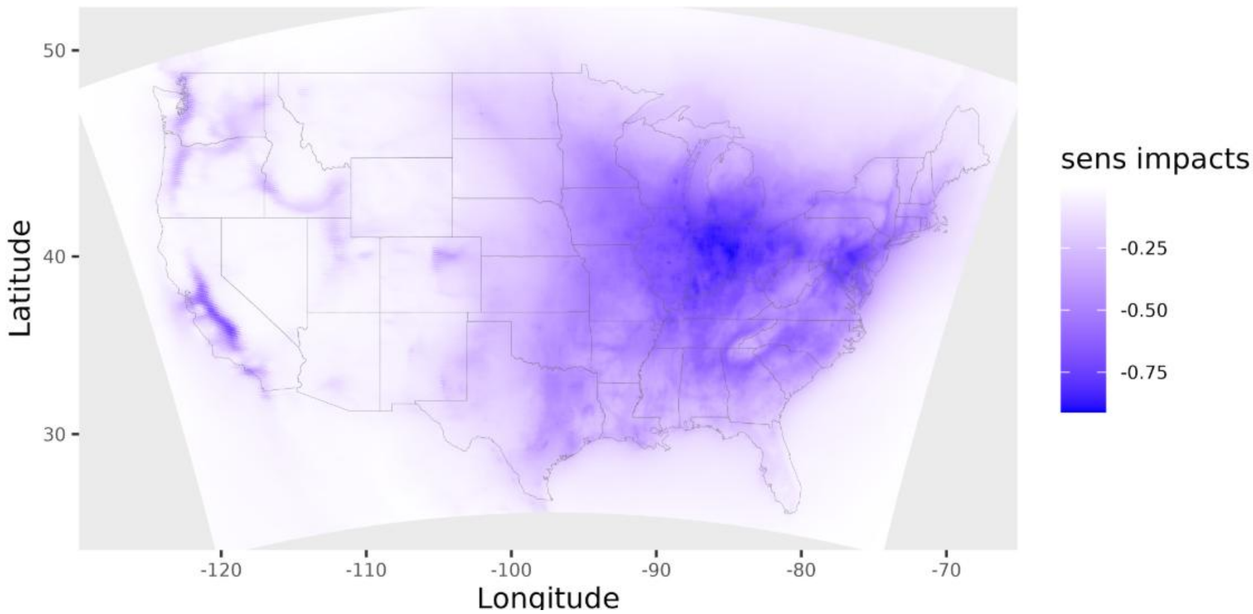

Figure 16 - 2022v2 CMAQ impacts of annual $PM_{2.5}$ average from all precursors (NOx, SO_2, VOCs, NH_3) 25% reduction (sens impacts = sensitivity – base simulation).
Blue color indicates that annual $PM_{2.5}$ decreases while precursors emissions decreases.

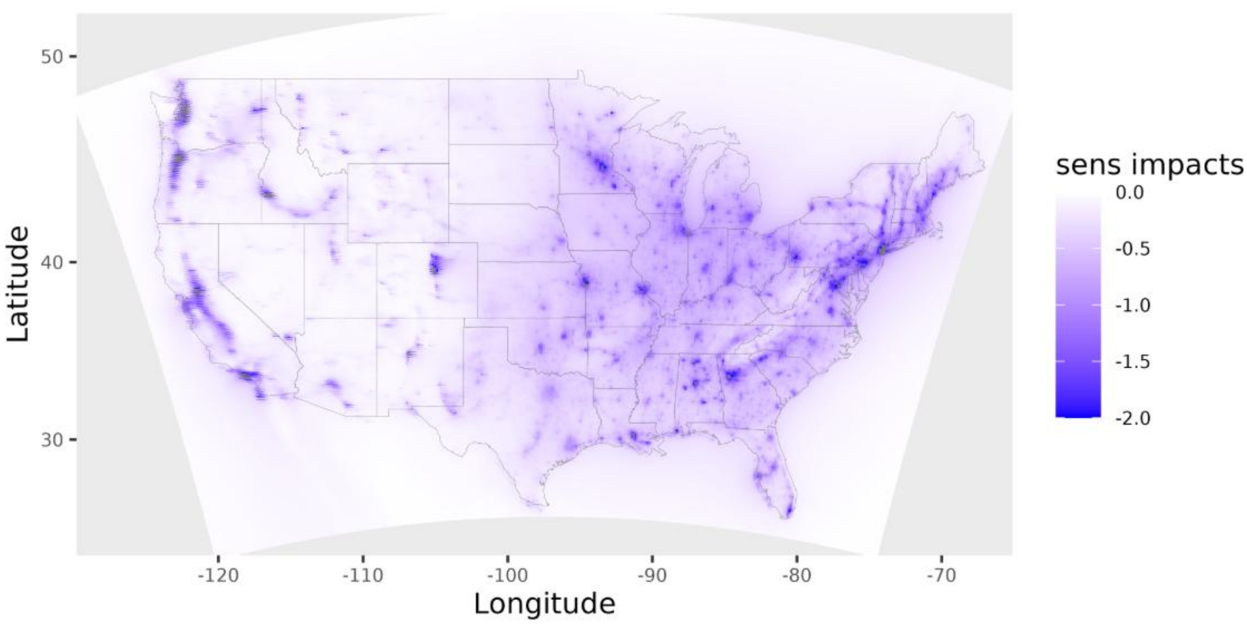

Figure 17 - 2022v2 CMAQ impacts of annual $PM_{2.5}$ average from direct $PM_{2.5}$ emissions 25% reduction (sens impacts = sensitivity – base simulation).
Blue color indicates that annual $PM_{2.5}$ decreases while direct $PM_{2.5}$ emissions decreases (e.g. urban and industrial areas).