EPA-454R26001

Technical Support Document (TSD): 2022 Regulatory Modeling Platform: Air Quality Modeling Version 1

U.S. Environmental Protection Agency
Office of State Air Partnerships
Air Quality Assessment Division
Research Triangle Park, NC

Table of Contents

Figure List

Table list

Acronym

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

IMPROVE: Interagency Monitoring of Protected Visual Environments

Kv: vertical eddy diffusivities

M3dry: mdoe-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

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

BEIS: Biogenic Emission Inventory System

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

WOUDC: World Ozone and Ultraviolet Radiation Data Centre

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 by EPA and state, local, and Tribal (SLT) air agencies. The EPA's modeling platform, using a 2016 base year, was initially released in 2019 and included multiple version updates. The 2016 platform has been used continually for various regulatory applications through the end of 2024. In 2023, EPA reviewed meteorological conditions and emissions, and selected 2022 as the base year for next EPA modeling platform, considering the following factors:

1. **Normal Weather Conditions**: Most of the contiguous United States (U.S.) experienced typical temperature and precipitation patterns in 2022.
2. **Ozone Levels**: Ozone levels across much of the U.S. were in the range of observed concentrations over the previous 5 years.
3. **COVID Impacts**: COVID impacts on emissions levels are expected to be mostly back to normal by the beginning of 2022.
4. **Wildfire Activity**: 2022 had the second-lowest number of wildfire acres burned over the past seven years, reducing potential complications from "atypical events" compared to other recent years.
5. **Regulatory and Data Timelines**: The timeline for required regulatory modeling and emissions data preparation aligns well with using 2022 as the base year.
6. **Recent Air Quality Data**: 2022 was the most recent year with measured air quality data when we made the selection (2023).

The EPA's 2022 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. The 2022 meteorological data were generated using Weather Research and Forecasting (WRF) model to support emissions and photochemical modeling applications for both the base and future years of the 2022 modeling platform. Detailed WRF configurations and model performance can be found in the 2022 WRF Technical Support Document (TSD)[1].

The 2022 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 TSD for the 2022v1 North American Emissions Modeling Platform (EMP)[2]. The abbreviation for the modeling case name was “2022hc”, where 2022 is the year modeled, ‘h’ indicates that it was based on the 2020 NEI, and ‘c’ represents that it was the third version of a 2020 NEI-based platform.

Air quality modeling was conducted using the Community Multiscale Air Quality (CMAQ) model version 5.4[3] and the Comprehensive Air Quality Model with Extensions (CAMx) version 7.20[4]. Both CMAQ and CAMx are widely used by the EPA, SLT air agencies, and Multi-Jurisdictional Organizations (MJOs) for various photochemical modeling applications under the Clean Air Act (CAA). The EPA tested two continental U.S. (CONUS) domains, a 36-km grid resolution domain (36US3) and a 12-km grid resolution domain (12US2) (see Figure 1). This TSD focuses on air quality model simulations in 12US2 domain, including the model configuration sensitivity and model performance evaluations for 2022.

In this document, model performance evaluation examines the ability of the 2022 air quality modeling platform to represent the magnitude and spatial and temporal variability of measured maximum daily average ozone (MDA8 O_3) concentrations and particulate matter with diameters < 2.5 μm ($PM_{2.5}$) species component concentrations within the modeling domain.

---

[1] https://www.epa.gov/system/files/documents/2024-03/wrf_2022_tsd.pdf

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

[3] CMAQ version 5.4: United States Environmental Protection Agency. (2022). CMAQ (Version 5.4) [Software]. Available from https://doi.org/10.5281/zenodo.7218076; https://www.epa.gov/cmaq. CMAQ v5.4 is also available from the Community Modeling and Analysis System (CMAS) at: http://www.cmascenter.org.

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

2 Platform Developments

2.1 Model Domain

The CMAQ modeling analyses were 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). It also 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 12US2 domain covers the entire CONUS and portions of Canada and Mexico using a 12-km by 12-km horizontal grid spacing. In the 2022 platform, the 12US2 domain used a Lambert Conformal map projection centered at -97, 40 degrees with true latitudes at 33 and 45 degrees north. The 12-km CMAQ domain consisted of 396 by 246 grid cells and 35 vertical layers extending up to 50 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.

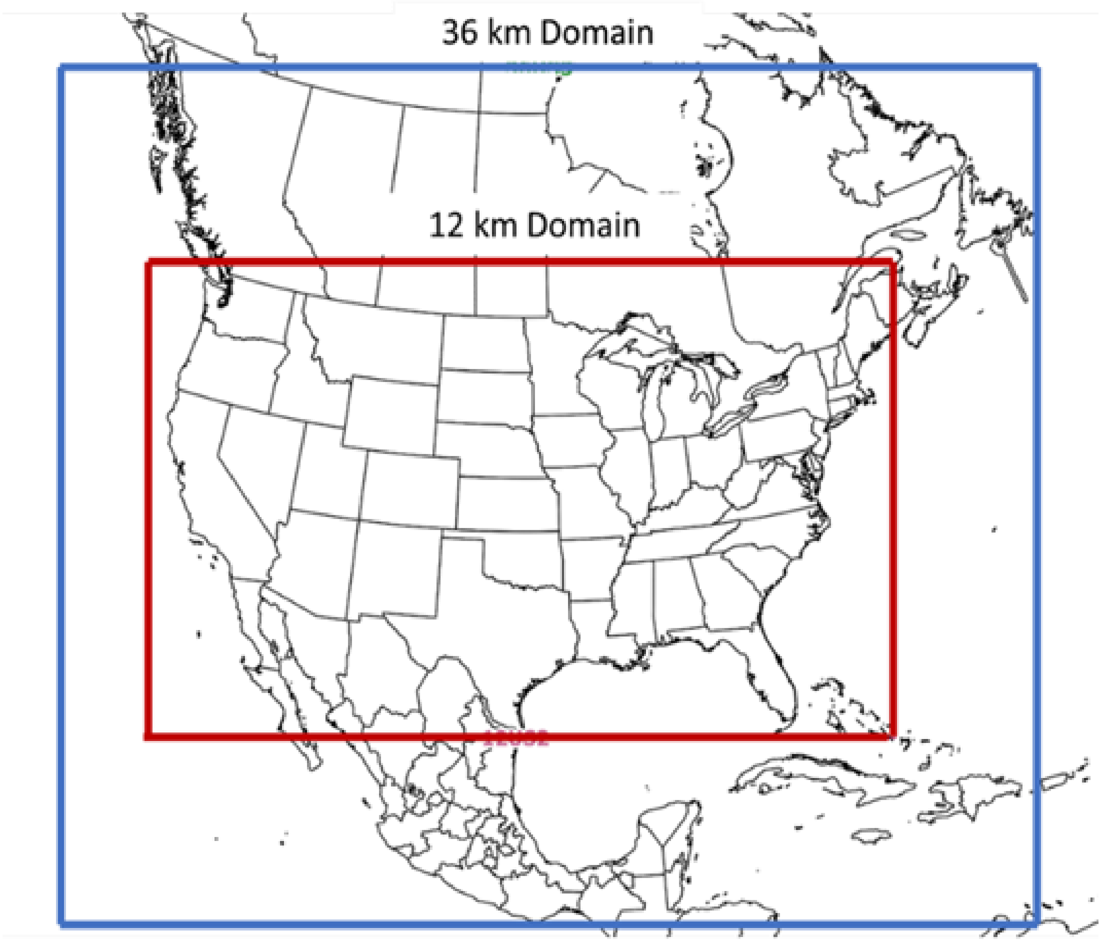

Figure 1 - Map of the 2022 CMAQ Modeling Domain. The blue box denotes the 36-km national modeling domain, and the red box denotes the 12-km domain.

2.2 2022 Meteorological Data

WRF was applied for the entire year of 2022 to generate meteorological data supporting emissions and photochemical modeling applications for the base year of the 2022 modeling platform. WRF was evaluated to ensure that its output fields reasonably represent the actual meteorological conditions during the modeling period. Identifying and quantifying these output fields allows for a downstream assessment of how the air quality modeling results are impacted by the meteorological data. For more information on the WRF model setup and evaluation, please refer to the WRF modeling TSD for 2022.[5]

[5] 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.

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)[6] 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 surface 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 2022 Emissions

The 2022 version 1 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 was the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system[7]. EPA used SMOKE version 5.1 to generate CMAQ-ready emissions files for a 12-km grid covering the continental U.S. Biogenic volatile organic compound (VOC), soil nitrogen oxide (NO), lightning nitrogen oxides (NOx), and fertilizer ammonia (NH_3) emissions were calculated inline in CMAQ. All CMAQ-ready emissions files, biogenic VOC, soil NO, lightning NOx, and fertilizer NH_3 emissions were then converted into CAMx format. Detailed information can be found in the 2022v1 Emissions Modeling Platform TSD document[8].

[6] 10.1175/MWR3199.1

[7] https://www.cmascenter.org/smoke/

[8] U.S. EPA: Technical Support Document (TSD): Preparation of Emissions Inventories for the 2022v1 North American Emissions Modeling Platform, EPA-454/B-25-001, 2025.

2.4 2022 Initial and Boundary Conditions (IC/BCs)

The EPA considered three global or hemispheric models for the generation of IC/BCs. In this section, we evaluated the three approaches and selected the best one for the purposes of the 2022 modeling platform. The three options have short names that link to a model platform:

- Hemispheric-scale CMAQ Boundary Conditions (HEMI-CMAQ-BC): HEMI-CMAQ v5.4 with aerosol nitrate (NO_3^-) photolysis.
- Goddard Earth Observing System Chemistry Model Black Carbon (GEOS-Chem-BC): GEOS-Chem version 14.0.1,
- GEOS Composition Forecast Model Black Carbon (GEOS-CF-BC): NASA's GEOS-CF, and
- Hemispheric-scale CMAQ Boundary Conditions (HEMI-CMAQ-BC): HEMI-CMAQ v5.4 with aerosol nitrate (NO_3^-) photolysis.

All model configurations, output data, and 36US3 IC/BCs are available on Amazon Web Services (AWS) Office of State Air Partnerships (OSAP) 2022 Modeling Platform Bucket[9]. Each configuration is described in more detail in sections 2.4.1, 2.4.2, and 2.4.3. A summary of model performance is provided in section 2.4.4.

2.4.1 HEMI-CMAQ-BC

The HEMI-CMAQ-BC option used CMAQ v5.4 with aerosol NO_3^- photolysis. This version of CMAQ is described in more detail by Sarwar et al.[10] It augments the v5.4 Carbon Bond 6 chemistry with aerosol NO_3^- photolysis as proposed by Shah et al. [11]. A brief summary of the configuration is provided below.

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

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

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

- **Meteorology and Resolution**: We applied 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. HEMI-CMAQ was run offline using MCIPv5.3.3.
- **Chemistry and Parameters**: We included the fifth generation of Carbon Bond 6 chemistry (CB6r5) with full halogen chemistry and the 7th generation aerosol module (AERO7) aerosols. Stratospheric ozone fluxes, which are very important at hemispheric scales, are parameterized based on potential vorticity.
- **Emissions**: Natural emissions were the same as used in the EPA's Air Quality Time Series (EQUATES) project[12]. The EQUATES hemispheric biogenic VOC and soil NOx emissions are developed from emission files for Copernicus Atmosphere Monitoring Service (CAMS). Wildfire emissions were developed globally from the Fire Inventory from NCAR (FINN) v1.5[13]. Anthropogenic emissions were derived from the Hemispheric Transport of Air Pollutants Task Force Phase 3 harmonized emissions[14].

The HEMI-CMAQ-BC option results were archived at hourly resolution for all 44 layers over the whole domain for IC/BCs. The standard CMAQ preprocessors ICON (initial conditions) and BCON (boundary conditions) were used to extract IC and BC for the 36US3 domain and vertically interpolate to the 35-layer vertical structure used by the regional platform.

2.4.2 GEOS-CHEM-BC

The GEOS-Chem-BC option used a global simulation with GEOS-Chem version 14.0.1 for 2022[15]. This application is nearly identical to the version described in the TSD for reporting of daily air quality[16].

---

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

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

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

[15] https://zenodo.org/records/7271974

[16] Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (AQI), EPA-454/R-24-002

- **Meteorology and Resolution:** We applied Modern-Era Retrospective analysis for research and Applications version 2 (MERRA2) meteorology at a 2 x 2.5-degree resolution with a 72-layer vertical structure, including 36 layers in the troposphere, using a hybrid terrain-following coordinate.
- **Chemistry and Parameters:** We included full chemistry with online stratosphere, non-local planetary boundary layer, simple secondary organic aerosols (SOAs), and updated parameters for methane, lightning, and others for 2022.
- **Emissions:** Natural emissions included the online Model Emissions of Gases and Aerosols from Nature (MEGAN) version 2.1[17] as implemented by Hu et al.[18], dust module[19], and sea salt module[20]. Fire emissions were generated from monthly mean data from the Global Fire Emissions Database (GFED)[21]. Anthropogenic emissions are based on Community Emissions Data System (CEDS) version 2[22] including land-based and marine shipping emissions. The emissions also included fugitive, combustion, and industrial dust[23]. Aircraft emissions were calculated from monthly data from the Aircraft Emissions Inventory Code[24].

The GEOS-Chem results were archived at 3-hour resolution over horizontal windows that cover the regional platform domains. The results were processed to BCs using the Air Quality Model Boundary Condition Tools ("aqmbc") Python package, which is publicly available on GitHub[25]. The package extracts species, vertically interpolates linearly using a reference surface pressure/vertical grid levels, vertical sigma-pressure layer edges or midpoints (VGLVLS)/VGTOP:

[17] https://doi.org/10.5194/gmd-5-1471-2012

[18] https://doi.org/10.1002/2014JD022732

[19] https://doi.org/10.1016/j.atmosenv.2006.09.048

[20] https://doi.org/10.5194/acp-11-3137-2011

[21] https://doi.org/10.1002/jgrg.20042

[22] https://doi.org/10.5194/gmd-11-369-2018

[23] https://doi.org/10.1088/1748-9326/aa65a4

[24] https://doi.org/10.1016/j.trd.2013.07.001

[25] https://github.com/barronh/aqmbc

pressure at the top of model domain (VGTOP) and translates species. The species translations take GEOS-Chem species and output CB6r5 AERO7 species.

2.4.3 GEOS-CF-BC

The global modeling for the GEOS-CF-BC option was conducted by National Oceanic and Atmospheric Administration (NASA)'s Global Modeling and Analysis Office (GMAO). GMAO's GEOS-CF setup is described in more detail by Keller et al.[26] and Knowland et al.[27] and is summarized here. GEOS-CF used the GEOS-Chem model version 12.0.1.

- **Meteorology and Resolution:** GEOS-CF applied GEOS for Instrument Teams (GEOS-IT) meteorology at a 0.25 x 0.25-degree resolution with a 72-layer vertical structure, including 36 layers in the troposphere, using a hybrid terrain-following coordinate.
- **Chemistry and Parameters:** GEOS-CF included full chemistry with online stratosphere, non-local planetary boundary layer, simple secondary organic aerosols.
- **Emissions:** Natural emissions included online MEGAN version 2.1[16] as implemented by Hu et al. [17], DUST module[18], and the sea salt module[19]. Fire emissions were generated from monthly mean data from the Quick Fire Emissions Database (QFED)[28]. Anthropogenic emissions are based on the Hemispheric Transport of Air Pollution (HTAP) version 2.2 including land-based and marine shipping emissions. The emissions also included fugitive, combustion, and industrial dust[20]. Aircraft Emissions were calculated from monthly data from the Aircraft Emissions Inventory Code (AEIC)[21].

The GEOS-CF 3-d outputs were downloaded at 3-hourly resolution over horizontal windows that cover the regional platform domains. The outputs were processed to boundary conditions using the Air Quality Model Boundary Condition Tools ("aqmbc") Python package, which is publicly available on GitHub[29]. The package extracts species, vertically interpolates linearly

[26] https://doi.org/10.1029/2020MS002413

[27] https://doi.org/10.1029/2021MS002852

[28] Report Number: NASA/TM-2015-104606 /Vol. 38

[29] https://github.com/barronh/aqmbc

using a reference surface pressure/VGLVLS/VGTOP, and translates species. The species translations take GEOS-Chem species and CB6r5 AERO7 species.

2.4.4 Global Model Performance Evaluation

Model performance evaluation of these simulations was documented more fully elsewhere[30] and is only summarized here. Typical surface monitor evaluations are not an ideal way to assess the quality of boundary conditions Model performance of predicted ozone is affected by the coarse model horizontal resolution more so than the upper atmospheric layers that are most important for boundary conditions. As a result, a global model with coarse horizontal resolution may perform well at representing background ozone while failing to capture local gradients that affect surface monitors. As a result, evaluation of modeled boundary conditions should rely on data from ambient air quality monitors in remote locations (e.g., from the Clean Air Status and Trends Network (CASTNET) and Interagency Monitoring of Protected Visual Environments (IMPROVE) network), ozone sondes, and satellite data. Because ozone is transported over long ranges, including international transport, it is the most important boundary condition for air quality modeling applications, thus ozone is the emphasis of boundary condition performance evaluation. EPA has previously assessed model performance of all three options described above and has documented publicly on AWS that the GEOS-Chem-BC option is strongest.

EPA compared the GEOS-Chem-BC results to data from CASTNET and IMPROVE ambient air quality monitors, World Ozone and Ultraviolet Radiation Data Centre (WOUDC) ozone sondes and satellites, as documented in Henderson et al.[31] The comparison to CASTNET data indicated very good model performance for capturing the diurnal ozone variation patterns in March-April-May and showed some overestimation in those patterns in June-July-August. The model performance for predicting ozone concentrations, when compared to results from ozone sondes, varies depending on the sites. The Hilo, HI and Boulder, CO sites, which represent

[30] Global models and satellite informed lateral boundary conditions, Henderson et al., 2024 CMAS

[31] 2022 GEOS-Chem v14 ozone evaluation using snodes, satellites, and surface measurements Henderson, 2024, the 11th international GEOS-Chem Conference.

incoming air, performed well. The Trinidad Head, CA and Yarmouth, ME coastal U.S. sites underestimated ozone in the mid-tropospheric (800hPa-400hPa) in June-July-August based on a limited number of sonde releases (Trinidad: 13; Yarmouth: 4). The cause of this is unclear and, but it is likely that the topography is not well captured by the coarse model where land and ocean are in the same grid cell. Although $PM_{2.5}$ performance is not the emphasis of evaluation, Henderson et al.[30] found overestimation of $PM_{2.5}$ at IMPROVE monitors, and highlighted that the modeling showed a diurnal pattern that was the opposite of observations at these remote sites. Satellite evaluation of nitrogen dioxide performed similarly to previous literature with lower biases in spring than summer.[32] Given the coarse resolution and relative importance of ozone, sondes and satellites, the GEOS-Chem performance was more than sufficient for use as boundary conditions.

Similar performance evaluation has been carried out for the HEMI-CMAQ-BC and GEOS-CF-BC options, but it has not been as thoroughly documented externally. CMAQ was also compared to GEOS-Chem as part of a Health and Air Quality Applied Science Team (HAQAST) project[33]. The results of that work were summarized in Henderson et al.[34] For ozone, the three models each have reasonable performance with different areas and seasons performing best. For carbon monoxide, the Hemi-CMAQ model is an outlier with much lower background mixing ratios than the other models. Preliminary investigation suggests this is only partly explained by the addition of particulate nitrate photolysis.

2.5 36US3 CMAQ tests

In order to compare the impacts of BC from these three global/hemispheric models on the CONUS domain, EPA conducted three 36US3 CMAQ model simulations with identical model configurations except for the BC inputs, which used the GEOS-CF-BC, GEOS-Chem-BC, and Hemi-CMAQ-BC 36US3 runs. Table 1 provides the model performance statistics and indicates that the 2022 MDA8 O_3 concentrations and daily $PM_{2.5}$ concentrations predicted by the GEOS-

[32] https://doi.org/10.5194/acp-23-6271-2023

[33] https://haqast.org/tiger-teams/

[34] Global models and satellite informed lateral boundary conditions, Henderson et al., 2024 CMAS

CF-BC, GEOS-Chem-BC, and 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) monitoring sites in the U.S. Model performance was analyzed in comparison to the range of performance statistics reported in recent state-of-the science regional CMAQ applications (Appel et al.[35]; Kelly et al.[36], Simon et al.[37]). These three studies focused on 12US2 CMAQ runs while the model performance results in Table 1 are based on 36US3 CMAQ runs.

Ozone vertical profile performance between observations (sonde)[38] and model predictions were evaluated by comparing the ozone distribution (5 percentile, mean, 95 percentile) in the mid-troposphere by season (Figure 2). There were 7 sonde sites available in 2022 within the 36US3 modeling domain, including Edmonton (AB, Canada), Boulder (CO, U.S.), Gosse Bay (NL, Canada), Churchill (MB, Canada), Trinidad Head (CA, U.S.), Yarmouth (NS, Canada), Port Hardy (BC, Canada). The 36US3 CMAQ run with HEMI-CMAQ-BC predicted ozone high and low values in the mid-troposphere better than GEOS-CF-BC and GEOS-Chem-BC, and the model results captured the seasonal variation from observations (Figure 2).

The 36US3 CMAQ runs were used to generate the ICs and BCs for 12US2 model runs; therefore, it is important to understand the performance of the ozone vertical profiles in 36US3 CMAQ runs near the 12US2 boundary. We investigated O_3 vertical profiles (from the surface layer to the model top) from model runs and sonde observations near the 12US2 boundary (Trinidad

---

[35] 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.

[36] 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.

[37] 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

[38] https://tropo.gsfc.nasa.gov/shadoz/NDACC_SondeWorkingGroup.html

Head, California, USA) for annual data (Figure 3). The Hemi-CMAQ-BC 36US3 CMAQ run predicted O3 vertical profiles from the surface to ~500 hPa better than the other two BCs.

Anomalous high $PM_{2.5}$ concentrations from the western boundary were noted in 36US3 CMAQ simulations using GEOS-CF-BC and GEOS-Chem-BC. These are due to a known bug in CMAQv5.4 which was resolved in CMAQv5.5[39]. The bug only occurs when particle number and surface area parameters are not available in the boundary (e.g., GEOS-CF and GEOS-Chem) and the number and surface area correction code is skipped (CMAQv5.4 or earlier). The fix (implemented in CMAQv5.5) updates the threshold used to check if number and surface area values were not provided. The anomalous $PM_{2.5}$ concentrations appear to be mostly limited to areas near the boundary as characterized in the fix release note. The anomalous $PM_{2.5}$ is largely seen over the Pacific Ocean near the Western boundary of the 36US3 CMAQ domain and does not obviously impact grid-cells covering the U.S. based on visual inspection of the $PM_{2.5}$ concentration field. Further testing would be required to quantify how much impact these anomalous $PM_{2.5}$ concentrations have in grid-cells covering the U.S.

Overall, compared to GEOS-CF-BC and GEOS-Chem-BC simulations, the Hemi-CMAQ-BC simulation has:

- A slightly better ability to capture ozone peaks at CASTNET and AQS monitors in June/July in the Southwest and West regions.
- Less negative annual bias of $PM_{2.5}$ at IMPROVE sites in the Southwest and Northen Rockies and Plains regions.
- More detailed PM_2.5 profiles which can avoid anomalous high $PM_{2.5}$ concentrations near boundaries.
- Slightly better ozone predictions (5-95%) between 40000 to 75000 Pa compared to sondes.
- Slightly better agreement of vertical profile of ozone at Trinidad Head, CA sonde.

39 https://github.com/USEPA/CMAQ/wiki/CMAQ-Release-Notes:-Chemistry:-Aerosol-Dynamics#improve-aerosol-boundary-condition-processing

The EPA decided to use BCs from Hemi-CMAQ-BC modeling based on a mix of model performance to generate 12US2 BC for 2022v1 modeling platform. Hemi-CMAQ-BC can be created at EPA, and this gives us flexibility to create various scenarios for sensitivity tests (e.g. zero-out international anthropogenic sources).

Table 1 – 2022 platform CMAQ Performance Statistics for $PM_{2.5}$ and MDA8 O_3 in 36km CONUS (unit of AvgObs, Avg Mod, mean bias (MB), and mean error (ME) for $PM_{2.5}$ is µg m^{-3} and for MDA8 O_3 is ppb; normalized mean bias (NMB) and normalized mean error (NME) are %). N is the number of data points. CSN = chemical speciation network.

Network	species	N	AvgObs	AvgMod	NMB	MB	NME	ME	Correlation
				36US3 CEOS-CF-BC simulations					
IMRPOVE	$PM_{2.5}$	16798	3.97	3.69	-15.9	-0.49	45.3	1.40	0.33
CSN	$PM_{2.5}$	84683	8.49	7.06	-17.0	-1.24	34.7	2.53	0.47
AQS	$PM_{2.5}$	439256	7.65	6.16	-21.4	-1.39	38.4	2.50	0.37
AQS	MDA8 O_3	364005	41.97	42.27	0.7	0.30	10.4	4.35	0.76
CASTNET	MDA8 O_3	28062	42.60	41.69	-2.0	-0.87	9.2	3.91	0.58
				36US3 GEOS-Chem-BC simulations					
IMRPOVE	$PM_{2.5}$	16798	3.97	3.92	-12.0	-0.37	46.9	1.44	0.33
CSN	$PM_{2.5}$	84683	8.49	7.32	-14.4	-1.05	35.1	2.56	0.46
AQS	$PM_{2.5}$	439256	7.65	6.45	-18.4	-1.19	38.7	2.51	0.37
AQS	MDA8 O_3	364005	41.97	41.30	-1.5	-0.61	11.3	4.71	0.74
CASTNET	MDA8 O_3	28062	42.60	40.82	-3.9	-1.66	10.2	4.36	0.56
				36US3 Hemispheric CMAQ-BC simulations					
IMRPOVE	$PM_{2.5}$	16798	3.97	4.20	1.5	0.05	39	1.21	0.35
CSN	$PM_{2.5}$	84683	8.49	7.39	-11.4	-0.83	31	2.28	0.49
AQS	$PM_{2.5}$	439256	7.65	6.50	-15.1	-0.98	34	2.22	0.37
AQS	MDA8 O_3	364347	41.95	43.92	4.9	2.03	12	4.78	0.74
CASTNET	MDA8 O_3	28062	42.60	43.76	2.9	1.23	10	4.25	0.57

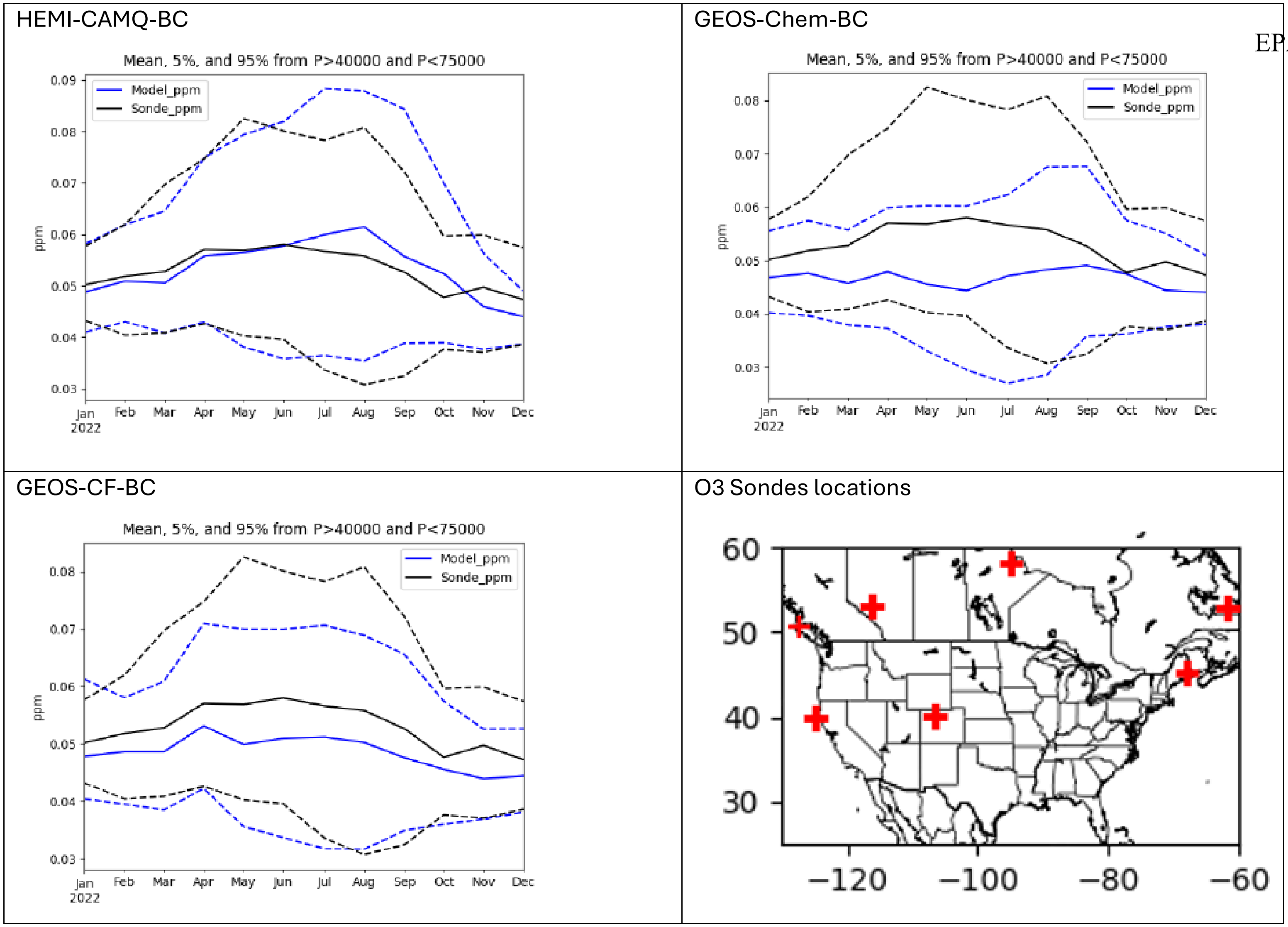

Figure 2 - CMAQ 36US3 Model performance: O3 vertical profile in mid-troposphere comparison to sonde data

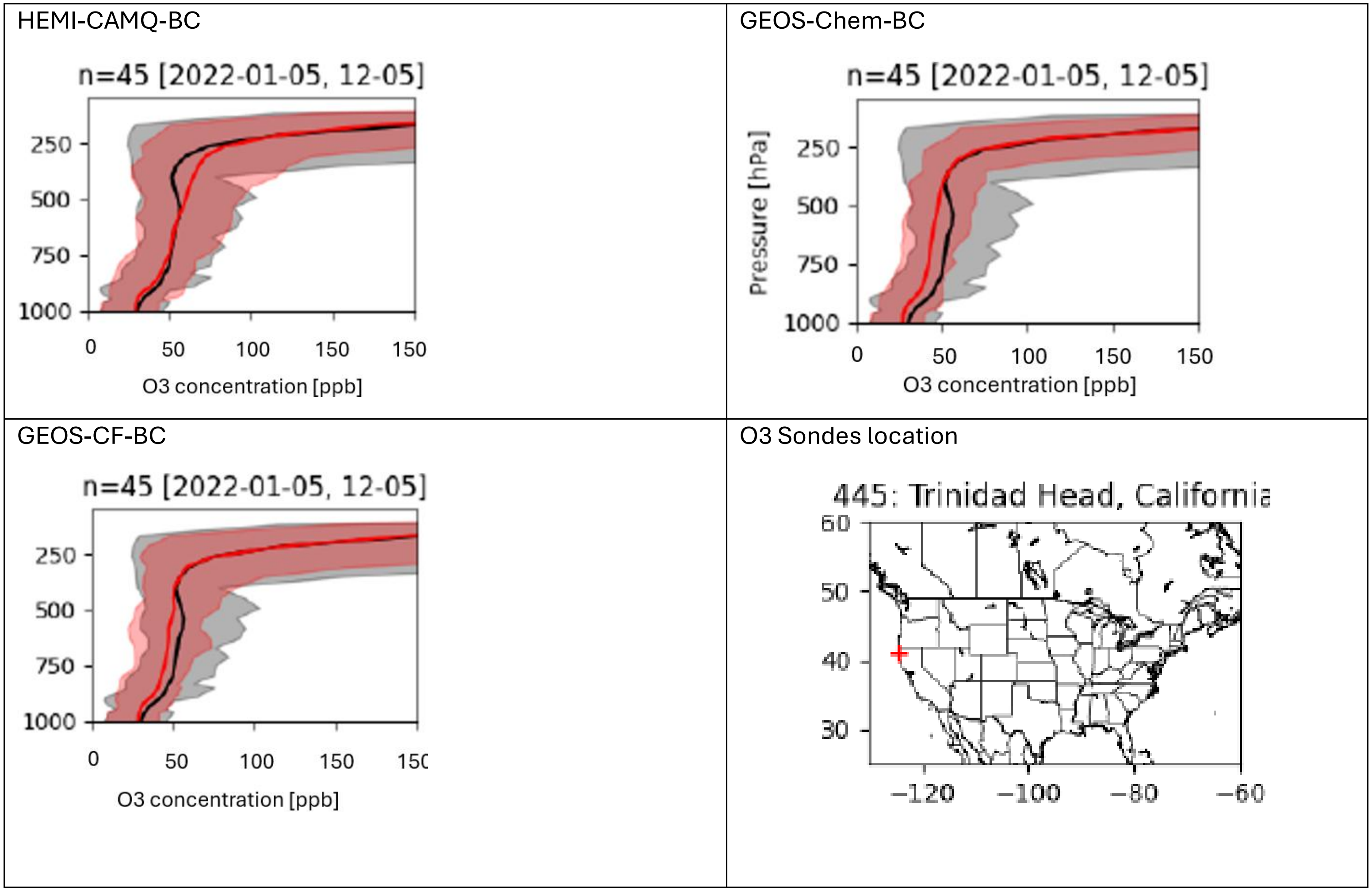

Figure 3 - CMAQ 36US3 Model performance: O3 vertical profile near 12US2 BC

2.6 12US2 CMAQ Configuration tests

CMAQ version 5.4 was used in the 2022 platform to generate $PM_{2.5}$ and ozone for various model configurations. The EPA started with a CMAQ configuration developed through internal discussion, which included:

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

To understand the impact of various option selections on CMAQ outputs, we modified the options one-by-one from the initial CMAQ run. Table 2 provides a summary of the options considered in the configuration sensitivity tests.

Table 2 – Description of CMAQ sensitivity tests

Configuration option	Starting configuration	Sensitivity test(s)
Deposition scheme	STAGE	M3dry
NH_3 bi-directional flux	On	Off
OA treatment	Non-volatile POA	Semi-volatile POA Potential combustion SOA
Chemistry	CB6r5	CB6r5 plus nitrate photolysis[40] and full marine halogen chemistry
Biogenic emissions model	BEIS	MEGAN

[40] Sarwar, G., Sidi, F., Simon, H., Henderson, B.H., Willison, J., Gilliam, R., Hogrefe, C., Foley, K., Mathur, R., Appel, W. Representing particulate nitrate photolysis over seawater improves CMAQ ozone predictions over the contiguous United States, Science of The Total Environment, 970, 2025, https://doi.org/10.1016/j.scitotenv.2025.178968.

2.7 12US2 CAMx Configuration tests

CAMx version 7.20 was used in the 2022 platform to generate $PM_{2.5}$ and ozone based on input sets of meteorological conditions and emissions. The EPA started with a CAMx configuration developed through internal discussions, which included:

- CB6r5_CF2E chemistry,
- ZHANG03 dry deposition model,
- bi-directional flux,
- BEIS biogenic emissions, and
- NH_3 Rscale = 1.

To understand the impact of various option selections on CAMx outputs, we modified the options one-by-one from the initial CAMx run. Table 3 provides a summary of the options considered for the configuration tetes: bi-directional flux off, NH_3 Rscale = 0, and MEGAN biogenic emissions.

Table 3 – Description of CAMx sensitivity tests

Configuration option	Starting configuration	Sensitivity test(s)
NH_3 bi-directional flux	On	Off
NH_3 Rscale parameter	1	0
Biogenic emissions model	BEIS	MEGAN

3 Selected CMAQ and CAMx configurations for v1

The EPA conducted 17 model configuration sensitivity simulations and analyzed the corresponding model performance evaluations at national, regional, and urban scales. The EPA developed a 2022v1 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 2022v1 configurations were 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. Therefore, we have the ability to compare against historical model simulations.
3. **Regulatory Relevance**: Ozone and $PM_{2.5}$ model performance relevant for policy applications.

In simulation using the 2022v1 base CMAQ configuration, the EPA employed 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 WWLLNs data. These emissions were converted into 2-D CAMx emission format and used in CAMx simulations.

1. EPA selected the BEIS for inline biogenic emissions and soil NO emissions based on several considerations: **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[41]and northern

[41] 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.

California [42]. Overall, these previous assessments [43] indicate BEIS tend to better match measurements of biogenic VOC in high emitting regions of the CONUS than MEGAN.

CMAQ version 5.4 with CB6r5 chemistry and the AERO7 aerosol module with non-volatile POA is the model configuration for 2022 platform v1 (Table 2). This chemistry configuration has been used in previous modeling applications[44,45] and remains a reliable modeling approach.

CMAQ version 5.4 with STAGE dry deposition scheme was selected as the 2022v1 base configuration. STAGE is used to generate fertilizer NH_3 emissions based on Environmental Policy Integrated Climate model (EPIC) inputs. 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 2022v1 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 2016 platform.

[42] 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.

[43] 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.

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

[45] 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 2022 platform 2022v1 12US2 CMAQ configuration

Options	Description
Initial and boundary conditions	36US3 CMAQ with Hemi-CMAQ BC
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 NH3 flux on
Lightning NOx calculation	Hourly 3D lightning NOx emissions were calculated inline using WWLLNs data
Biogenic emission calculation	Hourly biogenic emissions were calculated inline using BEIS data
Kz/Kv	use Min Kz option in eddy input table

Table 5 - Key options in EPA 2022 platform 2022v1 12US2 CAMx configuration

Options	Description
Initial and boundary conditions	36US3 CMAQ with Hemi-CAMQ BC
Gas and aerosol chemistry	CB6r5_CF2E similar to nvPOA option in CAMQ
Dry Deposition/Air-surface exchange	ZHANG03 with bi-directional NH3 calculation off
Lightning NOx calculation	Hourly 3D lightning NOx emissions calculated offline based on WWLLNs 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 in order to enhance mixing associated with the nighttime “urban heat island” effect

4 Model performance evaluation of selected CMAQ and CAMx configurations

4.1 MPE methods

Model performance statistics were created for the period 01/01/2022 to 12/31/2022 using the 2022v1 12US2 CMAQ and CAMx model configurations described in Table 4 and Table 5. The performance statistics include:

1. **Mean bias (MB)** is the average of the difference (predicted – observed) divided by the total number of replicates (*n*). Mean bias is given in units of ppb and is defined as:
   MB = $\frac{1}{n}\sum_{1}^{n}(P-O)$, where P = predicted and O = observed concentrations
2. **Mean error (ME)** calculates the absolute value of the difference (predicted - observed) divided by the total number of replicates (*n*). Mean error is given in units of ppb and is defined as:
   ME = $\frac{1}{n}\sum_{1}^{n}|P-O|$
3. **Normalized mean bias (NMB)** is the average 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. Normalized mean bias 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)** is the absolute value of the difference (predicted - observed) over the sum of observed values. Normalized mean error is given in percentage units and is defined as:
   NME = $\frac{\sum_{1}^{n}|P-O|}{\sum_{1}^{n}(O)} * 100$

The Atmospheric Model Evaluation Tool (AMET) v1.5[46] was used to calculate the model performance statistics in this document. There are various statistical metrics available and used

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

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, ME, and NME. Modeled $PM_{2.5}$ concentrations and O_3 concentrations were compared with available observations from U.S. EPA's AQS database (www.epa.gov/aqs). Statistics were generated for each of the nine National Oceanic and Atmospheric Administration (NOAA) climate regions[47] of the 12-km U.S. modeling domain (Figure 4). The regions include the Northeast, Ohio Valley, Upper Midwest, Southeast, South, Southwest, Northern Rockies/Plains, Northwest, and West[48] [49] as were originally identified in Karl and Koss (1984).[50]

In addition to the performance statistics, CONUS maps which show the NMB were prepared for the O_3 season, May through September, at individual monitoring sites as well as on an annual basis for $PM_{2.5}$ and its component species. Model performance statistics were created for the period 01/01/2022 to 12/31/2022 using the 2022v1 12US2 CMAQ and CAMx model configurations described in Table 4 and Table 5. The performance statistics include:

1. **Mean bias (MB):** The average of the difference (predicted – observed) divided by the total number of replicates (*n*). MB is given in either ppb or ug $m^{-3}$and is defined as:
   MB = $\frac{1}{n}\sum_{1}^{n}(P - O)$, where P = predicted concentrations and O = observed concentrations

[47] 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.

[48] 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.

[49] 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.

[50] 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.

2. **Mean error (ME):** Calculates the absolute value of the difference (predicted - observed) divided by the total number of replicates (*n*). ME is given in either ppb or ug $m^{-3}$and is defined as:

   ME = $\frac{1}{n}\sum_1^n |P - O|$

3. **Normalized mean bias (NMB):** The average 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)** is the absolute value of the difference (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)** is 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 unit of either ppb or ug m^{-3} and is defined as:

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

The Atmospheric Model Evaluation Tool (AMET) v1.5[51] was used to calculate the model performance statistics in this document. There are various statistical metrics available and 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, ME, 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). Statistics were generated for each of the nine National Oceanic and Atmospheric Administration (NOAA) climate regions[52] of the 12-km U.S. modeling domain (Figure 4). The regions include the Northeast, Ohio Valley, Upper Midwest, Southeast, South, Southwest, Northern Rockies/Plains, Northwest, and West[53,54] as were originally identified in Karl and Koss.[55]

In addition to the performance statistics, CONUS maps of the 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.

---

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

[52] 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.

[53] 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.

[54] 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.

[55] 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.

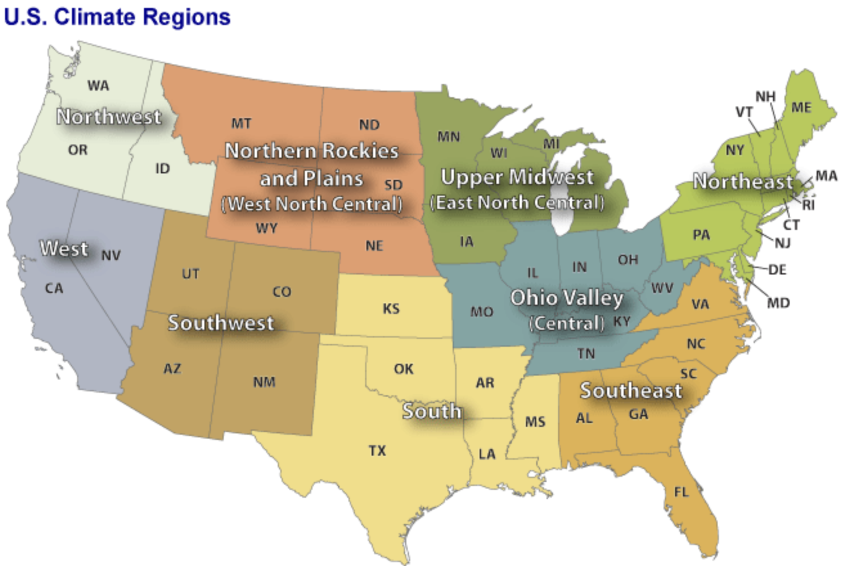

Figure 4 - NOAA climate regions (source: http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php)

4.2 CMAQ Results

This section summarizes the performance of CMAQ in predicting total $PM_{2.5}$, its constituent species, and the MDA8 O_3. The summary is organized by monitoring networks (AQS, IMPROVE, Chemical Speciation Network (CSN), CASTNET), seasons, and regions, 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, ME, NME and Pearson correlation coefficient (r) of $PM_{2.5}$ used in evaluating model performance are defined in Table 6. The annual NMBs in $PM_{2.5}$ predictions are within ± 30% for all regions except the Northeast (NMB: 35.7%) 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.

Tables 7 and 8 provide model performance statistics for SO_4^{2-} by regions and seasons for sites in the CSN and IMPROVE networks. The annual NMBs in SO_4^{2-}predictions are within ± 30% for all regions at CSN sites and within ± 30% for all regions except the Northwest (NMB: 44.7%) 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 5). 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}).

Tables 9 and 10 provide model performance statistics for NO_3^- by regions and seasons for sites in the CSN and IMPROVE networks. 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: 68.0%) 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 5). Model NO_3^- performance is reasonable in the regions where ammonium nitrate (NH_4NO_3) is important, such as Upper Midwest and Northern Rockies and Plains.

Tables 11 and 12 provide model performance statistics for OC by regions and seasons for sites in the CSN and IMPROVE networks. The annual NMBs in OC predictions are relatively high for all regions at CSN and IMPROVE sites. However, over-predicted OC concentrations are in 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 events, these high biases are also related to low planetary boundary layer height. The high NMBs of organic carbon in the Northwest region in summer is highly impacted by wildfires. Even the high biases of OC were found in the domain, overall correlations are moderate in most regions and seasons. Spatially, OC predictions tend to be biased high across the 12US2 domain (Figure 5), and the high biases in wintertime in Northeast region are discussed in detail in Section 5.

Tables 13 and 14 provide model performance statistics for EC by regions and seasons for sites in the CSN and IMPROVE networks. 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 eight of nine regions at IMPROVE sites are within ± 40%. Overall, annual and regional average EC mass are low across the domain (0.40 – 0.98 µg m^{-3} in the CSN network and 0.14 – 0.20 µg m^{-3} in the IMPROVE network). Spatially, EC predictions tend to be biased low across the 12US2 domain (Figure 5).

4.2.2 Daily max 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 MDA8 O_3 concentrations in space and time in each sub-region of the 12-km modeling domain, as indicated by the statistics in Table 15 and 16. Generally, predicted MDA8 O_3 at the AQS and CASTNET sites during the ozone season (spring, summer and fall) is within ± 15% for all climate regions (NMB ranging between -12.7 to 10.3%t).

NMB of MDA8 O_3 during the ozone season are within ± 20% at the vast majority of monitoring sites across the U.S. domain (Figure 6). In the Eastern domain, MDA8 O_3 tends to be overpredicted, and in southern California and urban sites in Arizona, MDA8 O_3 tends to be underpredicted. Figure 7 shows that the NMBs of MDA8 O_3 were underpredicted at most AQS and CASTNET sites when observing MDA8 O_3 > 60 ppb during the ozone 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	9.31	2.45	35.7	56.3	6.46	0.62
	Winter	22620	8.12	12.89	4.76	58.6	70.2	8.93	0.67
	Spring	24144	6.03	8.51	2.48	41.1	56.3	5.54	0.60
	Summer	24631	7.12	6.89	-0.23	-3.3	36.4	4.43	0.54
	Fall	23408	6.23	9.24	3.01	48.4	62.8	6.32	0.64
Southeast	All	73423	7.67	8.21	0.54	7.1	38.3	4.19	0.60
	Winter	17747	7.91	9.53	1.62	20.5	43.4	4.99	0.64
	Spring	18413	7.81	8.35	0.54	6.9	35.8	4.03	0.63
	Summer	18996	7.63	6.99	-0.64	-8.4	35.2	3.67	0.50
	Fall	18267	7.33	8.05	0.72	9.9	38.9	3.98	0.63
Ohio Valley	All	87586	8.24	9.66	1.42	17.2	38.6	4.62	0.64
	Winter	21179	8.85	11.26	2.41	27.2	43.1	5.35	0.68
	Spring	22061	7.32	8.92	1.60	21.9	40.3	4.09	0.69
	Summer	22341	8.66	8.37	-0.30	-3.4	30.8	4.00	0.48
	Fall	22005	8.15	10.17	2.02	24.8	40.7	4.95	0.70
Upper Midwest	All	50413	7.33	8.36	1.03	14.1	40.1	4.48	0.70
	Winter	12399	8.35	10.40	2.05	24.5	41.7	5.17	0.71
	Spring	12210	6.35	7.65	1.31	20.6	43.2	4.35	0.65
	Summer	12422	6.78	5.79	-0.99	-14.6	35.0	3.41	0.46
	Fall	13382	7.79	9.51	1.72	22.0	40.4	4.77	0.79
South	All	50911	8.62	7.68	-0.95	-11.0	41.6	5.47	0.40
	Winter	12261	7.40	8.00	0.59	8.0	43.4	5.06	0.49
	Spring	12861	9.06	8.29	-0.77	-8.5	37.8	5.18	0.51
	Summer	12952	9.54	5.75	-3.79	-39.8	49.8	7.04	0.25
	Fall	12837	8.43	8.71	0.28	3.3	34.8	4.18	0.59
Southwest	All	40373	6.42	6.46	0.04	0.6	57.9	5.94	0.35
	Winter	9912	8.01	8.47	0.46	5.7	67.6	8.38	0.33
	Spring	10299	5.96	6.88	0.92	15.5	55.9	5.12	0.28
	Summer	10111	5.89	4.04	-1.86	-31.5	50.6	4.35	0.15
	Fall	10051	5.87	6.48	0.61	10.5	54.2	5.16	0.46
Northern Rockies & Plains	All	25372	5.67	4.52	-1.16	-20.4	48.7	4.55	0.62
	Winter	6135	5.28	4.12	-1.16	-22.0	52.3	4.77	0.41
	Spring	6286	4.10	4.32	0.22	5.5	47.9	2.86	0.44
	Summer	6522	5.74	3.34	-2.41	-41.9	50.9	4.02	0.32
	Fall	6429	7.52	6.28	-1.24	-16.5	44.9	5.96	0.74
Northwest	All	52038	7.58	8.28	0.70	9.3	71.4	15.30	0.58
	Winter	12806	8.13	8.18	0.06	0.7	86.0	10.60	0.21
	Spring	13327	3.81	5.65	1.84	48.4	86.8	6.84	0.20
	Summer	13174	5.19	5.25	0.06	1.2	56.9	10.20	0.42
	Fall	12731	13.46	14.28	0.82	6.1	63.9	26.10	0.62
West	All	72477	8.00	7.27	-0.73	-9.1	46.6	7.25	0.53
	Winter	18018	9.34	9.06	-0.28	-3.0	52.7	7.76	0.59
	Spring	18145	6.93	7.06	0.13	1.9	43.7	4.79	0.42
	Summer	17956	7.14	5.24	-1.90	-26.6	42.1	7.34	0.46
	Fall	18358	8.58	7.72	-0.87	-10.1	46.2	8.56	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	0.77	-0.04	-4.9	34.9	0.50	0.47
	Winter	732	0.83	0.83	0.00	0.4	34.3	0.47	0.43
	Spring	781	0.76	0.88	0.11	15.0	32.0	0.38	0.63
	Summer	784	0.99	0.68	-0.31	-30.9	37.1	0.66	0.55
	Fall	737	0.67	0.70	0.04	5.6	35.6	0.42	0.49
Southeast	All	1788	0.86	0.87	0.00	0.5	33.8	0.42	0.45
	Winter	444	0.81	0.92	0.11	13.9	33.2	0.36	0.59
	Spring	451	0.91	0.96	0.05	5.3	32.4	0.41	0.48
	Summer	461	0.97	0.74	-0.23	-24.0	34.2	0.50	0.39
	Fall	432	0.76	0.86	0.10	13.3	35.4	0.37	0.53
Ohio Valley	All	2117	1.04	0.95	-0.09	-8.9	32.3	0.54	0.59
	Winter	518	1.04	0.97	-0.06	-6.3	30.5	0.49	0.59
	Spring	550	1.01	1.04	0.04	3.6	32.0	0.52	0.62
	Summer	547	1.25	0.92	-0.34	-26.8	36.1	0.71	0.58
	Fall	502	0.87	0.87	0.00	0.3	29.0	0.36	0.72
Upper Midwest	All	1029	0.84	0.83	-0.01	-1.7	32.7	0.47	0.65
	Winter	250	0.92	0.91	-0.01	-0.9	30.0	0.43	0.60
	Spring	265	0.84	0.91	0.06	7.4	34.5	0.50	0.70
	Summer	266	0.87	0.69	-0.18	-21.1	33.9	0.55	0.63
	Fall	248	0.73	0.81	0.08	11.0	32.6	0.35	0.76
South	All	1032	1.15	1.01	-0.14	-11.8	39.2	0.71	0.52
	Winter	254	0.94	0.97	0.03	3.2	40.1	0.58	0.68
	Spring	275	1.32	1.14	-0.19	-14.2	37.0	0.87	0.65
	Summer	256	1.34	0.84	-0.50	-37.5	42.9	0.77	0.36
	Fall	247	0.95	1.09	0.14	14.1	36.1	0.56	0.51
Southwest	All	1083	0.52	0.55	0.03	5.8	42.3	0.30	0.38
	Winter	259	0.45	0.46	0.01	1.5	51.7	0.36	0.12
	Spring	267	0.49	0.69	0.20	40.6	48.5	0.27	0.74
	Summer	276	0.68	0.50	-0.18	-26.1	34.6	0.34	0.44
	Fall	281	0.45	0.55	0.10	21.2	38.6	0.23	0.58
Northern Rockies & Plains	All	520	0.54	0.56	0.02	3.1	42.1	0.37	0.62
	Winter	130	0.50	0.47	-0.03	-5.9	44.6	0.31	0.58
	Spring	125	0.52	0.64	0.12	23.3	47.5	0.39	0.64
	Summer	134	0.60	0.50	-0.10	-16.3	36.3	0.37	0.67
	Fall	131	0.54	0.62	0.08	14.8	41.7	0.40	0.65
Northwest	All	542	0.49	0.62	0.13	26.3	52.9	0.45	0.35
	Winter	143	0.40	0.52	0.11	28.3	60.7	0.32	0.29
	Spring	149	0.41	0.60	0.19	46.9	56.6	0.28	0.54
	Summer	133	0.63	0.70	0.07	11.2	54.4	0.75	0.15
	Fall	117	0.54	0.67	0.13	24.6	40.3	0.27	0.74
West	All	1868	0.91	0.78	-0.13	-13.8	43.0	0.71	0.49
	Winter	462	0.62	0.63	0.01	1.7	61.6	0.63	0.30
	Spring	466	0.86	0.84	-0.03	-3.3	40.4	0.51	0.58
	Summer	473	1.28	0.86	-0.42	-32.8	41.1	1.06	0.41
	Fall	467	0.85	0.79	-0.06	-6.8	35.3	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	0.55	-0.03	-5.5	33.8	0.29	0.71
	Winter	484	0.61	0.61	0.00	-0.4	27.7	0.23	0.70
	Spring	486	0.53	0.63	0.09	17.5	31.7	0.23	0.78
	Summer	487	0.73	0.48	-0.25	-34.6	40.7	0.45	0.80
	Fall	495	0.46	0.49	0.03	7.0	33.4	0.21	0.77
Southeast	All	1619	0.81	0.72	-0.08	-10.3	34.6	0.40	0.52
	Winter	390	0.74	0.76	0.02	3.4	35.5	0.44	0.52
	Spring	408	0.84	0.83	-0.01	-1.3	31.1	0.36	0.57
	Summer	416	0.95	0.63	-0.32	-33.6	38.1	0.47	0.59
	Fall	405	0.69	0.67	-0.02	-2.4	33.1	0.31	0.60
Ohio Valley	All	939	0.88	0.79	-0.09	-10.3	32.5	0.41	0.67
	Winter	222	0.76	0.75	0.00	-0.3	31.7	0.34	0.65
	Spring	239	0.81	0.84	0.02	3.0	31.3	0.41	0.66
	Summer	241	1.18	0.81	-0.37	-31.3	35.8	0.54	0.72
	Fall	237	0.75	0.74	-0.01	-0.8	29.4	0.30	0.75
Upper Midwest	All	938	0.57	0.56	-0.02	-3.0	32.6	0.30	0.77
	Winter	229	0.64	0.63	-0.02	-2.7	28.9	0.26	0.73
	Spring	232	0.57	0.59	0.01	2.5	35.7	0.42	0.71
	Summer	241	0.58	0.44	-0.14	-24.1	33.1	0.28	0.91
	Fall	236	0.50	0.58	0.08	15.3	33.3	0.22	0.85
South	All	1138	0.87	0.77	-0.11	-12.2	43.1	0.59	0.47
	Winter	275	0.59	0.66	0.07	11.9	46.0	0.52	0.58
	Spring	281	0.98	0.91	-0.07	-7.2	41.6	0.70	0.53
	Summer	292	1.17	0.68	-0.49	-41.7	45.4	0.70	0.38
	Fall	290	0.74	0.81	0.08	10.4	39.1	0.39	0.55
Southwest	All	3639	0.41	0.47	0.06	14.9	51.5	0.33	0.51
	Winter	891	0.29	0.33	0.04	14.4	66.4	0.39	0.26
	Spring	897	0.41	0.63	0.22	53.2	65.5	0.35	0.57
	Summer	927	0.58	0.45	-0.13	-22.5	35.5	0.29	0.68
	Fall	924	0.36	0.48	0.12	33.8	50.1	0.27	0.72
Northern Rockies & Plains	All	1858	0.35	0.40	0.05	12.8	47.4	0.25	0.65
	Winter	446	0.31	0.31	0.00	0.2	55.2	0.25	0.77
	Spring	462	0.35	0.48	0.13	37.2	57.0	0.26	0.59
	Summer	483	0.37	0.34	-0.03	-8.8	32.7	0.21	0.67
	Fall	467	0.37	0.45	0.08	22.3	47.3	0.28	0.67
Northwest	All	1926	0.26	0.38	0.12	44.7	66.3	0.27	0.48
	Winter	445	0.16	0.27	0.11	72.7	103.0	0.20	0.47
	Spring	495	0.23	0.40	0.17	75.2	84.8	0.24	0.57
	Summer	502	0.33	0.40	0.08	23.0	52.2	0.39	0.29
	Fall	484	0.33	0.44	0.11	33.6	51.8	0.22	0.69
West	All	2231	0.45	0.48	0.03	7.6	50.4	0.32	0.51
	Winter	539	0.26	0.31	0.05	21.4	77.9	0.35	0.50
	Spring	607	0.49	0.63	0.14	27.7	51.2	0.32	0.53
	Summer	565	0.61	0.50	-0.11	-17.3	43.1	0.36	0.34
	Fall	520	0.41	0.45	0.04	10.9	43.4	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	1.00	0.18	22.0	57.9	0.85	0.82
	Winter	731	1.63	2.26	0.63	38.4	57.3	1.45	0.73
	Spring	781	0.80	0.92	0.12	15.1	51.8	0.65	0.78
	Summer	783	0.30	0.13	-0.17	-57.6	78.4	0.34	0.19
	Fall	737	0.60	0.78	0.18	29.7	57.0	0.57	0.83
Southeast	All	1787	0.39	0.60	0.21	54.1	91.1	0.66	0.67
	Winter	444	0.73	1.27	0.54	74.4	94.1	1.03	0.60
	Spring	451	0.32	0.41	0.09	28.9	73.4	0.36	0.32
	Summer	460	0.21	0.18	-0.03	-12.6	75.7	0.22	0.32
	Fall	432	0.31	0.56	0.25	80.0	114.0	0.72	0.57
Ohio Valley	All	2117	1.14	1.13	-0.01	-0.5	45.6	0.86	0.82
	Winter	518	2.41	2.40	-0.01	-0.2	38.1	1.31	0.71
	Spring	550	0.94	0.97	0.03	3.4	47.7	0.71	0.81
	Summer	547	0.40	0.17	-0.23	-57.9	74.7	0.40	0.29
	Fall	502	0.85	1.05	0.20	23.4	49.6	0.77	0.89
Upper Midwest	All	1028	1.30	1.24	-0.07	-5.2	37.3	0.81	0.88
	Winter	250	2.54	2.48	-0.06	-2.5	29.4	1.12	0.82
	Spring	265	1.31	1.16	-0.15	-11.6	38.8	0.82	0.86
	Summer	265	0.42	0.23	-0.19	-45.7	72.7	0.46	0.26
	Fall	248	1.00	1.15	0.15	15.0	39.6	0.72	0.93
South	All	1031	0.62	0.57	-0.05	-8.2	58.7	0.58	0.71
	Winter	253	1.11	1.14	0.03	2.6	45.1	0.74	0.72
	Spring	275	0.60	0.46	-0.14	-23.8	54.4	0.46	0.73
	Summer	256	0.34	0.18	-0.16	-46.3	71.4	0.30	0.41
	Fall	247	0.45	0.53	0.08	17.4	89.5	0.71	0.52
Southwest	All	1083	1.11	0.54	-0.57	-51.3	67.8	1.85	0.64
	Winter	259	2.99	1.17	-1.82	-60.9	67.4	3.61	0.58
	Spring	267	0.53	0.45	-0.08	-14.8	58.5	0.49	0.38
	Summer	276	0.30	0.17	-0.13	-43.4	93.8	0.36	0.07
	Fall	281	0.74	0.42	-0.32	-43.4	65.5	0.93	0.66
Northern Rockies & Plains	All	519	0.60	0.42	-0.18	-30.3	53.8	0.63	0.70
	Winter	130	1.08	0.80	-0.29	-26.4	45.7	0.92	0.68
	Spring	125	0.54	0.43	-0.11	-20.8	50.6	0.46	0.74
	Summer	133	0.24	0.08	-0.15	-64.7	71.3	0.24	0.58
	Fall	131	0.57	0.39	-0.18	-31.7	64.6	0.68	0.51
Northwest	All	541	0.90	1.46	0.56	61.4	125.0	1.89	0.34
	Winter	143	1.64	2.14	0.50	30.4	111.0	2.58	0.16
	Spring	148	0.46	1.03	0.57	123.0	157.0	1.25	0.44
	Summer	133	0.27	1.14	0.87	317.0	345.0	1.59	0.54
	Fall	117	1.28	1.54	0.25	19.8	80.3	1.86	0.48
West	All	1867	1.94	0.86	-1.09	-55.9	66.2	2.51	0.60
	Winter	462	3.54	1.86	-1.68	-47.4	60.5	3.70	0.60
	Spring	465	1.35	0.71	-0.64	-47.6	65.4	1.45	0.30
	Summer	473	0.93	0.29	-0.64	-68.5	71.2	1.03	0.62
	Fall	467	1.98	0.58	-1.39	-70.5	74.5	2.93	0.55

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	0.59	0.24	68.0	97.0	0.64	0.75
	Winter	486	0.68	1.30	0.62	90.3	102.0	1.04	0.72
	Spring	486	0.29	0.50	0.20	70.0	104.0	0.56	0.61
	Summer	486	0.16	0.16	0.00	-0.7	91.8	0.25	0.41
	Fall	495	0.28	0.42	0.14	50.8	82.6	0.40	0.78
Southeast	All	1619	0.31	0.43	0.12	37.3	89.6	0.53	0.68
	Winter	390	0.55	0.95	0.40	71.7	101.0	0.86	0.65
	Spring	408	0.29	0.33	0.04	13.4	68.5	0.29	0.49
	Summer	416	0.18	0.13	-0.05	-28.7	72.5	0.19	0.47
	Fall	405	0.23	0.33	0.10	42.9	104.0	0.55	0.56
Ohio Valley	All	939	0.59	0.70	0.11	18.1	63.3	0.69	0.77
	Winter	222	1.34	1.72	0.38	28.7	60.7	1.17	0.66
	Spring	239	0.42	0.47	0.05	12.1	62.1	0.46	0.73
	Summer	241	0.21	0.06	-0.15	-69.3	79.5	0.26	0.21
	Fall	237	0.45	0.61	0.16	35.5	63.9	0.56	0.88
Upper Midwest	All	936	0.58	0.58	0.00	0.0	45.3	0.53	0.87
	Winter	229	1.29	1.27	-0.02	-1.4	37.5	0.79	0.87
	Spring	231	0.49	0.46	-0.03	-6.8	52.0	0.51	0.71
	Summer	241	0.13	0.06	-0.06	-50.6	76.0	0.16	0.60
	Fall	235	0.44	0.56	0.12	26.4	50.9	0.48	0.93
South	All	1138	0.45	0.38	-0.07	-15.3	61.9	0.45	0.77
	Winter	275	0.75	0.77	0.02	2.2	50.4	0.58	0.79
	Spring	281	0.51	0.40	-0.11	-21.6	49.3	0.35	0.86
	Summer	292	0.26	0.04	-0.22	-83.4	87.5	0.30	0.19
	Fall	290	0.30	0.34	0.04	14.0	87.4	0.53	0.62
Southwest	All	3638	0.23	0.13	-0.10	-44.0	75.9	0.39	0.48
	Winter	891	0.37	0.17	-0.20	-54.8	74.0	0.68	0.55
	Spring	897	0.22	0.24	0.01	5.5	66.5	0.22	0.46
	Summer	927	0.17	0.03	-0.14	-81.7	89.0	0.20	0.18
	Fall	923	0.15	0.08	-0.07	-47.3	79.3	0.25	0.51
Northern Rockies & Plains	All	1858	0.22	0.20	-0.02	-6.9	65.8	0.28	0.71
	Winter	446	0.33	0.34	0.01	2.3	61.7	0.37	0.68
	Spring	462	0.23	0.23	0.00	-1.4	57.0	0.25	0.75
	Summer	482	0.10	0.03	-0.07	-68.9	78.4	0.13	0.61
	Fall	468	0.22	0.23	0.01	4.4	74.9	0.32	0.67
Northwest	All	1911	0.22	0.26	0.04	18.7	113.0	0.68	0.43
	Winter	440	0.34	0.39	0.05	13.7	111.0	0.88	0.38
	Spring	489	0.14	0.22	0.08	55.7	115.0	0.41	0.52
	Summer	498	0.10	0.15	0.05	52.8	180.0	0.58	0.56
	Fall	484	0.30	0.28	-0.02	-5.6	90.1	0.78	0.51
West	All	2230	0.45	0.21	-0.24	-52.7	68.8	0.85	0.79
	Winter	538	0.63	0.33	-0.30	-47.7	58.8	1.16	0.87
	Spring	607	0.44	0.29	-0.15	-33.8	64.3	0.52	0.47
	Summer	565	0.25	0.06	-0.20	-78.0	86.6	0.31	0.26
	Fall	520	0.48	0.17	-0.32	-65.5	77.1	1.13	0.78

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	3.34	1.74	108.0	117.0	3.04	0.37
	Winter	707	1.30	4.04	2.74	210.0	213.0	4.00	0.46
	Spring	760	1.35	3.15	1.80	133.0	138.0	2.94	0.45
	Summer	781	2.18	2.93	0.75	34.4	50.9	1.75	0.51
	Fall	703	1.56	3.32	1.76	113.0	118.0	3.16	0.47
Southeast	All	1724	2.25	3.46	1.21	53.6	68.7	2.17	0.55
	Winter	427	2.09	3.56	1.47	70.2	82.1	2.39	0.61
	Spring	423	2.29	3.44	1.15	50.3	65.7	2.15	0.58
	Summer	445	2.21	3.23	1.02	46.2	61.4	1.85	0.47
	Fall	429	2.42	3.62	1.20	49.5	66.9	2.26	0.52
Ohio Valley	All	2116	1.90	2.96	1.06	55.6	65.8	1.79	0.59
	Winter	535	1.49	3.35	1.87	126.0	131.0	2.54	0.47
	Spring	549	1.75	2.69	0.94	53.7	63.5	1.54	0.72
	Summer	525	2.37	2.88	0.50	21.3	33.6	1.07	0.72
	Fall	507	2.01	2.91	0.90	44.6	56.1	1.67	0.70
Upper Midwest	All	1162	1.61	2.82	1.21	75.0	87.8	2.15	0.46
	Winter	289	1.25	3.76	2.51	202.0	202.0	3.21	0.61
	Spring	288	1.27	2.42	1.15	90.7	98.6	1.80	0.56
	Summer	303	1.98	2.09	0.12	5.9	33.5	0.92	0.53
	Fall	282	1.95	3.06	1.11	56.8	65.3	2.08	0.68
South	All	936	2.18	2.58	0.40	18.3	52.2	2.87	0.29
	Winter	223	1.96	2.80	0.84	42.9	67.5	1.98	0.47
	Spring	233	1.81	2.20	0.40	21.9	48.5	1.41	0.66
	Summer	250	1.89	2.09	0.20	10.3	46.4	1.32	0.52
	Fall	230	3.10	3.30	0.20	6.5	48.8	5.08	0.19
Southwest	All	1110	1.68	2.75	1.08	64.3	88.9	2.71	0.32
	Winter	282	2.36	4.38	2.03	86.1	115.0	4.28	0.15
	Spring	280	1.14	2.12	0.99	86.7	96.4	1.86	0.30
	Summer	276	1.40	1.56	0.17	11.8	47.8	0.85	0.32
	Fall	272	1.81	2.92	1.11	61.4	81.3	2.60	0.32
Northern Rockies & Plains	All	488	1.46	1.26	-0.19	-13.3	57.5	1.75	0.68
	Winter	116	1.12	1.17	0.05	4.4	84.1	2.01	0.26
	Spring	113	0.68	0.86	0.18	27.1	64.0	0.68	0.52
	Summer	129	1.61	0.93	-0.68	-42.4	51.0	1.13	0.31
	Fall	130	2.29	2.04	-0.26	-11.2	48.8	2.48	0.81
Northwest	All	530	2.21	5.80	3.60	163.0	179.0	5.36	0.47
	Winter	143	1.92	6.09	4.18	218.0	225.0	5.42	0.47
	Spring	148	1.13	4.98	3.85	341.0	341.0	5.33	0.55
	Summer	134	1.67	4.91	3.24	194.0	200.0	4.35	0.51
	Fall	105	4.80	7.72	2.92	60.8	90.8	6.37	0.53
West	All	1232	2.75	3.59	0.85	30.8	55.4	3.11	0.49
	Winter	309	3.78	5.66	1.88	49.7	65.0	3.67	0.65
	Spring	306	1.81	2.63	0.82	45.2	57.0	1.56	0.59
	Summer	312	1.95	1.96	0.01	0.3	37.7	1.03	0.40
	Fall	305	3.46	4.15	0.69	19.9	54.2	4.68	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	1.75	0.89	105.0	123.0	3.21	0.34
	Winter	458	0.67	2.14	1.47	221.0	224.0	2.25	0.74
	Spring	451	0.65	1.83	1.18	181.0	188.0	5.79	0.29
	Summer	458	1.26	1.37	0.11	8.8	45.9	0.87	0.70
	Fall	463	0.84	1.66	0.82	97.6	108.0	1.50	0.79
Southeast	All	1727	1.31	1.96	0.65	49.7	67.4	1.93	0.67
	Winter	420	1.24	2.18	0.94	76.3	88.5	2.74	0.61
	Spring	437	1.35	2.12	0.77	57.0	73.3	2.14	0.65
	Summer	438	1.31	1.78	0.47	35.5	55.9	1.18	0.78
	Fall	432	1.34	1.78	0.44	32.4	54.1	1.22	0.81
Ohio Valley	All	930	1.23	1.92	0.69	56.0	67.0	1.39	0.72
	Winter	221	0.92	1.70	0.78	84.9	90.3	1.41	0.63
	Spring	236	1.19	1.90	0.71	60.0	71.6	1.70	0.79
	Summer	236	1.50	2.17	0.67	44.9	55.9	1.26	0.71
	Fall	237	1.29	1.89	0.60	46.0	60.0	1.12	0.76
Upper Midwest	All	1036	0.89	1.25	0.37	41.5	67.0	0.99	0.68
	Winter	253	0.63	1.42	0.79	126.0	128.0	1.30	0.84
	Spring	253	0.64	1.02	0.38	59.3	72.7	0.80	0.78
	Summer	266	1.23	1.07	-0.16	-12.7	39.8	0.63	0.60
	Fall	264	1.02	1.50	0.48	47.0	60.8	1.09	0.78
South	All	1142	1.08	1.39	0.31	28.3	54.3	1.25	0.70
	Winter	274	0.75	1.19	0.44	59.1	71.8	1.20	0.68
	Spring	290	1.23	1.65	0.42	33.9	58.6	1.87	0.77
	Summer	293	1.18	1.16	-0.02	-1.6	41.1	0.75	0.63
	Fall	285	1.16	1.56	0.40	34.5	52.4	0.89	0.76
Southwest	All	3637	0.66	0.65	-0.01	-1.6	53.5	0.72	0.65
	Winter	886	0.67	0.66	-0.01	-1.7	62.8	1.03	0.63
	Spring	894	0.58	0.77	0.19	32.1	57.3	0.69	0.78
	Summer	932	0.74	0.50	-0.24	-32.7	47.4	0.52	0.58
	Fall	925	0.65	0.68	0.03	4.8	47.9	0.56	0.68
Northern Rockies & Plains	All	1935	1.06	0.93	-0.13	-12.2	59.2	3.36	0.48
	Winter	462	0.31	0.49	0.18	57.6	83.1	0.86	0.24
	Spring	474	0.34	0.50	0.16	47.7	78.1	0.79	0.26
	Summer	504	1.16	0.70	-0.46	-39.7	57.1	1.60	0.24
	Fall	495	2.36	2.00	-0.36	-15.3	54.7	6.35	0.48
Northwest	All	1877	1.39	1.71	0.33	23.5	81.8	3.56	0.68
	Winter	430	0.51	1.03	0.52	102.0	147.0	1.86	0.46
	Spring	470	0.33	0.80	0.46	139.0	161.0	1.67	0.62
	Summer	500	1.09	1.22	0.13	11.6	74.6	1.79	0.45
	Fall	477	3.52	3.74	0.22	6.3	68.3	6.38	0.69
West	All	2185	1.02	1.05	0.03	2.8	60.6	2.78	0.43
	Winter	526	0.74	0.82	0.08	10.6	57.9	0.88	0.80
	Spring	584	0.68	0.75	0.07	10.3	47.2	0.52	0.63
	Summer	552	1.30	1.23	-0.06	-4.8	67.5	4.75	0.37
	Fall	523	1.38	1.41	0.03	1.9	62.7	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	0.42	-0.16	-27.9	44.7	0.44	0.47
	Winter	707	0.60	0.54	-0.06	-10.0	41.7	0.47	0.48
	Spring	761	0.53	0.39	-0.14	-26.5	42.8	0.42	0.52
	Summer	781	0.57	0.31	-0.26	-45.5	50.2	0.42	0.36
	Fall	703	0.62	0.44	-0.18	-28.6	43.9	0.43	0.54
Southeast	All	1725	0.76	0.38	-0.38	-49.7	58.0	0.67	0.41
	Winter	428	0.85	0.45	-0.40	-46.9	54.8	0.73	0.43
	Spring	423	0.77	0.37	-0.41	-52.4	57.5	0.67	0.51
	Summer	445	0.56	0.30	-0.27	-47.3	58.0	0.51	0.11
	Fall	429	0.85	0.41	-0.44	-51.8	61.4	0.75	0.36
Ohio Valley	All	2116	0.70	0.38	-0.32	-45.4	50.2	0.49	0.53
	Winter	535	0.64	0.47	-0.17	-26.2	41.4	0.44	0.40
	Spring	549	0.68	0.34	-0.34	-49.9	52.9	0.51	0.62
	Summer	525	0.71	0.31	-0.40	-56.3	56.9	0.53	0.47
	Fall	507	0.76	0.40	-0.36	-47.4	48.8	0.48	0.74
Upper Midwest	All	1164	0.50	0.37	-0.13	-25.5	45.8	0.33	0.52
	Winter	290	0.46	0.51	0.05	10.2	44.5	0.32	0.47
	Spring	289	0.40	0.32	-0.08	-19.7	42.8	0.24	0.57
	Summer	303	0.49	0.26	-0.23	-47.4	51.9	0.33	0.41
	Fall	282	0.64	0.40	-0.24	-37.6	43.5	0.40	0.69
South	All	936	0.68	0.38	-0.30	-44.3	49.4	1.29	0.25
	Winter	223	0.84	0.47	-0.36	-43.4	46.9	0.60	0.67
	Spring	233	0.52	0.31	-0.21	-40.7	43.6	0.34	0.73
	Summer	250	0.41	0.28	-0.12	-30.7	47.4	0.26	0.49
	Fall	230	0.98	0.46	-0.52	-53.1	55.4	2.50	0.09
Southwest	All	1110	0.63	0.41	-0.22	-35.1	50.5	0.58	0.49
	Winter	282	1.13	0.64	-0.49	-43.7	58.4	1.00	0.28
	Spring	280	0.36	0.32	-0.05	-12.5	42.8	0.24	0.52
	Summer	276	0.33	0.25	-0.08	-23.9	37.7	0.17	0.55
	Fall	272	0.71	0.44	-0.27	-38.0	47.4	0.50	0.47
Northern Rockies & Plains	All	488	0.40	0.17	-0.23	-56.6	64.6	0.68	0.35
	Winter	116	0.49	0.18	-0.31	-63.1	76.2	1.13	0.13
	Spring	113	0.20	0.13	-0.08	-37.3	50.6	0.19	0.47
	Summer	129	0.35	0.12	-0.23	-66.9	67.3	0.30	0.21
	Fall	130	0.55	0.27	-0.28	-51.1	58.2	0.70	0.54
Northwest	All	530	0.71	0.85	0.14	19.9	66.4	0.72	0.45
	Winter	143	0.86	0.82	-0.04	-5.0	51.1	0.60	0.47
	Spring	148	0.47	0.71	0.24	51.3	83.0	0.57	0.45
	Summer	134	0.47	0.85	0.38	81.8	102.0	0.66	0.59
	Fall	105	1.15	1.10	-0.06	-4.9	53.8	1.06	0.44
West	All	1232	0.98	0.51	-0.47	-48.0	50.9	0.84	0.75
	Winter	309	1.68	0.79	-0.89	-52.9	54.4	1.19	0.71
	Spring	306	0.61	0.39	-0.23	-36.9	43.7	0.38	0.70
	Summer	312	0.49	0.30	-0.19	-38.4	43.2	0.35	0.41
	Fall	305	1.14	0.56	-0.58	-51.0	52.9	1.07	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	3.8	47.8	0.15	0.71
	Winter	455	0.19	0.26	0.08	41.9	61.3	0.19	0.72
	Spring	449	0.15	0.18	0.03	20.2	51.7	0.17	0.68
	Summer	458	0.20	0.12	-0.08	-39.1	43.8	0.12	0.78
	Fall	461	0.20	0.20	0.00	-1.1	36.4	0.11	0.85
Southeast	All	1724	0.29	0.18	-0.11	-38.2	45.8	0.23	0.81
	Winter	420	0.32	0.23	-0.09	-26.8	39.6	0.20	0.81
	Spring	437	0.30	0.19	-0.11	-37.6	46.2	0.27	0.80
	Summer	435	0.23	0.12	-0.10	-45.7	51.1	0.18	0.80
	Fall	432	0.32	0.18	-0.14	-44.4	47.6	0.24	0.84
Ohio Valley	All	930	0.25	0.16	-0.09	-35.6	42.7	0.14	0.68
	Winter	221	0.24	0.20	-0.04	-18.0	35.5	0.13	0.59
	Spring	236	0.24	0.16	-0.08	-34.1	41.4	0.13	0.75
	Summer	236	0.24	0.11	-0.12	-52.7	54.5	0.16	0.63
	Fall	237	0.28	0.18	-0.10	-36.6	39.7	0.14	0.79
Upper Midwest	All	1033	0.20	0.13	-0.07	-33.4	46.7	0.14	0.74
	Winter	252	0.18	0.18	0.00	1.3	34.8	0.10	0.82
	Spring	253	0.16	0.11	-0.05	-29.4	42.7	0.11	0.79
	Summer	266	0.21	0.08	-0.12	-59.8	61.2	0.17	0.77
	Fall	262	0.25	0.16	-0.09	-37.2	45.2	0.17	0.79
South	All	1135	0.20	0.12	-0.08	-37.9	49.8	0.21	0.47
	Winter	274	0.19	0.13	-0.06	-31.1	40.8	0.12	0.72
	Spring	290	0.22	0.16	-0.06	-25.6	54.2	0.29	0.61
	Summer	286	0.16	0.07	-0.09	-54.6	56.8	0.12	0.49
	Fall	285	0.23	0.13	-0.10	-43.7	47.9	0.24	0.35
Southwest	All	3606	0.16	0.08	-0.08	-48.3	59.3	0.27	0.65
	Winter	876	0.24	0.09	-0.15	-60.9	66.7	0.47	0.71
	Spring	878	0.12	0.09	-0.03	-21.2	51.5	0.14	0.72
	Summer	928	0.11	0.06	-0.05	-48.0	56.9	0.09	0.66
	Fall	924	0.17	0.08	-0.08	-50.0	56.3	0.22	0.65
Northern Rockies & Plains	All	1913	0.14	0.11	-0.03	-21.2	62.3	0.30	0.51
	Winter	450	0.07	0.06	-0.01	-18.3	62.1	0.15	0.18
	Spring	470	0.06	0.06	0.00	-4.0	63.9	0.13	0.18
	Summer	498	0.13	0.07	-0.06	-47.9	69.2	0.21	0.15
	Fall	495	0.27	0.23	-0.04	-13.3	58.7	0.52	0.53
Northwest	All	1855	0.20	0.19	-0.01	-4.0	72.0	0.69	0.47
	Winter	415	0.13	0.13	0.01	4.0	76.8	0.20	0.70
	Spring	472	0.07	0.11	0.03	40.9	91.5	0.21	0.58
	Summer	494	0.14	0.15	0.01	9.0	84.2	0.27	0.68
	Fall	474	0.44	0.36	-0.08	-17.9	63.5	1.30	0.49
West	All	2145	0.17	0.11	-0.06	-37.0	56.8	0.28	0.69
	Winter	512	0.20	0.10	-0.09	-46.8	61.8	0.26	0.81
	Spring	573	0.10	0.09	-0.02	-17.2	45.9	0.09	0.69
	Summer	537	0.16	0.10	-0.06	-36.0	55.7	0.28	0.61
	Fall	523	0.24	0.14	-0.09	-39.4	58.6	0.40	0.70

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	41.9	2.1	5.2	12.7	6.43	0.80
	Winter	7926	33.9	37.8	3.8	11.3	15.0	6.47	0.70
	Spring	16165	42.5	45.0	2.5	5.9	11.7	6.26	0.67
	Summer	16222	44.8	45.4	0.7	1.5	11.3	6.55	0.78
	Fall	12390	33.5	35.7	2.3	6.8	15.2	6.47	0.73
Southeast	All	48275	39.4	41.5	2.0	5.1	12.8	6.50	0.79
	Winter	6842	36.7	39.4	2.7	7.4	12.6	6.17	0.71
	Spring	15220	43.9	43.7	-0.2	-0.5	10.2	5.78	0.79
	Summer	14520	37.9	41.7	3.9	10.3	15.8	7.49	0.80
	Fall	11693	37.2	39.4	2.2	6.0	12.9	6.22	0.77
Ohio Valley	All	60934	41.6	44.5	2.9	7.0	13.9	7.26	0.77
	Winter	5499	30.9	36.9	6.0	19.5	22.5	8.13	0.76
	Spring	20427	42.7	45.9	3.2	7.5	13.0	6.97	0.63
	Summer	20107	46.4	48.8	2.4	5.3	12.5	7.31	0.74
	Fall	14901	37.4	39.5	2.0	5.4	15.1	7.24	0.71
Upper Midwest	All	24294	40.2	42.8	2.6	6.4	13.5	6.82	0.77
	Winter	1492	33.3	38.9	5.6	16.9	18.0	7.41	0.73
	Spring	8201	42.0	46.3	4.3	10.3	13.8	7.07	0.69
	Summer	8620	43.4	44.2	0.8	1.9	11.4	6.42	0.79
	Fall	5981	34.8	36.8	2.0	5.8	15.8	6.88	0.74
South	All	45543	40.5	41.7	1.2	2.8	13.9	7.19	0.82
	Winter	9623	33.7	36.8	3.2	9.5	15.2	6.53	0.79
	Spring	12336	44.2	44.7	0.4	1.0	12.0	6.88	0.75
	Summer	12064	41.3	42.9	1.6	3.9	15.6	8.11	0.82
	Fall	11520	41.5	41.2	-0.3	-0.7	13.2	7.02	0.83
Southwest	All	46026	48.0	47.8	-0.2	-0.3	11.6	7.46	0.70
	Winter	10447	39.2	42.7	3.5	8.9	14.9	8.04	0.56
	Spring	11922	51.1	51.6	0.5	1.0	9.1	6.19	0.58
	Summer	12266	55.8	52.3	-3.6	-6.4	12.5	9.07	0.48
	Fall	11391	44.3	43.8	-0.5	-1.2	10.7	6.08	0.72
Northern Rockies & Plains	All	16891	42.1	44.8	2.8	6.5	12.0	6.50	0.72
	Winter	4042	38.0	43.0	5.0	13.2	15.4	7.58	0.61
	Spring	4278	44.6	47.9	3.3	7.5	10.5	6.08	0.62
	Summer	4335	47.1	48.0	0.9	1.9	10.4	6.23	0.67
	Fall	4236	38.3	40.2	1.9	4.9	12.3	6.05	0.73
Northwest	All	6337	37.7	39.0	1.4	3.6	14.7	7.43	0.74
	Winter	803	32.3	38.0	5.7	17.7	22.4	9.55	0.70
	Spring	1672	39.1	41.7	2.6	6.6	12.0	6.06	0.70
	Summer	2521	39.1	38.4	-0.7	-1.7	13.8	7.43	0.80
	Fall	1341	36.5	37.6	1.0	2.8	15.9	7.54	0.73
West	All	60629	44.5	43.3	-1.2	-2.7	13.8	8.18	0.79
	Winter	13437	34.9	38.9	4.0	11.5	17.4	8.22	0.61
	Spring	15970	47.4	46.2	-1.2	-2.5	10.8	6.81	0.71
	Summer	16392	49.8	45.5	-4.3	-8.7	14.8	9.52	0.84
	Fall	14830	44.2	41.7	-2.4	-5.5	13.4	7.91	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	4287	39.9	41.8	1.8	4.6	11.8	6.07	0.77
	Winter	1116	35.4	39.1	3.7	10.3	13.3	5.99	0.72
	Spring	1191	43.9	45.9	2.0	4.6	10.6	5.92	0.64
	Summer	984	45.1	45.4	0.3	0.7	10.8	6.47	0.72
	Fall	996	35.1	36.2	1.1	3.1	13.2	5.94	0.69
Southeast	All	4037	40.0	40.8	0.8	2.0	12.5	10.70	0.57
	Winter	997	37.0	38.7	1.7	4.6	12.1	5.97	0.71
	Spring	1069	45.4	44.3	-1.1	-2.4	9.7	5.51	0.77
	Summer	983	39.4	41.5	2.1	5.3	17.2	19.10	0.40
	Fall	988	37.7	38.4	0.7	2.0	11.6	5.73	0.72
Ohio Valley	All	5659	40.2	42.4	2.3	5.6	13.6	6.80	0.76
	Winter	1426	33.7	38.2	4.4	13.1	17.5	7.27	0.71
	Spring	1554	44.6	46.1	1.6	3.5	11.4	6.36	0.61
	Summer	1343	44.7	46.8	2.1	4.8	12.5	6.84	0.76
	Fall	1336	37.4	38.3	0.9	2.5	14.1	6.72	0.69
Upper Midwest	All	1772	38.2	40.7	2.6	6.8	13.7	6.58	0.77
	Winter	440	34.7	39.6	4.9	14.0	14.8	6.51	0.74
	Spring	454	42.9	46.7	3.8	8.9	12.8	6.63	0.66
	Summer	444	40.9	41.1	0.2	0.4	11.8	6.32	0.82
	Fall	434	33.9	35.4	1.5	4.3	16.3	6.85	0.69
South	All	2068	42.2	41.8	-0.4	-1.0	15.1	28.60	0.28
	Winter	524	35.9	38.0	2.1	5.9	14.0	6.95	0.72
	Spring	538	45.9	45.7	-0.2	-0.5	10.1	5.99	0.77
	Summer	501	42.3	43.5	1.2	2.9	14.9	7.91	0.79
	Fall	505	44.9	40.0	-4.9	-10.9	21.8	56.70	0.15
Southwest	All	4257	48.8	48.6	-0.1	-0.2	8.6	5.54	0.73
	Winter	1060	43.7	44.7	1.0	2.2	9.0	5.15	0.64
	Spring	1075	52.3	52.7	0.4	0.7	7.0	4.92	0.63
	Summer	1056	54.3	52.5	-1.8	-3.3	9.9	6.86	0.50
	Fall	1066	44.7	44.7	0.0	-0.1	8.7	5.02	0.70
Northern Rockies & Plains	All	2477	44.2	47.6	3.4	7.7	11.3	6.78	0.70
	Winter	610	40.8	45.4	4.6	11.2	14.6	8.38	0.43
	Spring	634	47.1	50.1	3.0	6.4	8.8	5.26	0.70
	Summer	624	47.8	50.8	3.0	6.3	10.1	6.12	0.73
	Fall	609	40.9	43.8	3.0	7.3	12.3	7.01	0.66
Northwest	All	1062	40.3	44.4	4.1	10.1	14.3	7.81	0.61
	Winter	258	36.6	44.4	7.8	21.2	23.1	11.30	0.19
	Spring	269	42.4	46.7	4.3	10.1	11.8	6.11	0.74
	Summer	269	44.1	44.8	0.7	1.6	9.2	5.28	0.78
	Fall	266	37.9	41.6	3.7	9.8	14.9	7.37	0.67
West	All	2443	49.4	46.6	-2.8	-5.6	12.5	8.34	0.67
	Winter	597	41.7	43.9	2.3	5.5	11.1	6.25	0.57
	Spring	607	50.9	48.9	-1.9	-3.8	10.3	6.79	0.62
	Summer	630	56.7	49.5	-7.2	-12.7	15.7	11.20	0.66
	Fall	609	48.1	44.1	-4.0	-8.4	12.2	8.05	0.68

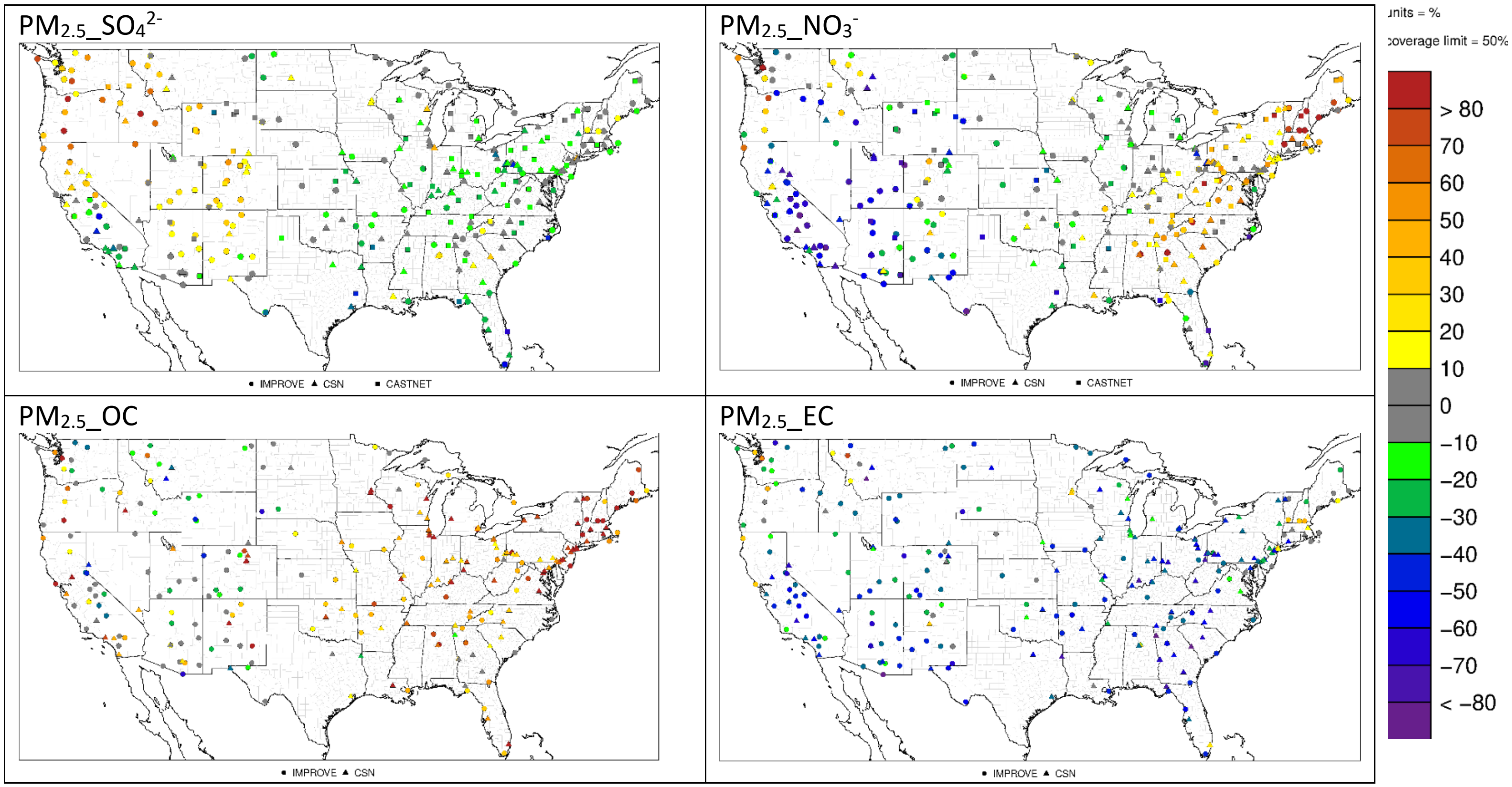

Figure 5 - NMB in 2022 CMAQ Predictions of $PM_{2.5}$ Components at CSN, CASTNET and IMPROVE Sites

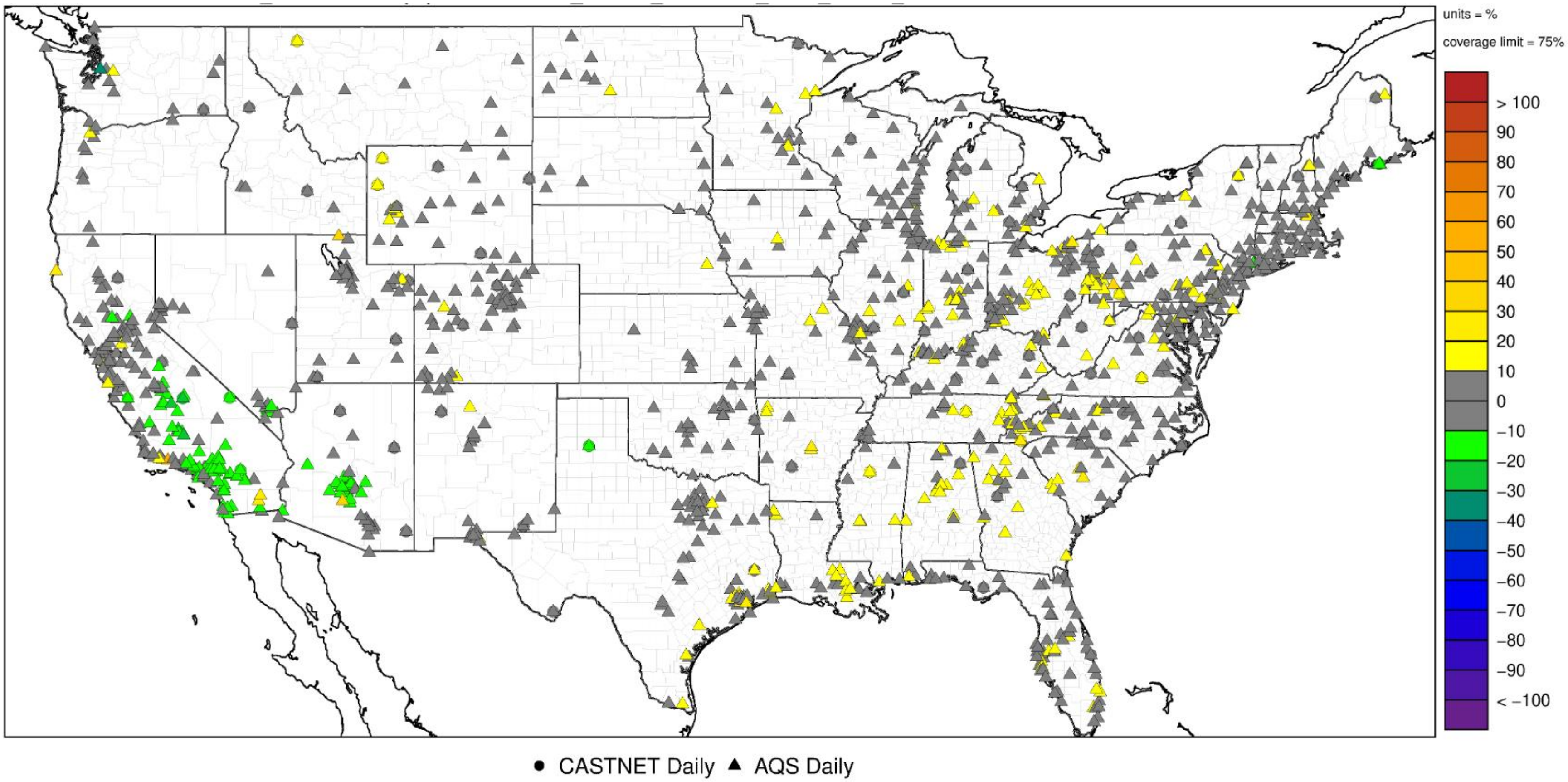

Figure 6 - NMB in 2022 CMAQ Predictions of MDA8 O_3 at AQS and CASTNET sites during ozone season (04/01/2022 – 09/30/2022)

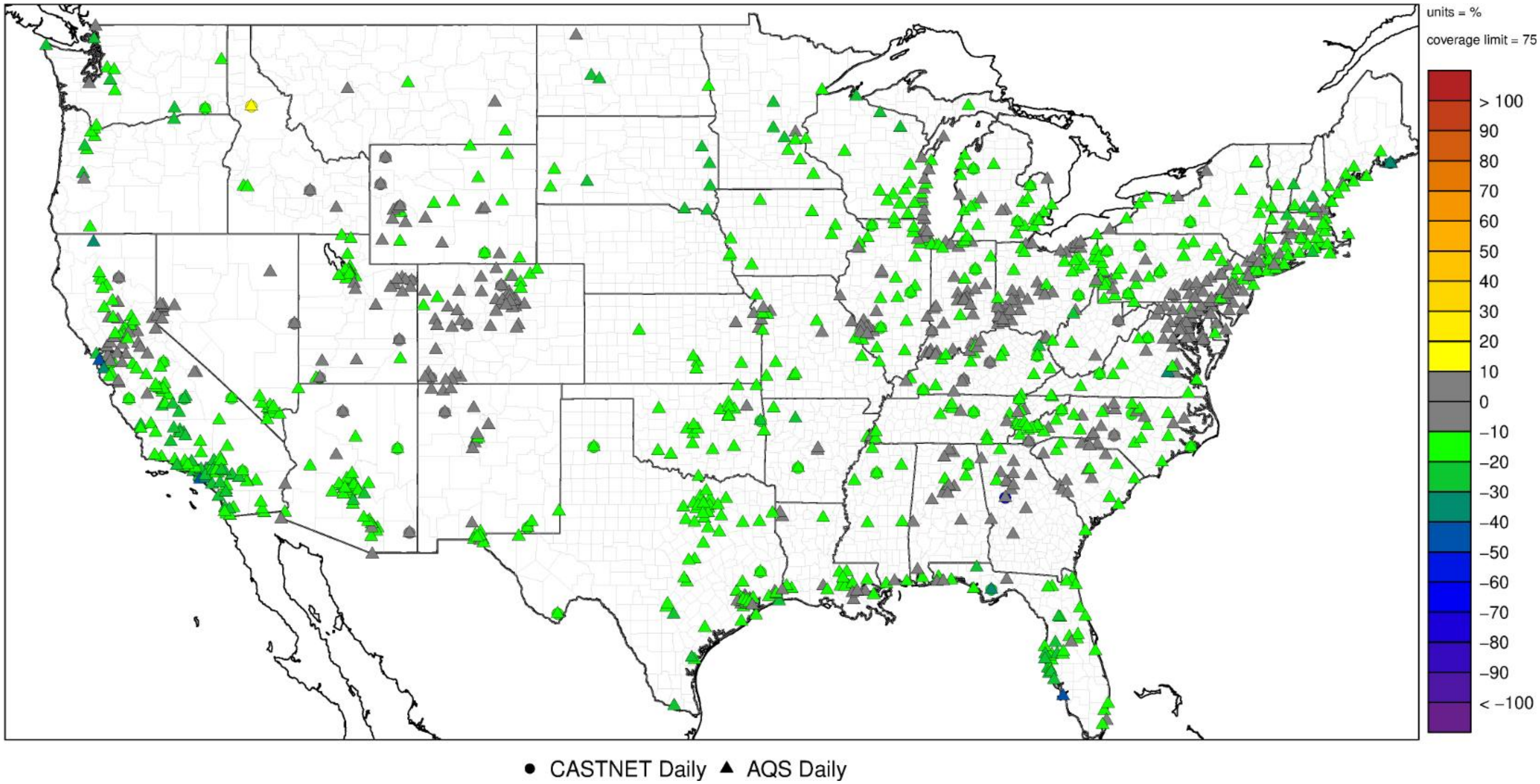

Figure 7 - NMB in 2022 CMAQ predictions of MDA8 O_3 at AQS and CASTNET sites when observation MDA8 O_3 > 60 ppb during ozone season (04/01/2022-09/30/2022)

4.3 CAMx Results

This section summarizes the performance of CAMx in predicting total $PM_{2.5}$, its constituent species, and the MDA8 O_3. The summary is organized by monitoring networks (AQS, IMPROVE, CSN, CASTNET), seasons, and regions, using the statistical metrics described in Section 4.1.

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

Table 17 provides the MB, NMB, ME, NME, and r of $PM_{2.5}$ used in evaluating model performance. The CAMx annual NMBs in $PM_{2.5}$ predictions are within ± 30% for all regions except the Northern Rockies & Plains (NMB: -37%) 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.

Tables 18 and 19 provide CAMx model performance statistics for SO_4^{2-} by regions and seasons for sites in the CSN and IMPROVE networks. The annual NMBs in SO_4^{2-} predictions are within ± 30% for all regions except the Northwest (NMB: 38.4 and 82.7 %) at CSN and IMPROVE sites. Spatially, SO_4^{2-} predictions tend to be biased slightly high toward the Eastern and Northwestern parts of the domain (Figure 8).

Tables 20 and 21 provide CAMx model performance statistics for NO_3^- by regions and seasons for sites in the CSN and IMPROVE networks. The annual NMBs in NO_3^- predictions are within ±65% for all regions except the Southeast (NMB: 85.8 and 75.0%) at CSN sites and IMPROVE sites. Model NO_3^- performance is reasonable in the regions where NH_4NO_3 is important, such as Upper Midwest and Northern Rockies & 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 8).

Tables 22 and 23 provide CAMx model performance statistics for OC by regions and seasons for sites in the CSN and IMPROVE networks. The annual NMBs in OC predictions are relatively high for all regions at CSN and IMPROVE sites. The over-predicted OC concentrations are similar to CMAQ model performance results in 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 8).

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 eight of nine regions at IMPROVE sites are within ± 40%. Spatially, EC predictions tend to be biased low across the 12US2 domain (Figure 8).

4.3.2 Daily max 8 hour O3 (MDA8 O3)

In general, the model performance statistics indicate that the MDA8 O_3 concentrations predicted by the 2022 CAMx simulation closely reflect the corresponding MDA8 O_3 concentrations in space and time in each sub-region of the 12-km modeling domain, as indicated by the statistics in Table 26 and 27. Generally, predicted MDA8 O_3 at the AQS and CASTNET sites during the ozone season (spring, summer and fall) is within ± 15% for all climate regions (NMB ranging between -11.6 to 11.5%).

NMB of MDA8 O_3 during the ozone season are within ± 20% at most monitoring sites across the U.S. domain (Figure 9). Figure 10 shows the NMBs of MDA8 O_3 were 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	8.41	1.55	22.6	46.4	5.29	0.59
	Winter	22620	8.12	10.50	2.38	29.3	50.6	6.50	0.63
	Spring	24144	6.03	7.78	1.75	29.0	46.2	4.49	0.62
	Summer	24631	7.12	6.81	-0.31	-4.3	34.4	4.02	0.51
	Fall	23408	6.23	8.74	2.51	40.3	55.8	5.91	0.55
Southeast	All	73423	7.67	7.75	0.08	1.1	34.4	3.75	0.59
	Winter	17747	7.91	9.04	1.13	14.3	38.4	4.37	0.65
	Spring	18413	7.81	7.72	-0.09	-1.2	32.0	3.64	0.63
	Summer	18996	7.63	6.85	-0.78	-10.2	34.7	3.67	0.42
	Fall	18267	7.33	7.46	0.14	1.9	32.6	3.26	0.62
Ohio Valley	All	87586	8.24	8.41	0.17	2.1	32.1	3.96	0.63
	Winter	21179	8.85	9.48	0.63	7.1	35.5	4.46	0.68
	Spring	22061	7.32	7.80	0.47	6.5	30.2	3.10	0.71
	Summer	22341	8.66	7.61	-1.05	-12.1	30.5	4.11	0.38
	Fall	22005	8.15	8.81	0.66	8.1	32.1	4.08	0.69
Upper Midwest	All	50413	7.33	7.03	-0.30	-4.1	34.1	3.67	0.71
	Winter	12399	8.35	8.20	-0.15	-1.8	34.2	4.08	0.72
	Spring	12210	6.35	6.57	0.22	3.5	36.1	3.51	0.68
	Summer	12422	6.78	5.41	-1.38	-20.3	36.2	3.52	0.42
	Fall	13382	7.79	7.89	0.09	1.2	30.9	3.54	0.81
South	All	50911	8.62	6.81	-1.81	-21.0	41.8	5.43	0.37
	Winter	12261	7.40	7.16	-0.24	-3.2	40.9	4.64	0.48
	Spring	12861	9.06	7.30	-1.76	-19.5	39.0	5.08	0.49
	Summer	12952	9.54	5.16	-4.38	-45.9	53.2	7.43	0.17
	Fall	12837	8.43	7.65	-0.78	-9.3	32.6	3.86	0.57
Southwest	All	40373	6.42	4.84	-1.59	-24.7	51.8	5.32	0.35
	Winter	9912	8.01	6.11	-1.91	-23.8	59.5	7.47	0.32
	Spring	10299	5.96	5.17	-0.79	-13.2	45.6	4.42	0.29
	Summer	10111	5.89	3.24	-2.65	-45.0	52.5	4.48	0.16
	Fall	10051	5.87	4.85	-1.01	-17.3	47.0	4.32	0.47
Northern Rockies & Plains	All	25372	5.67	3.57	-2.10	-37.0	51.2	4.75	0.64
	Winter	6135	5.28	3.02	-2.26	-42.8	56.6	4.98	0.40
	Spring	6286	4.10	3.45	-0.65	-15.9	43.9	2.65	0.46
	Summer	6522	5.74	2.91	-2.84	-49.4	55.3	4.28	0.29
	Fall	6429	7.52	4.90	-2.62	-34.8	48.2	6.32	0.76
Northwest	All	52038	7.58	7.26	-0.32	-4.2	64.0	13.60	0.58
	Winter	12806	8.13	6.85	-1.28	-15.8	76.5	8.96	0.17
	Spring	13327	3.81	5.01	1.20	31.4	73.7	5.85	0.18
	Summer	13174	5.19	4.84	-0.35	-6.7	50.6	7.60	0.49
	Fall	12731	13.46	12.55	-0.91	-6.7	58.9	24.20	0.62
West	All	72477	8.00	5.90	-2.10	-26.2	46.3	7.00	0.54
	Winter	18018	9.34	7.13	-2.21	-23.7	48.9	7.31	0.57
	Spring	18145	6.93	5.74	-1.20	-17.3	40.2	4.60	0.42
	Summer	17956	7.14	4.49	-2.65	-37.1	48.2	6.91	0.50
	Fall	18358	8.58	6.24	-2.35	-27.3	46.8	8.56	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	0.89	0.08	9.3	38.5	0.55	0.45
	Winter	732	0.83	0.89	0.06	7.4	39.8	0.55	0.38
	Spring	781	0.76	0.94	0.18	23.8	37.9	0.46	0.60
	Summer	784	0.99	0.85	-0.14	-13.6	31.6	0.63	0.54
	Fall	737	0.67	0.87	0.20	30.1	48.6	0.56	0.44
Southeast	All	1788	0.86	1.02	0.15	17.7	40.3	0.49	0.44
	Winter	444	0.81	1.10	0.29	36.0	44.6	0.51	0.62
	Spring	451	0.91	1.05	0.13	14.6	35.7	0.46	0.45
	Summer	461	0.97	0.88	-0.09	-9.2	32.9	0.50	0.38
	Fall	432	0.76	1.04	0.29	38.0	51.6	0.51	0.52
Ohio Valley	All	2117	1.04	1.05	0.00	0.4	33.6	0.60	0.59
	Winter	518	1.04	1.10	0.06	5.6	39.6	0.74	0.56
	Spring	550	1.01	1.04	0.04	3.8	29.3	0.50	0.67
	Summer	547	1.25	1.07	-0.18	-14.6	32.3	0.66	0.60
	Fall	502	0.87	0.98	0.12	13.5	33.9	0.45	0.74
Upper Midwest	All	1029	0.84	0.87	0.03	3.1	33.0	0.48	0.65
	Winter	250	0.92	0.90	-0.01	-1.3	32.4	0.50	0.58
	Spring	265	0.84	0.94	0.10	11.3	34.6	0.51	0.71
	Summer	266	0.87	0.79	-0.08	-8.9	32.6	0.53	0.62
	Fall	248	0.73	0.83	0.10	13.9	32.1	0.38	0.74
South	All	1032	1.15	1.09	-0.06	-4.8	39.6	0.75	0.49
	Winter	254	0.94	1.05	0.11	11.4	40.3	0.56	0.73
	Spring	275	1.32	1.16	-0.16	-12.2	36.8	0.88	0.62
	Summer	256	1.34	0.90	-0.44	-32.8	40.3	0.74	0.36
	Fall	247	0.95	1.25	0.29	30.7	42.2	0.78	0.48
Southwest	All	1083	0.52	0.54	0.02	3.2	40.3	0.29	0.39
	Winter	259	0.45	0.45	0.00	-0.6	50.7	0.35	0.12
	Spring	267	0.49	0.65	0.16	32.6	41.4	0.24	0.76
	Summer	276	0.68	0.49	-0.19	-27.4	35.2	0.34	0.43
	Fall	281	0.45	0.55	0.10	21.5	37.0	0.22	0.63
Northern Rockies & Plains	All	520	0.54	0.54	0.00	0.9	40.7	0.37	0.63
	Winter	130	0.50	0.45	-0.05	-9.4	46.8	0.33	0.52
	Spring	125	0.52	0.60	0.08	15.2	39.6	0.35	0.72
	Summer	134	0.60	0.52	-0.08	-12.7	36.7	0.37	0.66
	Fall	131	0.54	0.61	0.07	12.3	40.6	0.41	0.63
Northwest	All	542	0.49	0.68	0.19	38.4	59.9	0.49	0.35
	Winter	143	0.40	0.56	0.16	39.8	70.0	0.38	0.26
	Spring	149	0.41	0.64	0.24	58.2	63.5	0.32	0.59
	Summer	133	0.63	0.81	0.18	28.8	64.5	0.78	0.15
	Fall	117	0.54	0.71	0.17	30.8	41.1	0.29	0.75
West	All	1868	0.91	0.81	-0.10	-10.9	43.5	0.71	0.48
	Winter	462	0.62	0.63	0.01	1.3	61.9	0.65	0.28
	Spring	466	0.86	0.86	-0.01	-1.0	40.8	0.50	0.59
	Summer	473	1.28	0.94	-0.34	-26.4	40.5	1.04	0.38
	Fall	467	0.85	0.80	-0.05	-6.1	37.6	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	0.66	0.08	13.4	37.6	0.32	0.71
	Winter	484	0.61	0.68	0.07	12.2	36.6	0.32	0.58
	Spring	486	0.53	0.69	0.16	29.8	38.9	0.28	0.76
	Summer	487	0.73	0.65	-0.08	-11.2	32.0	0.39	0.77
	Fall	495	0.46	0.62	0.16	34.5	46.1	0.28	0.75
Southeast	All	1619	0.81	0.87	0.06	7.7	38.6	0.43	0.51
	Winter	390	0.74	0.95	0.21	28.5	47.3	0.51	0.54
	Spring	408	0.84	0.90	0.06	7.1	32.9	0.37	0.56
	Summer	416	0.95	0.77	-0.18	-18.5	33.5	0.43	0.57
	Fall	405	0.69	0.85	0.17	24.2	44.2	0.41	0.55
Ohio Valley	All	939	0.88	0.94	0.06	7.3	35.5	0.50	0.62
	Winter	222	0.76	0.97	0.22	28.8	51.4	0.69	0.57
	Spring	239	0.81	0.87	0.06	7.2	29.6	0.38	0.72
	Summer	241	1.18	1.03	-0.15	-12.8	29.6	0.48	0.72
	Fall	237	0.75	0.89	0.14	18.9	36.4	0.41	0.71
Upper Midwest	All	938	0.57	0.61	0.04	6.6	33.8	0.32	0.76
	Winter	229	0.64	0.65	0.00	0.3	32.7	0.33	0.67
	Spring	232	0.57	0.64	0.07	12.0	40.0	0.44	0.69
	Summer	241	0.58	0.55	-0.03	-5.2	28.7	0.25	0.88
	Fall	236	0.50	0.61	0.11	22.1	34.0	0.22	0.88
South	All	1138	0.87	0.83	-0.05	-5.3	43.9	0.61	0.45
	Winter	275	0.59	0.71	0.12	20.0	54.1	0.58	0.53
	Spring	281	0.98	0.93	-0.06	-5.8	39.3	0.67	0.58
	Summer	292	1.17	0.75	-0.42	-35.8	41.7	0.66	0.39
	Fall	290	0.74	0.92	0.18	24.9	45.5	0.52	0.51
Southwest	All	3639	0.41	0.48	0.07	16.1	51.0	0.32	0.51
	Winter	891	0.29	0.35	0.06	20.6	70.7	0.40	0.25
	Spring	897	0.41	0.60	0.19	45.2	56.9	0.31	0.64
	Summer	927	0.58	0.46	-0.12	-20.6	36.5	0.30	0.64
	Fall	924	0.36	0.50	0.14	40.1	52.5	0.28	0.73
Northern Rockies & Plains	All	1858	0.35	0.42	0.07	18.8	50.4	0.26	0.65
	Winter	446	0.31	0.34	0.03	8.2	59.9	0.28	0.69
	Spring	462	0.35	0.49	0.13	37.6	57.8	0.26	0.57
	Summer	483	0.37	0.37	-0.01	-1.4	36.7	0.22	0.61
	Fall	467	0.37	0.48	0.11	30.6	50.2	0.27	0.73
Northwest	All	1926	0.26	0.48	0.22	82.7	95.4	0.35	0.45
	Winter	445	0.16	0.33	0.18	115.0	139.0	0.26	0.38
	Spring	495	0.23	0.47	0.24	107.0	112.0	0.30	0.56
	Summer	502	0.33	0.56	0.24	71.9	88.7	0.49	0.22
	Fall	484	0.33	0.53	0.21	62.3	72.1	0.29	0.67
West	All	2231	0.45	0.52	0.08	17.2	54.7	0.34	0.48
	Winter	539	0.26	0.34	0.08	31.5	84.4	0.36	0.50
	Spring	607	0.49	0.66	0.17	33.6	53.4	0.32	0.55
	Summer	565	0.61	0.58	-0.03	-4.8	47.6	0.41	0.22
	Fall	520	0.41	0.49	0.08	20.5	48.7	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	1.03	0.21	25.8	62.6	1.00	0.67
	Winter	731	1.63	1.61	-0.02	-1.5	49.1	1.17	0.65
	Spring	781	0.80	1.07	0.28	34.8	54.2	0.82	0.80
	Summer	783	0.30	0.33	0.03	8.4	61.2	0.32	0.37
	Fall	737	0.60	1.17	0.58	96.4	112.0	1.40	0.56
Southeast	All	1787	0.39	0.72	0.34	85.8	109.0	0.77	0.53
	Winter	444	0.73	1.26	0.53	72.3	97.5	1.12	0.43
	Spring	451	0.32	0.63	0.31	96.9	111.0	0.63	0.17
	Summer	460	0.21	0.26	0.05	23.4	62.5	0.20	0.17
	Fall	432	0.31	0.78	0.47	151.0	166.0	0.83	0.54
Ohio Valley	All	2117	1.14	1.13	-0.01	-0.8	56.5	1.16	0.69
	Winter	518	2.41	1.95	-0.46	-19.0	53.7	1.84	0.60
	Spring	550	0.94	0.99	0.05	5.0	48.6	0.70	0.76
	Summer	547	0.40	0.40	0.00	0.4	64.3	0.41	0.22
	Fall	502	0.85	1.24	0.38	44.7	70.2	1.23	0.76
Upper Midwest	All	1028	1.30	1.09	-0.22	-16.7	42.3	0.91	0.83
	Winter	250	2.54	1.74	-0.80	-31.4	42.3	1.40	0.80
	Spring	265	1.31	1.16	-0.15	-11.6	37.6	0.81	0.86
	Summer	265	0.42	0.36	-0.06	-13.9	54.7	0.40	0.42
	Fall	248	1.00	1.13	0.13	13.0	43.2	0.76	0.86
South	All	1031	0.62	0.68	0.05	8.5	64.0	0.69	0.55
	Winter	253	1.11	1.05	-0.06	-5.7	53.0	0.81	0.59
	Spring	275	0.60	0.61	0.01	2.1	54.3	0.55	0.56
	Summer	256	0.34	0.27	-0.07	-21.1	60.7	0.31	0.16
	Fall	247	0.45	0.80	0.35	77.2	109.0	0.93	0.42
Southwest	All	1083	1.11	0.41	-0.70	-62.8	70.2	2.07	0.63
	Winter	259	2.99	0.72	-2.27	-75.8	76.5	4.06	0.57
	Spring	267	0.53	0.41	-0.12	-22.5	54.0	0.48	0.30
	Summer	276	0.30	0.20	-0.10	-34.2	56.4	0.24	0.15
	Fall	281	0.74	0.35	-0.39	-53.1	63.2	1.03	0.68
Northern Rockies & Plains	All	519	0.60	0.38	-0.23	-37.7	57.5	0.70	0.59
	Winter	130	1.08	0.53	-0.56	-51.3	59.1	1.08	0.61
	Spring	125	0.54	0.43	-0.11	-19.8	49.9	0.49	0.68
	Summer	133	0.24	0.19	-0.05	-21.3	51.8	0.22	0.45
	Fall	131	0.57	0.37	-0.20	-35.3	63.6	0.71	0.41
Northwest	All	541	0.90	1.03	0.12	13.5	87.6	1.46	0.36
	Winter	143	1.64	1.46	-0.18	-10.7	87.9	2.32	0.08
	Spring	148	0.46	0.76	0.30	64.4	100.0	0.70	0.45
	Summer	133	0.27	0.64	0.36	133.0	147.0	0.58	0.65
	Fall	117	1.28	1.28	-0.01	-0.5	67.1	1.53	0.52
West	All	1867	1.94	0.87	-1.07	-55.0	63.4	2.50	0.62
	Winter	462	3.54	1.70	-1.84	-51.9	62.5	3.78	0.59
	Spring	465	1.35	0.71	-0.64	-47.4	55.7	1.25	0.60
	Summer	473	0.93	0.41	-0.51	-55.3	63.7	0.92	0.64
	Fall	467	1.98	0.68	-1.30	-65.7	70.0	2.90	0.55

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	0.58	0.23	65.8	93.3	0.62	0.64
	Winter	486	0.68	0.92	0.24	34.8	70.4	0.79	0.63
	Spring	486	0.29	0.56	0.27	93.5	107.0	0.62	0.63
	Summer	486	0.16	0.25	0.09	54.3	91.7	0.27	0.47
	Fall	495	0.28	0.61	0.33	119.0	135.0	0.67	0.62
Southeast	All	1619	0.31	0.54	0.23	75.0	104.0	0.59	0.53
	Winter	390	0.55	0.98	0.43	78.0	108.0	0.93	0.46
	Spring	408	0.29	0.49	0.20	66.9	86.4	0.41	0.31
	Summer	416	0.18	0.21	0.03	15.0	68.2	0.18	0.26
	Fall	405	0.23	0.52	0.29	128.0	151.0	0.58	0.48
Ohio Valley	All	939	0.59	0.75	0.16	27.4	73.3	0.80	0.67
	Winter	222	1.34	1.43	0.10	7.2	66.7	1.33	0.58
	Spring	239	0.42	0.59	0.16	38.2	68.8	0.45	0.61
	Summer	241	0.21	0.27	0.07	31.5	82.0	0.28	0.20
	Fall	237	0.45	0.78	0.32	70.9	91.7	0.79	0.71
Upper Midwest	All	936	0.58	0.54	-0.04	-6.5	54.6	0.64	0.79
	Winter	229	1.29	0.83	-0.46	-35.2	45.8	1.03	0.83
	Spring	231	0.49	0.50	0.00	0.8	53.4	0.52	0.69
	Summer	241	0.13	0.22	0.09	69.6	89.5	0.24	0.71
	Fall	235	0.44	0.64	0.20	45.1	70.9	0.55	0.83
South	All	1138	0.45	0.44	-0.02	-3.7	62.4	0.51	0.63
	Winter	275	0.75	0.65	-0.10	-13.2	55.7	0.68	0.65
	Spring	281	0.51	0.50	-0.01	-1.9	47.9	0.38	0.79
	Summer	292	0.26	0.15	-0.12	-44.3	67.5	0.25	-0.02
	Fall	290	0.30	0.46	0.16	52.4	97.8	0.62	0.50
Southwest	All	3638	0.23	0.15	-0.07	-32.7	62.8	0.37	0.54
	Winter	891	0.37	0.15	-0.22	-59.0	67.6	0.66	0.65
	Spring	897	0.22	0.29	0.06	28.2	56.4	0.19	0.51
	Summer	927	0.17	0.08	-0.09	-54.6	63.2	0.16	0.42
	Fall	923	0.15	0.10	-0.05	-33.6	60.3	0.23	0.56
Northern Rockies & Plains	All	1858	0.22	0.20	-0.02	-9.6	64.1	0.30	0.63
	Winter	446	0.33	0.24	-0.10	-29.0	62.2	0.40	0.62
	Spring	462	0.23	0.26	0.03	12.6	69.3	0.28	0.69
	Summer	482	0.10	0.10	-0.01	-6.7	60.6	0.11	0.55
	Fall	468	0.22	0.20	-0.01	-6.3	63.1	0.33	0.58
Northwest	All	1911	0.22	0.27	0.05	24.7	104.0	0.53	0.43
	Winter	440	0.34	0.35	0.00	1.3	112.0	0.78	0.29
	Spring	489	0.14	0.27	0.13	90.4	123.0	0.29	0.57
	Summer	498	0.10	0.16	0.06	61.2	104.0	0.23	0.64
	Fall	484	0.30	0.31	0.02	5.1	85.9	0.66	0.52
West	All	2230	0.45	0.26	-0.19	-41.3	66.4	0.86	0.78
	Winter	538	0.63	0.37	-0.26	-41.2	62.3	1.18	0.87
	Spring	607	0.44	0.36	-0.08	-19.1	57.7	0.46	0.55
	Summer	565	0.25	0.11	-0.14	-56.5	73.7	0.29	0.21
	Fall	520	0.48	0.21	-0.27	-56.8	76.9	1.19	0.70

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	2.88	1.27	78.9	90.8	2.41	0.37
	Winter	707	1.30	3.38	2.08	159.0	163.0	3.17	0.44
	Spring	760	1.35	2.66	1.30	96.3	104.0	2.11	0.53
	Summer	781	2.18	2.58	0.40	18.5	41.7	1.45	0.46
	Fall	703	1.56	2.93	1.38	88.5	94.3	2.66	0.42
Southeast	All	1724	2.25	3.12	0.87	38.7	55.9	1.80	0.56
	Winter	427	2.09	3.26	1.17	55.7	70.9	2.18	0.62
	Spring	423	2.29	3.14	0.85	37.0	52.8	1.79	0.63
	Summer	445	2.21	3.08	0.87	39.6	53.3	1.57	0.42
	Fall	429	2.42	3.02	0.60	24.7	48.3	1.60	0.50
Ohio Valley	All	2116	1.90	2.46	0.56	29.6	49.1	1.36	0.54
	Winter	535	1.49	2.85	1.36	91.7	97.8	1.95	0.51
	Spring	549	1.75	2.31	0.57	32.4	45.1	1.16	0.71
	Summer	525	2.37	2.33	-0.04	-1.7	30.2	0.91	0.56
	Fall	507	2.01	2.35	0.34	16.9	38.1	1.17	0.68
Upper Midwest	All	1162	1.61	2.36	0.74	46.1	68.2	1.67	0.42
	Winter	289	1.25	3.18	1.93	155.0	155.0	2.54	0.64
	Spring	288	1.27	2.08	0.82	64.7	78.1	1.45	0.52
	Summer	303	1.98	1.80	-0.18	-8.9	33.0	0.86	0.42
	Fall	282	1.95	2.39	0.44	22.3	42.8	1.37	0.65
South	All	936	2.18	2.18	-0.01	-0.3	45.0	2.75	0.29
	Winter	223	1.96	2.35	0.39	19.8	54.9	1.68	0.43
	Spring	233	1.81	1.89	0.09	4.8	43.9	1.42	0.66
	Summer	250	1.89	1.82	-0.08	-4.0	43.1	1.20	0.47
	Fall	230	3.10	2.70	-0.40	-13.0	40.9	4.94	0.22
Southwest	All	1110	1.68	1.94	0.26	15.8	62.7	1.83	0.32
	Winter	282	2.36	3.16	0.80	34.1	83.3	2.94	0.13
	Spring	280	1.14	1.40	0.26	23.0	61.8	1.23	0.26
	Summer	276	1.40	1.11	-0.28	-20.3	39.6	0.72	0.34
	Fall	272	1.81	2.07	0.26	14.5	53.4	1.62	0.34
Northern Rockies & Plains	All	488	1.46	0.97	-0.49	-33.6	53.7	1.69	0.76
	Winter	116	1.12	0.86	-0.26	-22.9	72.4	1.96	0.27
	Spring	113	0.68	0.58	-0.10	-14.1	50.1	0.53	0.59
	Summer	129	1.61	0.74	-0.86	-53.7	56.9	1.18	0.37
	Fall	130	2.29	1.62	-0.67	-29.4	44.2	2.39	0.87
Northwest	All	530	2.21	3.92	1.72	78.0	103.0	3.45	0.50
	Winter	143	1.92	4.39	2.48	129.0	141.0	3.30	0.49
	Spring	148	1.13	3.43	2.30	204.0	207.0	2.92	0.58
	Summer	134	1.67	2.82	1.15	68.9	80.1	1.64	0.60
	Fall	105	4.80	5.39	0.59	12.2	58.3	5.46	0.50
West	All	1232	2.75	2.55	-0.20	-7.4	41.2	2.53	0.52
	Winter	309	3.78	3.95	0.17	4.6	44.0	2.35	0.57
	Spring	306	1.81	1.77	-0.04	-2.3	39.1	1.00	0.53
	Summer	312	1.95	1.47	-0.49	-25.0	37.1	1.05	0.38
	Fall	305	3.46	3.01	-0.45	-13.0	41.5	4.25	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	1.50	0.65	75.9	91.1	2.00	0.44
	Winter	458	0.67	1.74	1.08	162.0	165.0	1.69	0.74
	Spring	451	0.65	1.47	0.82	125.0	134.0	3.41	0.38
	Summer	458	1.26	1.34	0.08	6.2	36.5	0.76	0.65
	Fall	463	0.84	1.47	0.63	74.9	82.5	1.08	0.79
Southeast	All	1727	1.31	1.87	0.56	42.3	61.6	1.77	0.66
	Winter	420	1.24	2.13	0.89	72.1	87.9	2.72	0.62
	Spring	437	1.35	1.93	0.58	43.2	61.7	1.80	0.67
	Summer	438	1.31	1.82	0.50	38.4	57.0	1.13	0.72
	Fall	432	1.34	1.59	0.25	18.5	42.7	0.88	0.80
Ohio Valley	All	930	1.23	1.73	0.50	40.9	50.1	1.14	0.70
	Winter	221	0.92	1.49	0.57	61.8	65.3	1.09	0.72
	Spring	236	1.19	1.78	0.60	50.1	58.0	1.57	0.79
	Summer	236	1.50	2.05	0.55	36.8	46.1	1.02	0.55
	Fall	237	1.29	1.60	0.30	23.5	37.3	0.70	0.77
Upper Midwest	All	1036	0.89	1.02	0.13	14.9	45.9	0.71	0.69
	Winter	253	0.63	1.07	0.44	70.4	78.7	0.92	0.85
	Spring	253	0.64	0.87	0.22	34.8	56.0	0.68	0.77
	Summer	266	1.23	1.00	-0.23	-18.7	34.0	0.55	0.55
	Fall	264	1.02	1.13	0.11	10.9	35.0	0.64	0.79
South	All	1142	1.08	1.21	0.13	12.1	48.9	1.26	0.68
	Winter	274	0.75	1.00	0.26	34.3	61.4	1.16	0.67
	Spring	290	1.23	1.56	0.33	26.6	61.4	2.02	0.78
	Summer	293	1.18	1.04	-0.14	-12.2	40.0	0.72	0.57
	Fall	285	1.16	1.25	0.09	7.9	36.9	0.65	0.74
Southwest	All	3637	0.66	0.43	-0.23	-34.9	52.0	0.72	0.65
	Winter	886	0.67	0.44	-0.23	-34.5	59.2	1.06	0.62
	Spring	894	0.58	0.42	-0.17	-28.3	52.0	0.66	0.77
	Summer	932	0.74	0.39	-0.35	-47.0	52.7	0.53	0.66
	Fall	925	0.65	0.48	-0.18	-27.2	44.2	0.50	0.69
Northern Rockies & Plains	All	1935	1.06	0.75	-0.31	-29.0	57.3	3.26	0.51
	Winter	462	0.31	0.33	0.02	6.1	66.7	0.79	0.23
	Spring	474	0.34	0.31	-0.03	-8.6	66.3	0.78	0.25
	Summer	504	1.16	0.61	-0.55	-47.1	62.3	1.37	0.29
	Fall	495	2.36	1.72	-0.64	-27.1	52.4	6.20	0.51
Northwest	All	1877	1.39	1.49	0.11	7.8	71.4	3.32	0.72
	Winter	430	0.51	0.81	0.30	58.8	121.0	1.41	0.43
	Spring	470	0.33	0.54	0.20	60.9	108.0	0.93	0.62
	Summer	500	1.09	0.97	-0.12	-11.0	56.5	1.08	0.56
	Fall	477	3.52	3.60	0.08	2.3	66.4	6.29	0.70
West	All	2185	1.02	0.79	-0.23	-22.8	58.1	2.31	0.49
	Winter	526	0.74	0.57	-0.17	-23.5	54.2	0.79	0.75
	Spring	584	0.68	0.42	-0.26	-38.5	49.1	0.52	0.63
	Summer	552	1.30	1.02	-0.27	-20.9	69.1	3.80	0.41
	Fall	523	1.38	1.17	-0.21	-15.5	54.3	2.45	0.70

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	0.41	-0.17	-28.6	45.3	0.44	0.45
	Winter	707	0.60	0.52	-0.08	-14.1	42.4	0.47	0.47
	Spring	761	0.53	0.39	-0.15	-27.4	42.6	0.42	0.52
	Summer	781	0.57	0.31	-0.25	-44.8	50.2	0.43	0.33
	Fall	703	0.62	0.45	-0.17	-27.6	45.6	0.45	0.48
Southeast	All	1725	0.76	0.38	-0.38	-50.1	57.8	0.67	0.41
	Winter	428	0.85	0.44	-0.40	-47.7	55.0	0.73	0.44
	Spring	423	0.77	0.37	-0.40	-51.8	57.3	0.67	0.51
	Summer	445	0.56	0.31	-0.26	-45.5	56.1	0.50	0.09
	Fall	429	0.85	0.39	-0.46	-54.0	62.1	0.76	0.34
Ohio Valley	All	2116	0.70	0.36	-0.34	-48.3	51.9	0.51	0.52
	Winter	535	0.64	0.44	-0.19	-30.3	41.3	0.44	0.45
	Spring	549	0.68	0.33	-0.35	-51.2	53.9	0.53	0.60
	Summer	525	0.71	0.30	-0.42	-58.4	59.1	0.55	0.39
	Fall	507	0.76	0.37	-0.39	-51.5	52.2	0.51	0.73
Upper Midwest	All	1164	0.50	0.35	-0.15	-30.0	46.2	0.33	0.51
	Winter	290	0.46	0.48	0.01	2.8	40.3	0.29	0.53
	Spring	289	0.40	0.31	-0.09	-21.7	42.7	0.23	0.58
	Summer	303	0.49	0.25	-0.24	-49.1	52.7	0.33	0.40
	Fall	282	0.64	0.36	-0.28	-43.7	47.3	0.43	0.68
South	All	936	0.68	0.36	-0.32	-46.4	51.4	1.30	0.23
	Winter	223	0.84	0.44	-0.39	-47.0	49.9	0.64	0.63
	Spring	233	0.52	0.31	-0.22	-41.5	44.8	0.35	0.70
	Summer	250	0.41	0.28	-0.13	-31.2	49.2	0.27	0.44
	Fall	230	0.98	0.44	-0.54	-55.3	57.1	2.51	0.09
Southwest	All	1110	0.63	0.34	-0.29	-46.1	53.8	0.61	0.50
	Winter	282	1.13	0.52	-0.61	-53.9	61.1	1.05	0.27
	Spring	280	0.36	0.27	-0.09	-25.8	43.6	0.24	0.53
	Summer	276	0.33	0.21	-0.12	-35.2	41.2	0.18	0.57
	Fall	272	0.71	0.36	-0.35	-49.0	52.8	0.53	0.47
Northern Rockies & Plains	All	488	0.40	0.16	-0.25	-61.0	65.9	0.69	0.36
	Winter	116	0.49	0.16	-0.33	-68.2	76.8	1.14	0.13
	Spring	113	0.20	0.11	-0.09	-43.5	51.6	0.19	0.48
	Summer	129	0.35	0.11	-0.24	-68.9	69.0	0.31	0.25
	Fall	130	0.55	0.24	-0.31	-55.9	59.9	0.71	0.56
Northwest	All	530	0.71	0.64	-0.07	-9.9	50.9	0.62	0.52
	Winter	143	0.86	0.66	-0.20	-22.9	46.5	0.58	0.52
	Spring	148	0.47	0.57	0.10	20.6	62.7	0.41	0.44
	Summer	134	0.47	0.56	0.09	19.6	50.8	0.30	0.59
	Fall	105	1.15	0.82	-0.34	-29.3	48.8	1.07	0.48
West	All	1232	0.98	0.42	-0.56	-56.7	58.4	0.93	0.73
	Winter	309	1.68	0.63	-1.05	-62.5	63.3	1.36	0.65
	Spring	306	0.61	0.33	-0.29	-46.7	50.7	0.44	0.67
	Summer	312	0.49	0.27	-0.22	-45.3	48.2	0.37	0.40
	Fall	305	1.14	0.47	-0.67	-58.5	59.8	1.14	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	0.18	0.00	0.1	43.5	0.13	0.74
	Winter	455	0.19	0.24	0.06	30.3	53.1	0.16	0.73
	Spring	449	0.15	0.17	0.02	14.5	47.1	0.13	0.75
	Summer	458	0.20	0.13	-0.07	-36.5	41.5	0.11	0.78
	Fall	461	0.20	0.19	0.00	-2.3	33.7	0.10	0.85
Southeast	All	1724	0.29	0.19	-0.11	-36.2	44.7	0.23	0.78
	Winter	420	0.32	0.24	-0.08	-24.6	39.1	0.20	0.80
	Spring	437	0.30	0.19	-0.11	-36.2	45.2	0.28	0.77
	Summer	435	0.23	0.13	-0.09	-40.9	47.7	0.17	0.78
	Fall	432	0.32	0.18	-0.14	-44.1	47.7	0.25	0.83
Ohio Valley	All	930	0.25	0.16	-0.09	-35.4	41.6	0.14	0.70
	Winter	221	0.24	0.19	-0.05	-21.0	33.4	0.11	0.69
	Spring	236	0.24	0.16	-0.07	-31.5	39.6	0.12	0.76
	Summer	236	0.24	0.12	-0.12	-48.9	51.3	0.15	0.61
	Fall	237	0.28	0.17	-0.11	-38.8	41.6	0.15	0.78
Upper Midwest	All	1033	0.20	0.12	-0.07	-37.7	46.6	0.14	0.76
	Winter	252	0.18	0.16	-0.02	-10.4	32.8	0.08	0.86
	Spring	253	0.16	0.11	-0.04	-28.4	41.9	0.11	0.78
	Summer	266	0.21	0.09	-0.12	-58.9	59.8	0.16	0.80
	Fall	262	0.25	0.14	-0.11	-44.1	47.7	0.19	0.82
South	All	1135	0.20	0.13	-0.07	-37.1	52.1	0.25	0.43
	Winter	274	0.19	0.12	-0.07	-36.6	42.9	0.13	0.75
	Spring	290	0.22	0.18	-0.04	-15.9	59.1	0.40	0.58
	Summer	286	0.16	0.07	-0.08	-53.5	56.0	0.12	0.49
	Fall	285	0.23	0.12	-0.11	-46.8	50.0	0.24	0.37
Southwest	All	3606	0.16	0.07	-0.08	-53.5	61.6	0.28	0.62
	Winter	876	0.24	0.08	-0.16	-66.2	69.9	0.49	0.71
	Spring	878	0.12	0.09	-0.03	-27.0	52.1	0.14	0.70
	Summer	928	0.11	0.05	-0.06	-51.0	57.1	0.09	0.70
	Fall	924	0.17	0.07	-0.09	-56.0	59.8	0.23	0.66
Northern Rockies & Plains	All	1913	0.14	0.10	-0.03	-23.7	61.7	0.29	0.54
	Winter	450	0.07	0.05	-0.02	-26.5	62.2	0.14	0.19
	Spring	470	0.06	0.06	0.00	-6.8	63.7	0.14	0.17
	Summer	498	0.13	0.07	-0.06	-45.8	68.3	0.19	0.18
	Fall	495	0.27	0.22	-0.04	-16.4	58.0	0.50	0.56
Northwest	All	1855	0.20	0.18	-0.02	-9.0	64.9	0.68	0.49
	Winter	415	0.13	0.12	-0.01	-4.3	71.4	0.17	0.67
	Spring	472	0.07	0.10	0.02	29.4	76.4	0.15	0.58
	Summer	494	0.14	0.13	-0.01	-10.0	58.8	0.15	0.70
	Fall	474	0.44	0.37	-0.07	-16.3	63.3	1.32	0.47
West	All	2145	0.17	0.10	-0.07	-40.7	58.4	0.28	0.71
	Winter	512	0.20	0.09	-0.10	-53.5	66.1	0.30	0.75
	Spring	573	0.10	0.08	-0.02	-22.6	46.0	0.08	0.70
	Summer	537	0.16	0.10	-0.06	-36.4	56.4	0.27	0.65
	Fall	523	0.24	0.14	-0.10	-42.0	59.5	0.39	0.78

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	41.3	1.5	3.9	11.3	5.84	0.84
	Winter	7926	33.9	33.3	-0.6	-1.9	10.3	4.55	0.77
	Spring	16165	42.5	42.9	0.4	1.0	9.2	5.11	0.76
	Summer	16222	44.8	47.6	2.9	6.4	11.4	6.63	0.83
	Fall	12390	33.5	36.1	2.6	7.9	15.0	6.33	0.78
Southeast	All	48275	39.4	41.8	2.4	6.0	12.4	6.39	0.82
	Winter	6842	36.7	38.4	1.7	4.6	10.1	4.92	0.81
	Spring	15220	43.9	44.2	0.2	0.5	9.2	5.26	0.83
	Summer	14520	37.9	42.2	4.3	11.5	16.8	8.03	0.81
	Fall	11693	37.2	40.3	3.1	8.4	13.0	6.20	0.82
Ohio Valley	All	60934	41.6	43.7	2.2	5.2	11.8	6.33	0.83
	Winter	5499	30.9	33.0	2.0	6.6	12.7	5.00	0.83
	Spring	20427	42.7	43.9	1.2	2.7	9.6	5.35	0.78
	Summer	20107	46.4	49.7	3.3	7.0	12.8	7.45	0.76
	Fall	14901	37.4	39.6	2.2	5.8	13.5	6.37	0.80
Upper Midwest	All	24294	40.2	40.5	0.3	0.7	10.8	5.64	0.83
	Winter	1492	33.3	32.8	-0.5	-1.5	9.8	4.20	0.77
	Spring	8201	42.0	41.6	-0.4	-1.0	8.7	4.71	0.80
	Summer	8620	43.4	43.8	0.4	0.9	11.3	6.29	0.80
	Fall	5981	34.8	36.0	1.2	3.4	13.7	6.11	0.79
South	All	45543	40.5	40.8	0.3	0.6	13.0	6.93	0.82
	Winter	9623	33.7	34.5	0.9	2.6	11.1	4.84	0.86
	Spring	12336	44.2	44.2	0.0	0.0	11.4	6.64	0.77
	Summer	12064	41.3	42.1	0.9	2.1	16.4	8.56	0.78
	Fall	11520	41.5	40.9	-0.6	-1.5	12.7	6.79	0.84
Southwest	All	46026	48.0	46.3	-1.6	-3.4	11.5	7.30	0.74
	Winter	10447	39.2	38.7	-0.5	-1.4	13.8	7.15	0.56
	Spring	11922	51.1	50.0	-1.1	-2.1	9.6	6.42	0.61
	Summer	12266	55.8	52.2	-3.6	-6.4	12.5	9.08	0.51
	Fall	11391	44.3	43.1	-1.2	-2.6	10.7	6.02	0.76
Northern Rockies & Plains	All	16891	42.1	40.3	-1.8	-4.3	11.3	6.10	0.75
	Winter	4042	38.0	35.1	-2.9	-7.6	12.6	6.02	0.65
	Spring	4278	44.6	43.0	-1.5	-3.4	9.1	5.36	0.64
	Summer	4335	47.1	45.9	-1.2	-2.6	11.8	7.03	0.64
	Fall	4236	38.3	36.7	-1.6	-4.1	12.0	5.86	0.76
Northwest	All	6337	37.7	38.3	0.7	1.8	14.0	6.96	0.77
	Winter	803	32.3	31.8	-0.5	-1.5	18.8	7.76	0.67
	Spring	1672	39.1	40.0	1.0	2.5	11.6	5.90	0.63
	Summer	2521	39.1	39.5	0.5	1.2	13.7	7.19	0.81
	Fall	1341	36.5	37.9	1.3	3.6	15.2	7.21	0.75
West	All	60629	44.5	43.8	-0.7	-1.6	13.4	7.93	0.80
	Winter	13437	34.9	38.0	3.1	8.8	17.4	8.21	0.55
	Spring	15970	47.4	46.5	-0.9	-1.9	10.4	6.52	0.73
	Summer	16392	49.8	46.9	-2.9	-5.8	14.1	9.14	0.83
	Fall	14830	44.2	42.6	-1.6	-3.5	12.9	7.63	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	4287	39.9	40.3	0.4	1.0	9.9	5.24	0.83
	Winter	1116	35.4	34.3	-1.1	-3.2	8.6	3.88	0.81
	Spring	1191	43.9	43.2	-0.7	-1.7	8.0	4.56	0.79
	Summer	984	45.1	47.9	2.8	6.1	11.3	6.73	0.78
	Fall	996	35.1	36.2	1.2	3.3	12.2	5.62	0.76
Southeast	All	4037	40.0	41.0	1.0	2.5	12.4	10.90	0.56
	Winter	997	37.0	36.5	-0.5	-1.4	10.2	4.96	0.80
	Spring	1069	45.4	44.6	-0.8	-1.9	8.9	5.23	0.80
	Summer	983	39.4	43.2	3.8	9.8	19.6	19.90	0.36
	Fall	988	37.7	39.5	1.8	4.6	11.8	5.92	0.75
Ohio Valley	All	5659	40.2	41.6	1.4	3.5	11.2	5.84	0.83
	Winter	1426	33.7	34.6	0.9	2.5	10.5	4.61	0.83
	Spring	1554	44.6	44.7	0.1	0.3	8.6	4.96	0.78
	Summer	1343	44.7	48.4	3.7	8.3	14.0	7.68	0.73
	Fall	1336	37.4	38.5	1.2	3.2	12.1	5.83	0.79
Upper Midwest	All	1772	38.2	37.8	-0.4	-1.0	10.2	5.10	0.84
	Winter	440	34.7	33.5	-1.2	-3.5	8.5	3.68	0.81
	Spring	454	42.9	41.5	-1.4	-3.1	8.1	4.44	0.82
	Summer	444	40.9	41.7	0.8	2.0	11.4	6.06	0.84
	Fall	434	33.9	34.2	0.3	0.8	13.1	5.85	0.77
South	All	2068	42.2	41.1	-1.1	-2.6	15.4	28.60	0.28
	Winter	524	35.9	35.5	-0.3	-0.9	11.0	5.48	0.82
	Spring	538	45.9	45.3	-0.6	-1.3	10.8	6.38	0.74
	Summer	501	42.3	43.9	1.6	3.7	17.9	9.33	0.64
	Fall	505	44.9	39.7	-5.1	-11.4	21.5	56.50	0.16
Southwest	All	4257	48.8	46.3	-2.4	-5.0	10.5	6.45	0.73
	Winter	1060	43.7	40.0	-3.7	-8.5	12.4	6.75	0.55
	Spring	1075	52.3	50.0	-2.3	-4.4	9.5	6.30	0.55
	Summer	1056	54.3	51.8	-2.5	-4.5	10.2	7.02	0.56
	Fall	1066	44.7	43.4	-1.3	-2.9	10.0	5.64	0.71
Northern Rockies & Plains	All	2477	44.2	42.7	-1.5	-3.3	11.7	6.50	0.71
	Winter	610	40.8	36.4	-4.4	-10.9	14.7	7.21	0.65
	Spring	634	47.1	44.2	-3.0	-6.3	9.2	5.65	0.65
	Summer	624	47.8	49.7	1.9	4.0	11.1	6.62	0.66
	Fall	609	40.9	40.4	-0.4	-1.1	12.2	6.45	0.69
Northwest	All	1062	40.3	40.1	-0.2	-0.5	11.3	6.00	0.72
	Winter	258	36.6	34.5	-2.1	-5.7	16.8	7.72	0.35
	Spring	269	42.4	41.9	-0.4	-1.1	8.5	4.73	0.70
	Summer	269	44.1	44.4	0.4	0.9	9.2	5.21	0.80
	Fall	266	37.9	39.2	1.3	3.5	12.0	5.98	0.74
West	All	2443	49.4	45.3	-4.1	-8.3	12.5	8.19	0.74
	Winter	597	41.7	40.2	-1.4	-3.5	12.1	6.22	0.52
	Spring	607	50.9	47.0	-3.9	-7.6	10.5	6.68	0.74
	Summer	630	56.7	50.1	-6.6	-11.6	14.8	10.90	0.66
	Fall	609	48.1	43.6	-4.5	-9.3	12.3	8.03	0.71

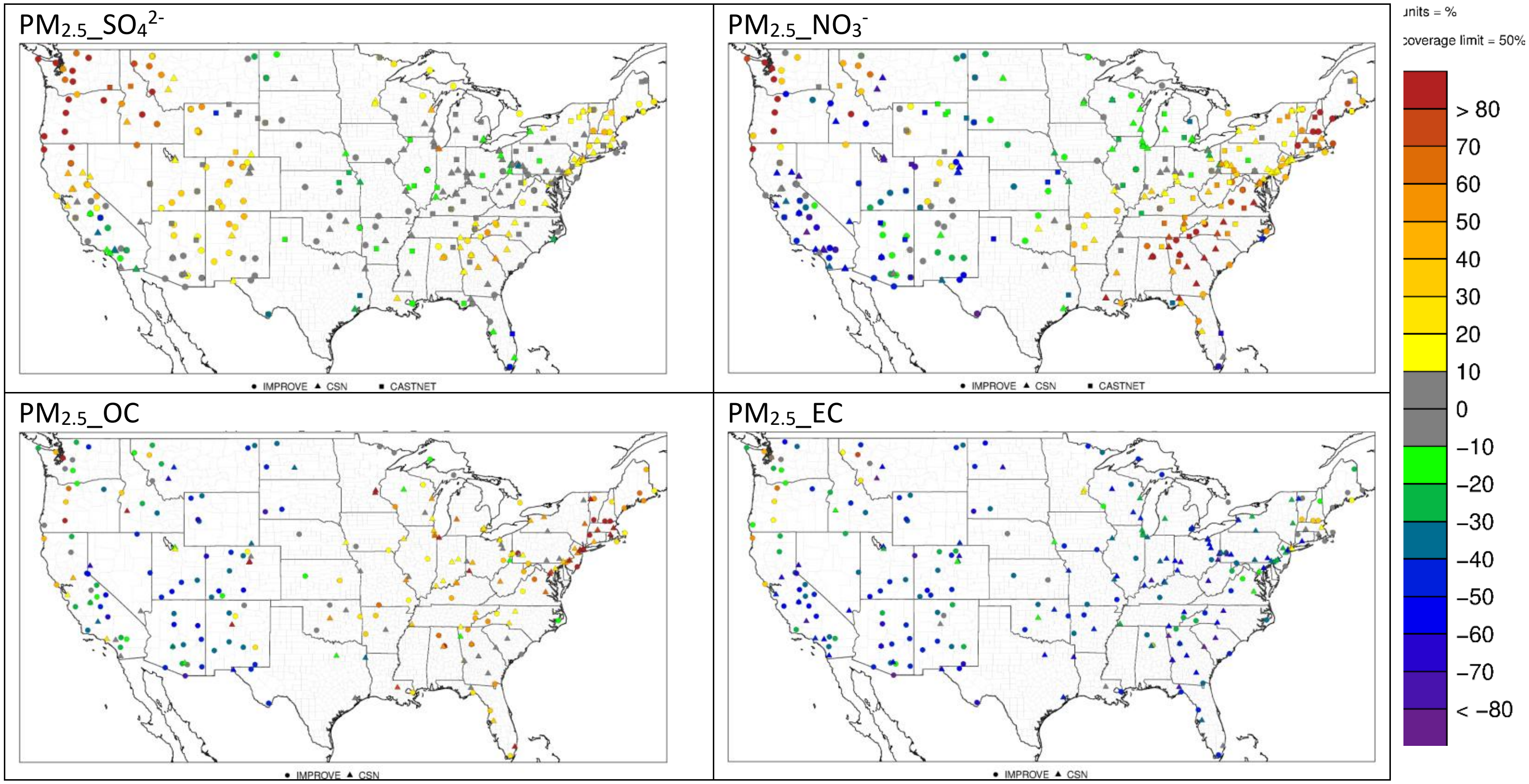

Figure 8 - NMB in 2022 CAMx Predictions of $PM_{2.5}$ Components at CSN, CASTNET and IMPROVE Sites

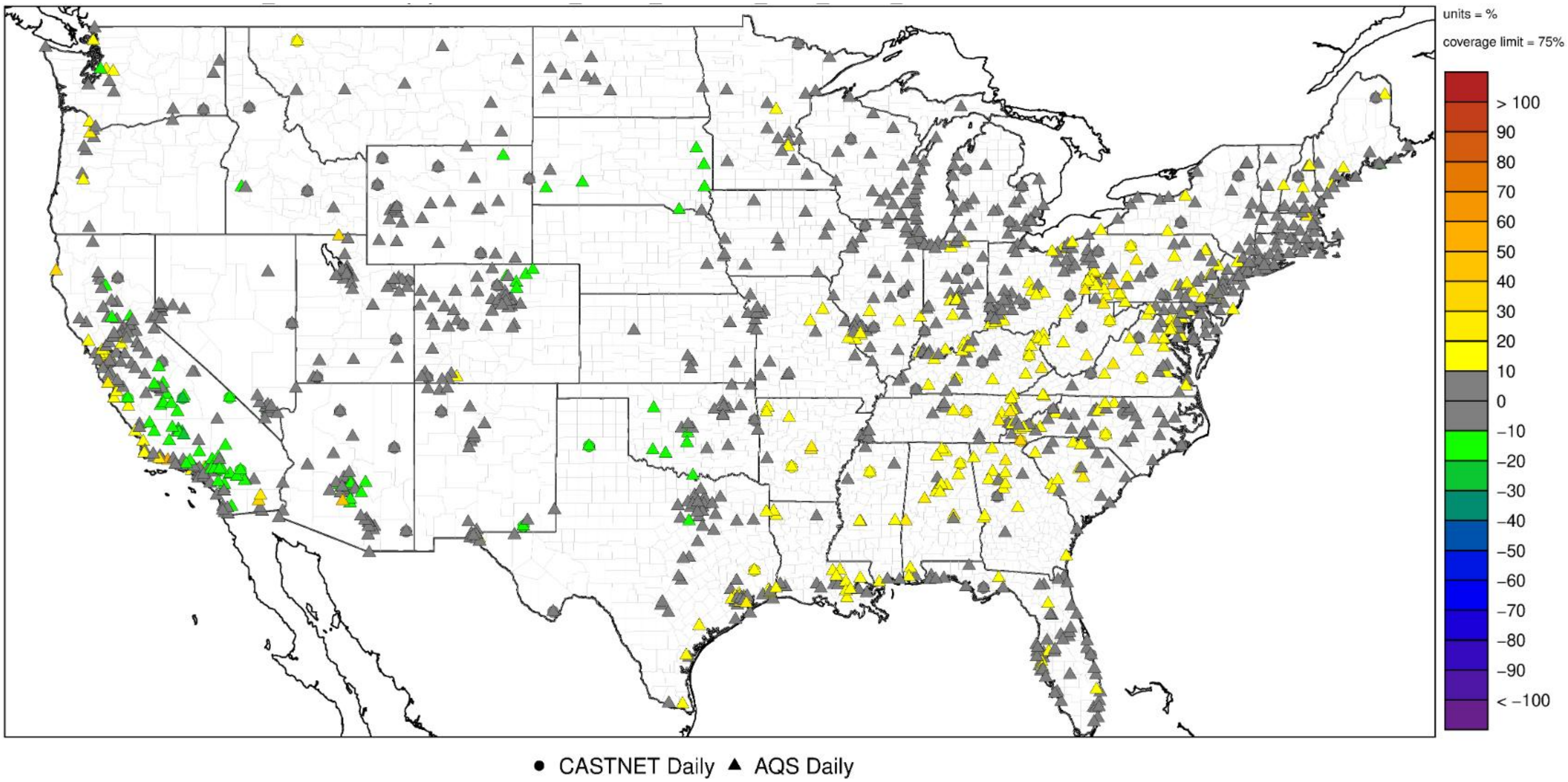

Figure 9 - NMB in 2022 CAMx Predictions of MDA8 O_3 at AQS and CASTNET sites during O_3 season (04/01/2022-09/30/2022)

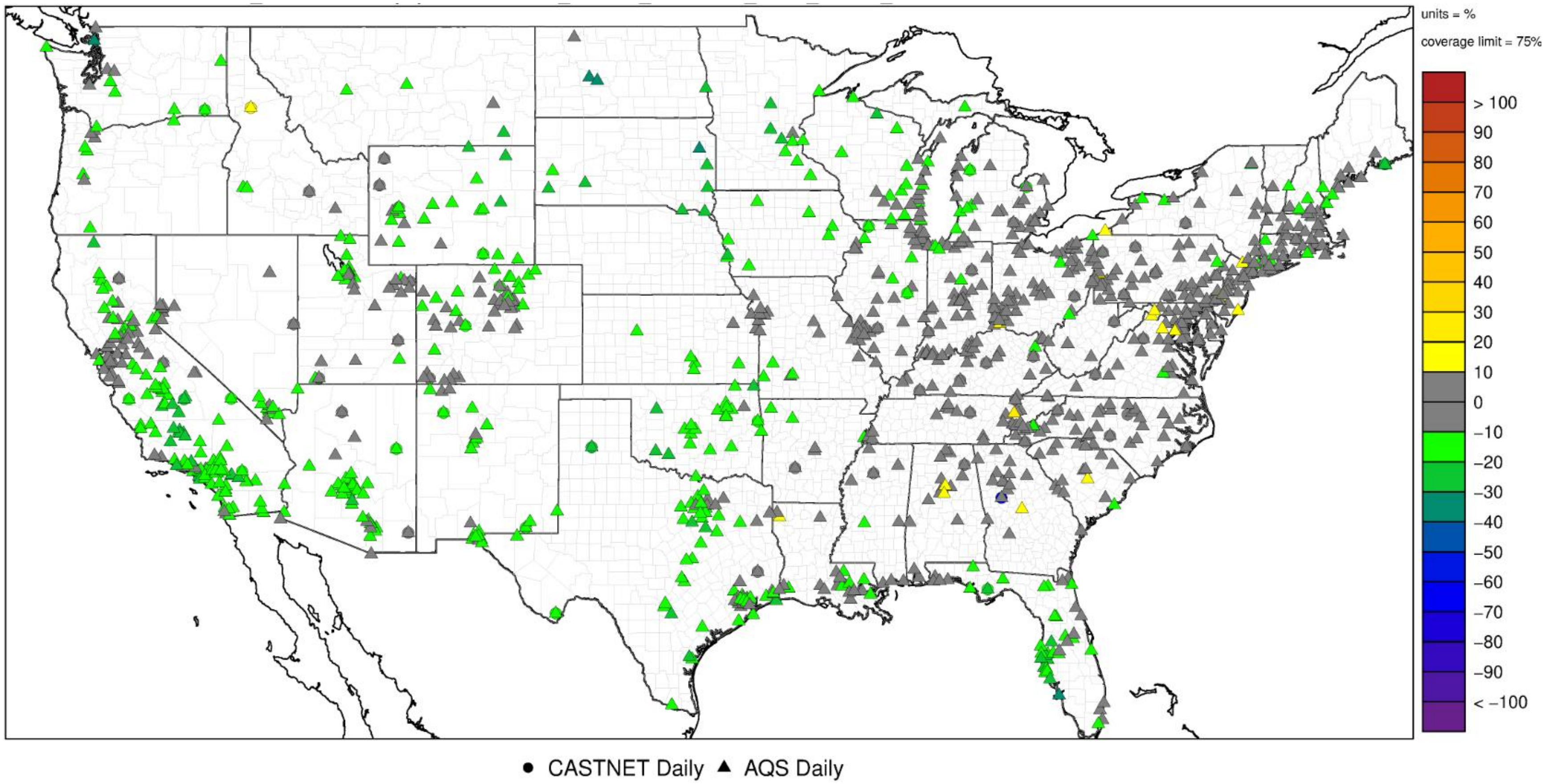

Figure 10 - NMB in 2022 CAMx predictions of MDA8 O_3 at AQS and CASTNET sites when observation MDA8 O_3 > 60 ppb during O_3 season (04/01/2022-09/30/2022)

5 Summary and Plan for v2

As described above, the model performance statistics for 2022v1 platform are generally within the range of those reported in previous applications [56,57] and suggest that the simulations are suitable for use of national scale applications. Detailed CMAQ and CAMx site comparison files are available on AWS as described in Section 2.4.

Overall, CMAQ and CAMx predictions for $PM_{2.5}$ SO_4^{2-} and NO_3^- are in reasonable agreement with observations. However, for $PM_{2.5}$ OC, the CMAQ and CAMx predictions 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: atmospheric mixing under stagnant conditions, direct PM emissions, and chemistry (e.g., volatility). The EPA is investigating the role of these factors during periods with degraded model performance. The spatial allocation of residential wood combustion emissions between urban and rural areas will be improved in the 2022v2 platform and may influence $PM_{2.5}$ OC performance. $PM_{2.5}$ EC is underpredicted across the domain in the CMAQ and CAMx simulations; however, MBs are generally small due to the low ambient EC concentrations.

The CMAQ and CAMx NMBs of MDA8 O_3 predictions during the ozone 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); however, both models underpredicted MDA8 O_3 concentrations when the values were higher than 60 ppb (NMBs: -10 to -20 %).

The MDA8 O_3 underprediction could be due to a number of different factors. Recently, Sawar et al.[58] demonstrated that adding particulate nitrate (pNO_3^-) photolysis to CMAQ improves ozone underestimation in Western U.S. especially during spring months. In this modeling platform,

---

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

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

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

EPA included pNO_3^- photolysis in the Hemi-CMAQ model runs; however, using the boundary conditions with pNO_3^- photolysis CMAQ and CAMx 12US2 runs still resulted in a negative ozone bias in the Southwestern and Western U.S. The EPA also tested out pNO_3^- photolysis in 36US3 and 12US2 CMAQ runs, which slightly improved the model performance of ozone predictions in Southwestern and Western U.S. but over predicted ozone elsewhere. Another potential reason for ozone underprediction is the emissions uncertainties, (e.g., underprediction of NOx emissions from emerging source categories or due to changes in activity not captured in the 2022 emissions inventories). The EPA is continuing to investigate causes of ozone model underpredictions in the Western U.S.

Additional planned work includes emission sensitivity runs for precursors of ozone (NO_X and VOC) and $PM_{2.5}$ (NO_X, SO_2, VOC, primary $PM_{2.5}$ and NH_3) using 2022v1 emissions to characterize modeled ozone chemical regimes and the model-predicted response to emissions perturbations. In addition, the EPA is currently working on the 2022v2 emission platform. Once 2022v2 emissions are ready, the EPA plans to re-run CMAQ and CAMx with key configurations and to develop a modeling TSD that reflects the 2022v2 improvements.