

Air Quality Modeling Technical Support Document:
2016 CAMx PM_{2.5} Model Evaluation to Support of EGU
Benefits Assessments

Office of Air Quality Planning and Standards
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I. Introduction

An operational model evaluation was conducted for the 2016 base year CAMx v7.10 simulation performed for the 12 km U.S. modeling domain. CAMx model configurations and inputs are described in US EPA (2022a) and in Appendix J of US EPA (2022b). This modeling is being used by EPA to support PM_{2.5} benefits assessments for multiple EGU rulemakings. The purpose of this evaluation is to examine the ability of the 2016 air quality modeling platform to represent the magnitude and spatial and temporal variability of measured (i.e., observed) concentration in the context of its use as the base-year from which future year EGU PM_{2.5} benefits can be projected. In this context, we evaluated the model's representation of 2016 spatial and temporal patterns of the following PM_{2.5} component species: organic carbon (OC), elemental carbon (EC), sulfate (SO₄), nitrate (NO₃) and crustal material (soil). The evaluation presented here is based on model simulations using the 2016v2 emissions platform (i.e., scenario name 2016fj) (US EPA, 2022c).

II. Methodology

The model evaluation for PM_{2.5} focuses on comparisons of daily (24-hr average) concentrations of PM_{2.5} component species to the corresponding observed data at CSN and IMPROVE monitoring sites in the EPA Air Quality System (AQS). The locations of the CSN and IMPROVE monitoring sites in this network are shown in Figure 1. CSN monitoring sites are more often located in urban and suburban areas while IMPROVE monitoring sites are often located in rural areas. Therefore, concentrations at CSN sites are higher, on average, than concentrations in nearby IMPROVE sites. CSN sites provide more information on the model performance in the more densely populated locations while IMPROVE sites provide more information on the model performance in pristine locations and class I areas.

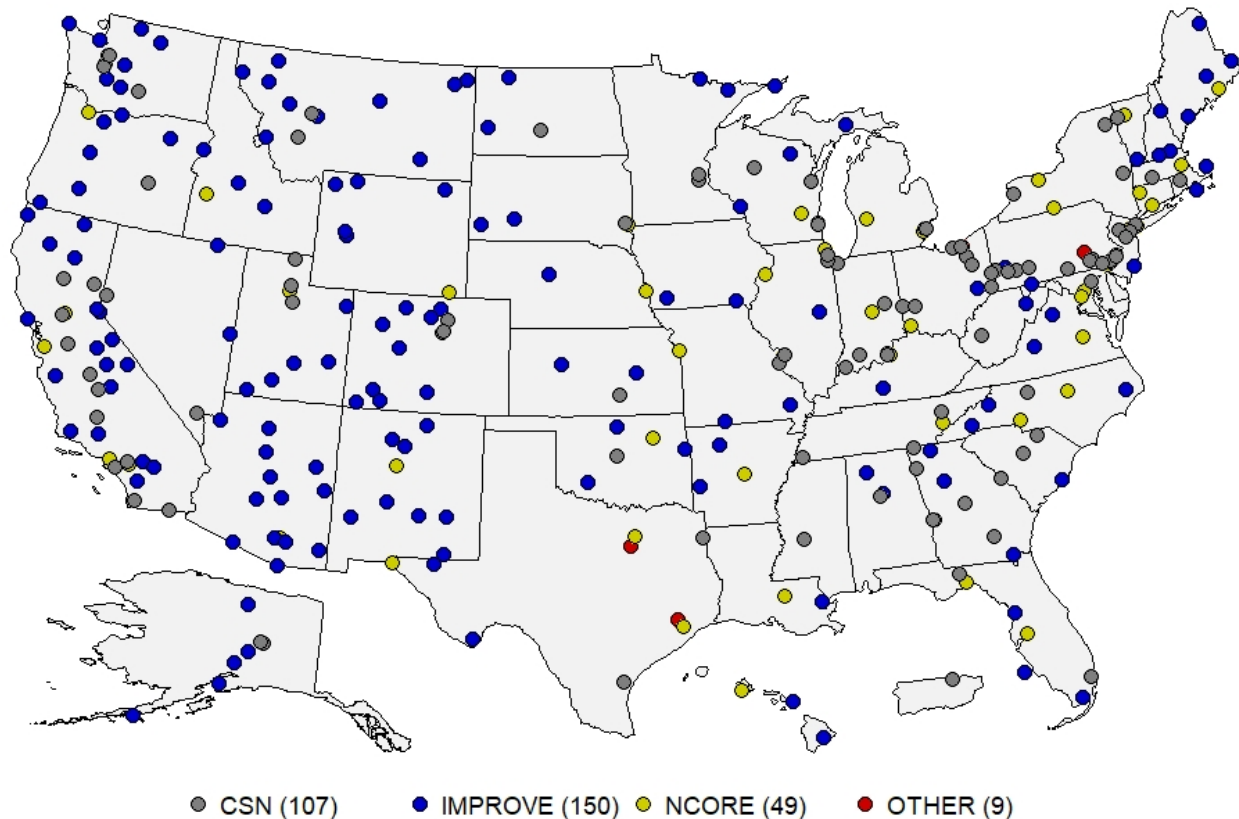


Figure 1. Location of PM monitoring sites that include speciated measurements from CSN, IMPROVE, NCORE and Other networks as of 2021.

This evaluation includes statistical measures and graphical displays of model performance based upon model-predicted versus observed concentrations. The evaluation focusses on model predicted and observed PM_{2.5} component species concentrations that were paired in space and time. Model performance statistics were calculated for several spatial scales and temporal periods. Statistics were calculated for individual monitoring sites and in aggregate for monitoring sites within each of nine climate regions of the 12 km U.S. modeling domain. The regions include the Northeast, Ohio Valley, (Upper) Midwest, Southeast, South, Southwest, Northern Rockies, Northwest and West^{1,2}, which are

¹ 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.

² Note most monitoring sites in the West region are located in California (see Figure 2), therefore the statistics for the West region will be mostly representative of model performance in California ozone.

defined based upon the states contained within the National Oceanic and Atmospheric Administration (NOAA) climate regions (Figure 2)³ as defined in Karl and Koss (1984).

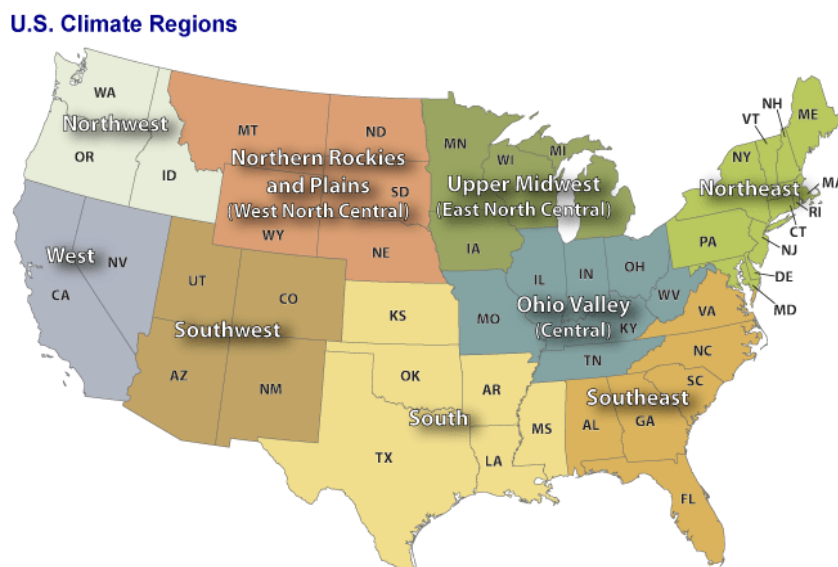


Figure 2. NOAA climate regions (source: <http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php#references>)

Seasonal model performance statistics were created for monitoring locations within each climate region. Seasons are defined as follows: Winter includes December, January and February; Spring includes March, April, and May; Summer includes June, July and August; Fall includes September, October and November.

Statistics were created using data on all days with valid observed data during this period. The aggregate statistics by season and climate region are presented in Tables 1-10.

For this evaluation we have selected the mean bias, mean error, normalized mean bias, normalized mean error and correlation to characterize model performance. These statistics are consistent with the recommendations in Simon et al. (2012) and EPA’s photochemical modeling guidance (U.S. EPA, 2018).

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 $\mu\text{g}/\text{m}^3$ and is defined as:

$$\text{MB} = \frac{1}{n} \sum_{i=1}^n (P - O) , \text{ where } P = \text{predicted and } O = \text{observed concentrations}$$

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 $\mu\text{g}/\text{m}^3$ and is defined as:

³ 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>.

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

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:

$$NMB = \frac{\sum_1^n (P-O)}{\sum_1^n (O)} * 100$$

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:

$$NME = \frac{\sum_1^n |P-O|}{\sum_1^n (O)} * 100$$

Correlation is a measure of how well the model captures spatial and temporal variations in the observed concentrations as is calculated as:

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

In addition to the above performance statistics presented in Tables 1-10, we prepared several graphical presentations of model performance for MDA8 ozone. These graphical presentations include:

- (1) maps that show the observed and modeled PM component species concentrations at individual monitoring sites;
- (2) maps that show PM component species mean bias at individual monitoring sites;
- (3) bar and whisker plots that show the distribution of the predicted and observed PM_{2.5} component species concentrations by month for the US as a whole.

III. Results

Summary of Findings

The PM_{2.5} component species model performance statistics by season and climate region are provided in Tables 1-10. Maps and boxplot figures also provide additional information on spatial and temporal patterns of observed and modeled PM_{2.5} component species and associated model biases.

As indicated by the information in the tables and figures, the model generally captures the observed spatial and temporal patterns of sulfate but overestimates the magnitude of concentrations at CSN and IMPROVE sites in most regions and season by 0.1-0.6 µg/m³ depending on the region season with the exception of small model underestimates noted in summer in the Southeast (IMPROVE only), South, Southwest and West (CSN only) regions.

Observed nitrate concentrations are highest during winter in the Midwestern US and in the San Joaquin Valley, CA and the Salt Lake Valley, UT. The model generally captures these spatial patterns but overestimates the magnitude of wintertime nitrate in the Southeastern US by over 1 µg/m³ at some

sites, underestimates the nitrate in the San Joaquin Valley by 0.5-1 $\mu\text{g}/\text{m}^3$, and mostly misses the elevated nitrate observed near Salt Lake City. In addition, the model overestimates nitrate in the Eastern US by 0-0.6 $\mu\text{g}/\text{m}^3$ in seasons when observed concentrations are low. The observations also show elevated sulfate in the Los Angeles areas which is also predicted by the model but is underestimated.

The CAMx modeling generally captures the spatial and temporal patterns of organic carbon which are the result of a myriad of source category and atmosphere formation mechanisms. The model underpredicts the magnitude of wintertime episodes in California and Utah but overestimates the concentrations in Washington and the Eastern US. Similarly, the organic carbon concentrations in the Southeast and along the Atlantic coast tend to be overpredicted in spring, summer and fall while predictions of organic carbon in the Western US are mixed during these seasons. Nationally, the organic carbon NMB was 40% in winter, 34% in spring, 14% in summer and 17% in fall at CSN monitoring locations and 36% in winter, -26% in spring, -5% in summer and 9% in fall at IMPROVE monitoring locations.

The highest elemental carbon concentrations are generally observed in winter and fall when mixing of local pollution is most limited. At most monitors observed elemental carbon concentrations are less than 0.5 $\mu\text{g}/\text{m}^3$ but concentrations of 1-2 $\mu\text{g}/\text{m}^3$ in winter and fall are observed in the San Joaquin Valley and in certain urban areas. CAMx predictions of elemental carbon concentrations generally follow the same spatial and temporal patterns as observations. Model predictions of seasonal elemental carbon concentrations fall within $\pm 20\%$ of observations in most regions and seasons at both CSN and IMPROVE sites.

CAMx model predictions generally overpredict soil concentrations over much of the US in all seasons by ± 0.2 -0.8 at CSN sites and ± 0.1 -0.4 $\mu\text{g}/\text{m}^3$ at IMPROVE sites for most regions and seasons except in the Southwest most likely because windblown dust emissions are not included in the simulation. Underpredictions of soil in the summer across the South, Southwest, and West range from -0.5 to -0.9 $\mu\text{g}/\text{m}^3$.

Below we describe in more detail the results shown in these figures and tables for sulfate, nitrate, organic carbon, elemental carbon, and soil.

Detailed Description of Model Performance Statistics and Graphics

Sulfate:

Spatial patterns of observed and modeled 2016 sulfate concentrations vary seasonally (Figures 3 and 4). Observed and modeled sulfate concentrations are generally higher in the US Midwest and South compared to the Western US and the Northeast. Observed seasonally averaged concentrations at monitoring sites in the Midwest and South range from 1-3 $\mu\text{g}/\text{m}^3$ depending on location and season, while observed seasonally averaged concentrations in Northeast and most of the Western US are generally less than 1 $\mu\text{g}/\text{m}^3$. In Southern California, summertime sulfate observations also reach levels of 2-3 $\mu\text{g}/\text{m}^3$ similar to the higher observed values in the Ohio Valley region. While the modeled concentrations tend to be somewhat higher than observed values, the model depicts these same spatial and seasonal patterns. The spatial extent of the modeled elevated summertime sulfate above 1 $\mu\text{g}/\text{m}^3$ in the Western US covers the entire West Coast from Washington state down to Southern California

while the observations only register summertime concentrations above $1 \mu\text{g}/\text{m}^3$ at sites in the southern half of California. Overall, Figure 5 shows a consistent mean bias of about $0.1\text{-}0.5 \mu\text{g}/\text{m}^3$ at most sites across seasons with the exception of model underpredictions across the southern half of the US during summer. When bias is expressed as a percent of the observed concentrations, the sulfate overestimates at CSN monitors are generally less than 50% in most regions and seasons except the Northeast and Upper Midwest during fall, the Northern Rockies and Plains during fall, the southwest during spring and the Northwest during all seasons. The sulfate overestimates at IMPROVE monitors are generally less than 50% in most regions and season except the Northeast during fall, the west and southwest during winter and spring, and the Northern Rockies and Plains and the Northwest during all seasons. The overestimates on a percentage basis are especially pronounced in the Northwest, given the low observed concentrations.

Figure 6 shows the magnitude of 25th to 75th percentile modeled and observed sulfate values at CSN and IMPROVE monitors by month. Observed sulfate concentrations peak in July with mean values just above $1 \mu\text{g}/\text{m}^3$ at the more urban CSN monitors and around $0.6 \mu\text{g}/\text{m}^3$ at the more rural IMPROVE monitor. Modeled sulfate concentrations also peak in July at CSN monitors although the seasonal pattern is not as pronounced in the model as in the observations. This results in a smaller overpredictions of median sulfate concentrations across sites in July (around $0.2 \mu\text{g}/\text{m}^3$) than in other months with the largest overpredictions occurring in the fall. At IMPROVE monitors the model sulfate concentrations peak in spring rather than the observed mid-summer peak leading to an overall median of bias across monitors/days of around $0.3 \mu\text{g}/\text{m}^3$ in the spring with a somewhat smaller bias in July of around $0.1 \mu\text{g}/\text{m}^3$.

Tables 1 and 2 further break down the sulfate model performance statistics by season and region. In addition to the biases already discussed, the tables provide correlation which show how well the model captures spatial and temporal variation. The correlations are generally greater than 0.5 for sulfate at CSN sites except in the Northeast and Ohio River Valley during winter, the Southeast and South during summer, the Southwest during winter, summer and fall, the Northwest during winter and summer and the West during winter spring and summer. Correlations are generally greater than 0.5 for sulfate at IMPROVE sites except in the Southeast during spring, the Northern Rockies and Plains during summer, the Southwest during winter, summer and fall, the Northwest during summer and the West during winter spring and summer.

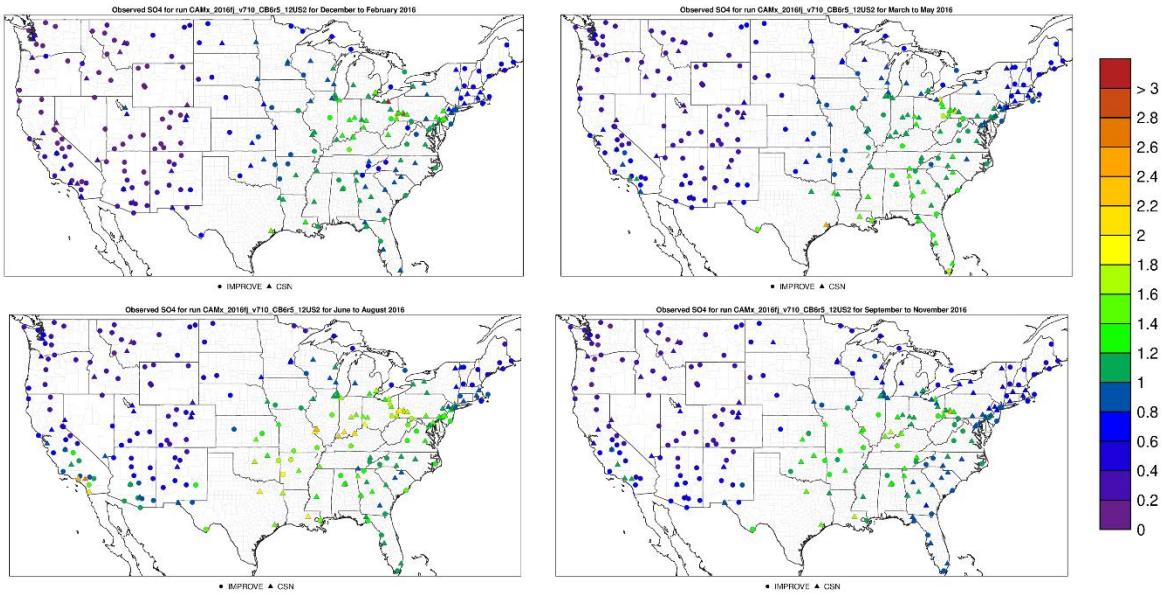


Figure 3. Observed sulfate concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

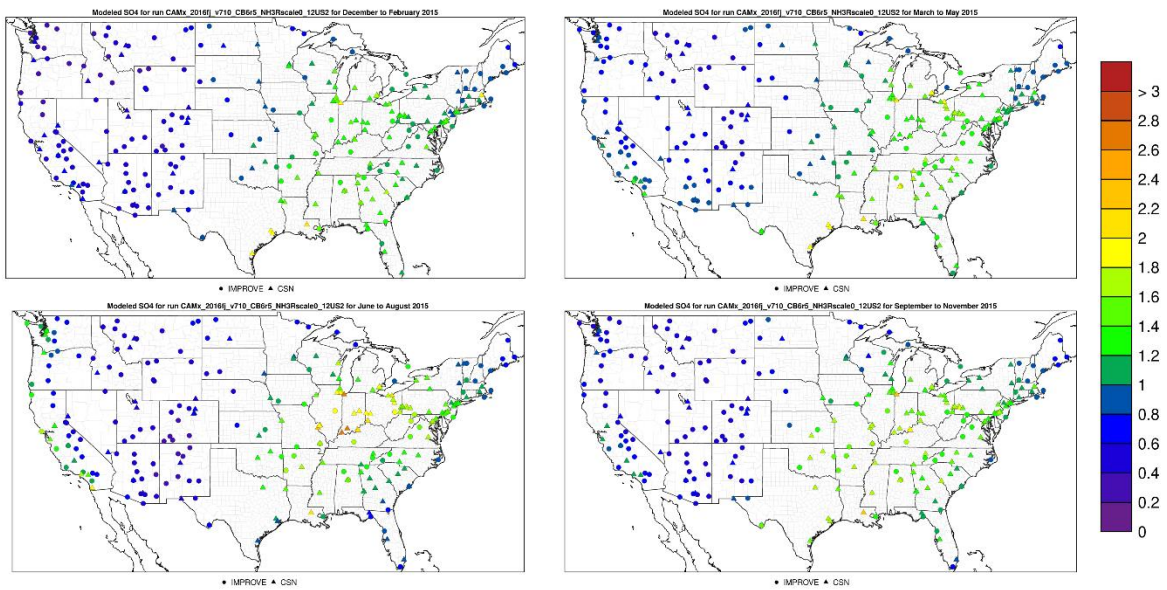


Figure 4. Modeled sulfate concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

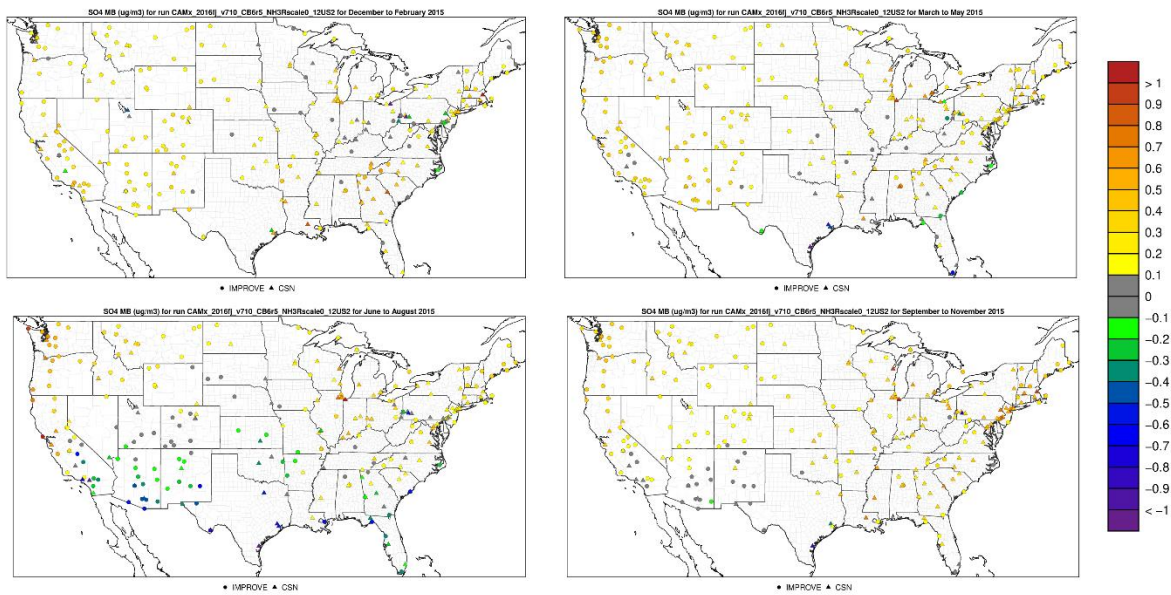


Figure 5. CAMx sulfate mean bias ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

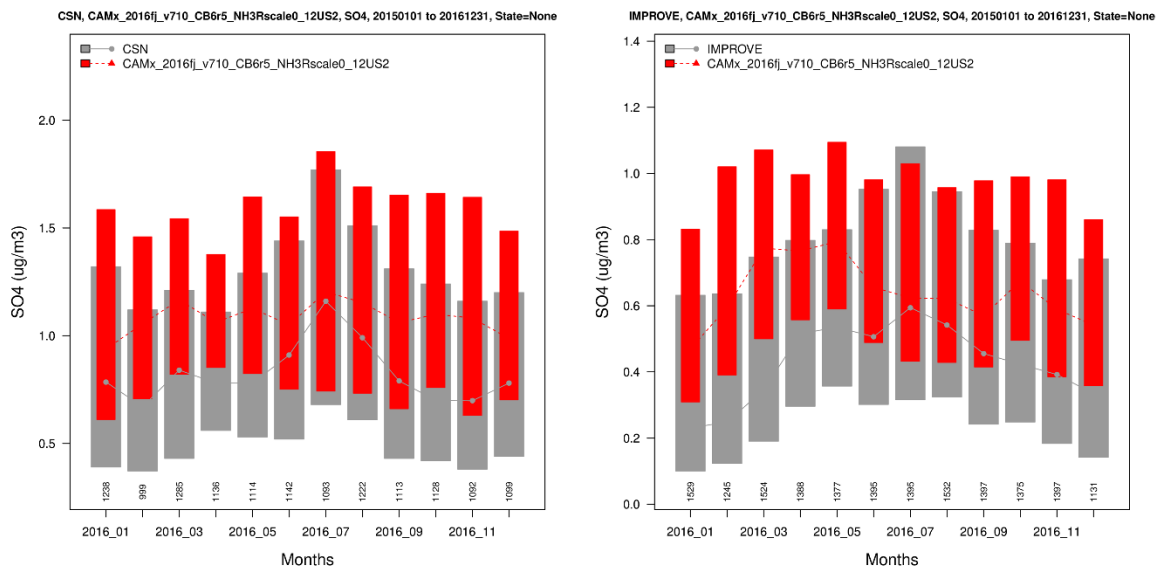


Figure 6: Boxplots of observed and modeled sulfate concentrations ($\mu\text{g}/\text{m}^3$) by month at CSN (right)

and IMPROVE (left) monitoring sites. Lines indicate median concentrations across monitors in each month. Boxes delineate the 25th and 75th percentile ranges.

Table 1: sulfate model performance at CSN sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-----------------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 747 | 1.04 | 1.27 | 0.23 | 21.74 | 0.54 | 51.70 | 0.21 |
| | spring | 800 | 0.92 | 1.32 | 0.34 | 36.78 | 0.45 | 48.92 | 0.68 |
| | summer | 813 | 1.16 | 1.49 | 0.20 | 17.60 | 0.39 | 33.88 | 0.77 |
| | fall | 762 | 0.87 | 1.35 | 0.51 | 58.79 | 0.59 | 67.47 | 0.65 |
| | Annual | 3122 | 1.00 | 1.36 | 0.32 | 31.92 | 0.49 | 49.02 | 0.56 |
| Upper Midwest | winter | 326 | 1.00 | 1.26 | 0.28 | 27.53 | 0.44 | 43.74 | 0.68 |
| | spring | 354 | 0.91 | 1.32 | 0.38 | 42.00 | 0.48 | 52.03 | 0.66 |
| | summer | 314 | 0.99 | 1.32 | 0.33 | 33.15 | 0.46 | 46.36 | 0.81 |
| | fall | 310 | 0.73 | 1.29 | 0.49 | 67.53 | 0.54 | 73.07 | 0.75 |
| | Annual | 1304 | 0.91 | 1.30 | 0.37 | 40.58 | 0.48 | 52.29 | 0.73 |
| Ohio River Valley | winter | 547 | 1.35 | 1.46 | 0.10 | 7.29 | 0.53 | 39.38 | 0.48 |
| | spring | 562 | 1.18 | 1.51 | 0.27 | 22.71 | 0.49 | 41.75 | 0.50 |
| | summer | 554 | 1.63 | 1.85 | 0.32 | 19.30 | 0.61 | 37.50 | 0.65 |
| | fall | 541 | 1.24 | 1.64 | 0.40 | 32.36 | 0.57 | 46.00 | 0.65 |
| | Annual | 2204 | 1.35 | 1.62 | 0.27 | 20.04 | 0.55 | 40.83 | 0.60 |
| Southeast | winter | 513 | 0.92 | 1.32 | 0.42 | 45.66 | 0.53 | 57.17 | 0.59 |
| | spring | 551 | 1.12 | 1.42 | 0.30 | 26.79 | 0.47 | 42.37 | 0.56 |
| | summer | 524 | 1.12 | 1.21 | 0.09 | 8.05 | 0.44 | 39.52 | 0.42 |
| | fall | 506 | 0.97 | 1.39 | 0.40 | 41.15 | 0.48 | 49.50 | 0.70 |
| | Annual | 2094 | 1.03 | 1.34 | 0.30 | 29.07 | 0.48 | 46.44 | 0.55 |
| South | winter | 327 | 1.08 | 1.47 | 0.32 | 29.69 | 0.54 | 49.80 | 0.64 |
| | spring | 351 | 1.45 | 1.46 | -0.04 | -2.43 | 0.64 | 44.34 | 0.69 |
| | summer | 336 | 1.55 | 1.27 | -0.30 | -19.39 | 0.65 | 42.01 | 0.41 |
| | fall | 331 | 1.40 | 1.57 | 0.23 | 16.22 | 0.58 | 41.57 | 0.60 |
| | Annual | 1345 | 1.37 | 1.44 | 0.05 | 3.61 | 0.60 | 44.03 | 0.56 |
| Northern Rockies and Plains | winter | 143 | 0.51 | 0.65 | 0.22 | 43.42 | 0.37 | 73.30 | 0.65 |
| | spring | 151 | 0.54 | 0.75 | 0.27 | 49.71 | 0.35 | 64.91 | 0.61 |
| | summer | 153 | 0.54 | 0.66 | 0.16 | 29.65 | 0.28 | 52.44 | 0.72 |
| | fall | 139 | 0.47 | 0.68 | 0.28 | 60.35 | 0.33 | 71.07 | 0.82 |
| | Annual | 586 | 0.52 | 0.69 | 0.23 | 45.01 | 0.33 | 64.86 | 0.69 |
| Southwest | winter | 247 | 0.57 | 0.58 | 0.05 | 8.88 | 0.45 | 79.32 | 0.29 |
| | spring | 255 | 0.43 | 0.75 | 0.36 | 82.92 | 0.37 | 86.85 | 0.54 |
| | summer | 250 | 0.79 | 0.57 | -0.21 | -27.23 | 0.35 | 44.24 | 0.24 |

| | | | | | | | | | |
|-----------|--------|--------|------|------|-------|--------|-------|--------|-------|
| | fall | 260 | 0.55 | 0.62 | 0.10 | 18.15 | 0.27 | 48.56 | 0.31 |
| | Annual | 1012 | 0.58 | 0.63 | 0.07 | 12.83 | 0.36 | 61.58 | 0.19 |
| Northwest | winter | 157 | 0.29 | 0.59 | 0.30 | 104.04 | 0.35 | 122.80 | 0.29 |
| | spring | 161 | 0.40 | 0.83 | 0.47 | 116.07 | 0.48 | 117.82 | 0.65 |
| | summer | 166 | 0.54 | 1.09 | 0.60 | 112.00 | 0.62 | 115.42 | 0.47 |
| | fall | 161 | 0.36 | 0.76 | 0.47 | 129.93 | 0.49 | 136.39 | 0.57 |
| | Annual | 645 | 0.40 | 0.82 | 0.46 | 115.66 | 0.49 | 122.04 | 0.54 |
| | West | winter | 341 | 0.48 | 0.73 | 0.27 | 55.60 | 0.42 | 86.24 |
| spring | | 352 | 0.84 | 1.03 | 0.23 | 27.60 | 0.50 | 60.11 | 0.47 |
| summer | | 349 | 1.45 | 1.27 | -0.11 | -7.48 | 0.62 | 42.86 | 0.30 |
| fall | | 332 | 0.83 | 0.96 | 0.15 | 18.13 | 0.38 | 46.13 | 0.57 |
| Annual | | 1374 | 0.90 | 1.00 | 0.13 | 14.94 | 0.48 | 53.44 | 0.46 |
| National | winter | 3348 | 0.92 | 1.19 | 0.24 | 26.42 | 0.49 | 53.20 | 0.51 |
| | spring | 3537 | 0.96 | 1.28 | 0.28 | 29.37 | 0.48 | 49.83 | 0.62 |
| | summer | 3459 | 1.20 | 1.34 | 0.12 | 10.22 | 0.49 | 41.15 | 0.59 |
| | fall | 3342 | 0.91 | 1.29 | 0.37 | 40.14 | 0.50 | 54.93 | 0.68 |
| | Annual | 13686 | 1.00 | 1.28 | 0.25 | 25.32 | 0.49 | 49.11 | 0.59 |

Table 2: sulfate model performance at IMPROVE sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 431 | 0.73 | 0.92 | 0.19 | 25.53 | 0.34 | 46.42 | 0.50 |
| | spring | 477 | 0.76 | 1.00 | 0.22 | 28.51 | 0.30 | 39.07 | 0.72 |
| | summer | 486 | 0.76 | 1.06 | 0.26 | 34.77 | 0.35 | 46.36 | 0.83 |
| | fall | 456 | 0.62 | 1.01 | 0.36 | 58.49 | 0.41 | 66.44 | 0.73 |
| | Annual | 1850 | 0.72 | 1.00 | 0.26 | 35.90 | 0.35 | 48.65 | 0.73 |
| Upper Midwest | winter | 200 | 0.76 | 0.94 | 0.12 | 16.33 | 0.29 | 37.74 | 0.74 |
| | spring | 208 | 0.76 | 1.02 | 0.17 | 22.00 | 0.31 | 40.87 | 0.60 |
| | summer | 210 | 0.68 | 0.94 | 0.16 | 23.67 | 0.28 | 41.34 | 0.85 |
| | fall | 215 | 0.63 | 0.99 | 0.27 | 42.52 | 0.34 | 53.62 | 0.84 |
| | Annual | 833 | 0.71 | 0.97 | 0.18 | 25.68 | 0.31 | 43.12 | 0.77 |
| Ohio River Valley | winter | 220 | 1.10 | 1.25 | 0.14 | 12.73 | 0.39 | 35.61 | 0.68 |
| | spring | 244 | 1.17 | 1.22 | 0.06 | 5.54 | 0.33 | 28.07 | 0.64 |
| | summer | 239 | 1.49 | 1.61 | 0.14 | 9.43 | 0.57 | 38.60 | 0.67 |
| | fall | 227 | 1.31 | 1.50 | 0.20 | 15.64 | 0.39 | 29.87 | 0.81 |
| | Annual | 930 | 1.27 | 1.40 | 0.14 | 10.72 | 0.42 | 33.24 | 0.70 |
| Southeast | winter | 342 | 0.95 | 1.18 | 0.21 | 22.21 | 0.41 | 43.21 | 0.57 |
| | spring | 379 | 1.24 | 1.27 | 0.06 | 5.00 | 0.41 | 32.72 | 0.40 |
| | summer | 394 | 1.21 | 1.05 | -0.10 | -8.34 | 0.44 | 35.98 | 0.57 |

| | | | | | | | | | |
|-----------|-----------------------------|--------|------|------|-------|--------|-------|--------|-------|
| | fall | 366 | 1.04 | 1.18 | 0.20 | 19.77 | 0.35 | 33.32 | 0.73 |
| | Annual | 1481 | 1.12 | 1.17 | 0.09 | 7.93 | 0.40 | 35.87 | 0.54 |
| South | winter | 240 | 0.78 | 1.00 | 0.25 | 32.83 | 0.40 | 51.46 | 0.63 |
| | spring | 273 | 0.96 | 1.03 | 0.06 | 6.61 | 0.34 | 35.46 | 0.69 |
| | summer | 252 | 1.44 | 1.05 | -0.37 | -25.89 | 0.58 | 40.09 | 0.56 |
| | fall | 264 | 1.12 | 1.29 | 0.16 | 14.43 | 0.42 | 37.97 | 0.69 |
| | Annual | 1029 | 1.08 | 1.09 | 0.03 | 2.42 | 0.43 | 40.34 | 0.60 |
| | Northern Rockies and Plains | winter | 542 | 0.32 | 0.56 | 0.24 | 74.42 | 0.29 | 90.27 |
| spring | | 573 | 0.38 | 0.64 | 0.26 | 68.47 | 0.28 | 74.35 | 0.74 |
| summer | | 603 | 0.36 | 0.54 | 0.18 | 50.72 | 0.25 | 69.38 | 0.42 |
| fall | | 574 | 0.34 | 0.57 | 0.22 | 65.37 | 0.27 | 80.33 | 0.67 |
| Annual | | 2292 | 0.35 | 0.58 | 0.22 | 64.19 | 0.27 | 77.90 | 0.68 |
| Southwest | winter | 910 | 0.25 | 0.48 | 0.24 | 97.42 | 0.29 | 115.01 | 0.37 |
| | spring | 991 | 0.38 | 0.69 | 0.30 | 78.94 | 0.33 | 85.25 | 0.54 |
| | summer | 985 | 0.65 | 0.46 | -0.19 | -28.77 | 0.30 | 45.72 | 0.36 |
| | fall | 962 | 0.47 | 0.52 | 0.06 | 12.32 | 0.24 | 52.67 | 0.36 |
| | Annual | 3848 | 0.44 | 0.54 | 0.10 | 23.20 | 0.29 | 65.71 | 0.30 |
| Northwest | winter | 427 | 0.15 | 0.37 | 0.23 | 154.69 | 0.24 | 164.51 | 0.60 |
| | spring | 505 | 0.31 | 0.68 | 0.37 | 121.66 | 0.37 | 121.85 | 0.68 |
| | summer | 519 | 0.34 | 0.82 | 0.48 | 139.43 | 0.49 | 141.27 | 0.43 |
| | fall | 499 | 0.24 | 0.59 | 0.35 | 144.72 | 0.36 | 149.10 | 0.62 |
| | Annual | 1950 | 0.27 | 0.62 | 0.36 | 137.21 | 0.37 | 140.12 | 0.62 |
| West | winter | 565 | 0.21 | 0.50 | 0.29 | 138.53 | 0.33 | 156.35 | 0.38 |
| | spring | 608 | 0.49 | 0.78 | 0.30 | 61.86 | 0.36 | 73.92 | 0.46 |
| | summer | 603 | 0.71 | 0.83 | 0.11 | 15.30 | 0.37 | 51.55 | 0.29 |
| | fall | 576 | 0.46 | 0.67 | 0.20 | 43.81 | 0.29 | 62.41 | 0.52 |
| | Annual | 2352 | 0.47 | 0.70 | 0.23 | 47.80 | 0.34 | 71.39 | 0.47 |
| National | winter | 3877 | 0.47 | 0.71 | 0.23 | 48.85 | 0.32 | 68.35 | 0.72 |
| | spring | 4258 | 0.61 | 0.86 | 0.24 | 39.24 | 0.33 | 55.14 | 0.70 |
| | summer | 4291 | 0.74 | 0.82 | 0.07 | 9.56 | 0.37 | 50.49 | 0.62 |
| | fall | 4139 | 0.58 | 0.81 | 0.21 | 35.59 | 0.32 | 54.82 | 0.77 |
| | Annual | 16565 | 0.60 | 0.80 | 0.18 | 30.66 | 0.34 | 55.98 | 0.69 |

Nitrate:

Observed nitrate concentrations have distinct seasonal and regional patterns shown in Figures 7. Nitrate concentrations are low (e.g. less than $1 \mu\text{g}/\text{m}^3$) at most locations throughout most of the year. In the Eastern US, the exceptions are the Midwest during the winter when nitrate concentrations are in the range of $2\text{-}5 \mu\text{g}/\text{m}^3$ and along the mid-Atlantic coast where the range is $1.5\text{-}2.5 \mu\text{g}/\text{m}^3$. In the Western US there are several locations with elevated observed nitrate concentrations during winter with concentrations above $5 \mu\text{g}/\text{m}^3$ in Salt Lake City, UT and in the San Joaquin Valley, CA. In southern California near Los Angeles, nitrate concentrations in the range of $3\text{-}4 \mu\text{g}/\text{m}^3$ are observed year-round. The model also generally predicts low nitrate concentrations in most locations and seasons with

localized elevated nitrate during winter in the Midwest (2-3.5 $\mu\text{g}/\text{m}^3$) and along mid-Atlantic coast (1.5-3.5 $\mu\text{g}/\text{m}^3$). The model also shows moderately elevated nitrate concentrations of 1.5-2.5 $\mu\text{g}/\text{m}^3$ in the Great Lakes region in the spring in the Ohio Valley region in the fall. In the Western US model-predicted elevated winter nitrate only reached around 1 $\mu\text{g}/\text{m}^3$ in Salt Lake City, UT, 3.5 $\mu\text{g}/\text{m}^3$ in San Juaquin Valley, CA and 1.5-2 $\mu\text{g}/\text{m}^3$ in southern California. Moderately elevated nitrate in the range of 1-2 $\mu\text{g}/\text{m}^3$ in California were modeled in spring, summer, and fall but were not as high as monitored levels in these locations. Figure 9 shows a mix of over- and under-predictions at different monitoring sites and in different seasons. Across all sites there is a modest underprediction of nitrate in the winter at CSN and IMPROVE sites (-6% and -11% respectively). This is driven by wintertime underpredictions in all regions except for the Northeast and Southeast where the model overpredicts nitrate concentrations. In the summer, nitrate is overpredicted in the Ohio Valley and Upper Midwest regions, underpredicted in the West, Southwest and along the East Coast and relatively unbiased (within $\pm 0.1 \mu\text{g}/\text{m}^3$) throughout most of the rest of the country leading to overall summertime normalized mean biases across all CSN sites of 10% and across all IMPROVE sites of -26%.

Figure 10 shows the distribution of modeled monthly nitrate concentrations at CSN and IMPROVE monitors closely track the overall temporal patterns of the observed concentrations at both CSN and IMPROVE monitors. Observed nitrate concentrations peak in December and January with median values between 1-1.5 $\mu\text{g}/\text{m}^3$ at the more urban CSN monitors and around 0.2 $\mu\text{g}/\text{m}^3$ at the more rural IMPROVE monitors. The observed nitrate concentrations are lowest during summer months of June-September with median concentrations around 0.2 $\mu\text{g}/\text{m}^3$ at CSN monitors and around 0.1 at IMPROVE monitors. Modeled nitrate concentrations generally follow the same seasonal pattern as observed concentrations but are slightly higher in most months at CSN sites and higher in the winter but lower in the summer at IMPROVE sites.

Nitrate correlations shown in Tables 3 and 4 above 0.5 in most regions in the winter, spring, and fall seasons when nitrate concentrations are highest. The exceptions are somewhat lower correlations at CSN sites during winter and spring in the Ohio Valley and the Southeast, during winter in the Southwest, and during winter, spring and fall in the Northwest. At IMPROVE sites, the exceptions are lower correlations during winter in the Ohio Valley, during winter and spring in the Southeast, during winter and spring in the Southwest, and during winter and fall in the Northwest. During summer when observed concentrations were low, correlations are also in most regions (0.07-0.56 at CSN sites and 0.19-0.53 at IMPROVE sites).

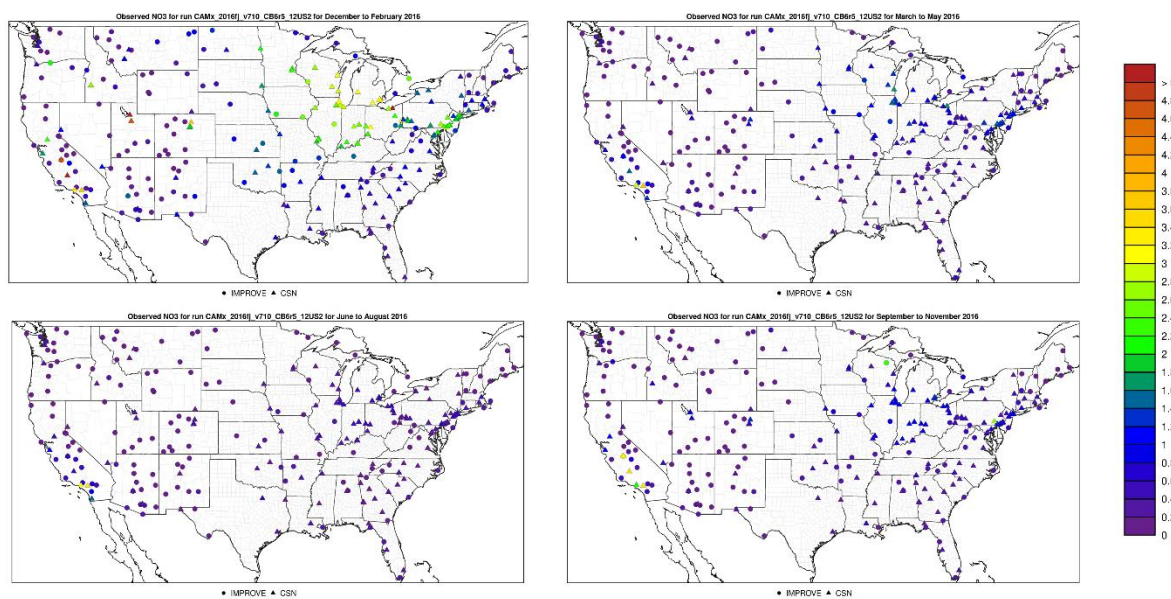


Figure 7. Observed nitrate concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

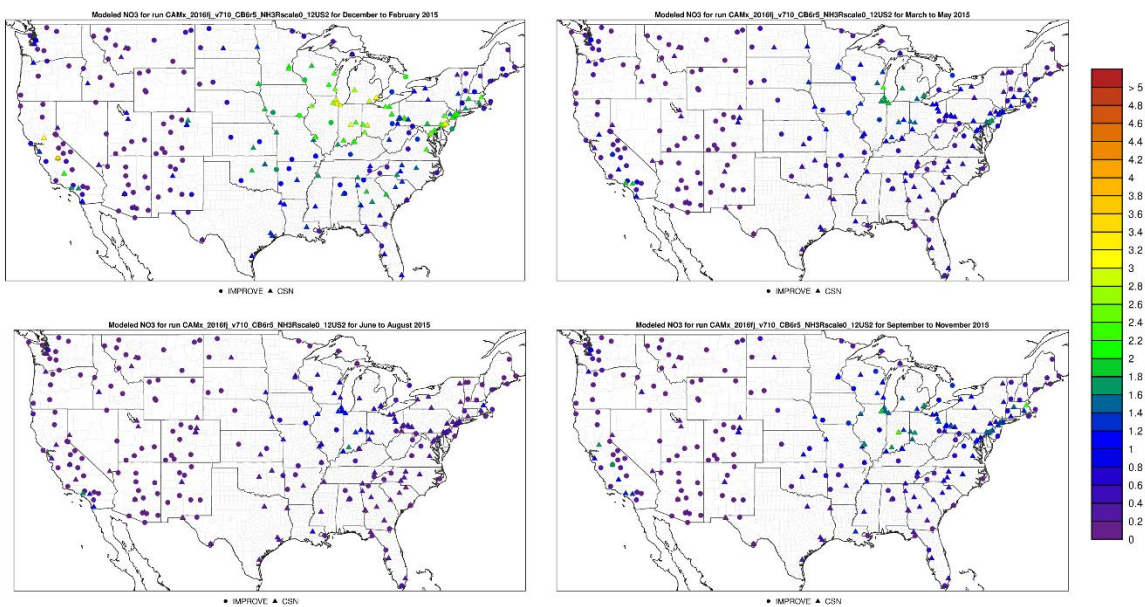


Figure 8. Modeled nitrate concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

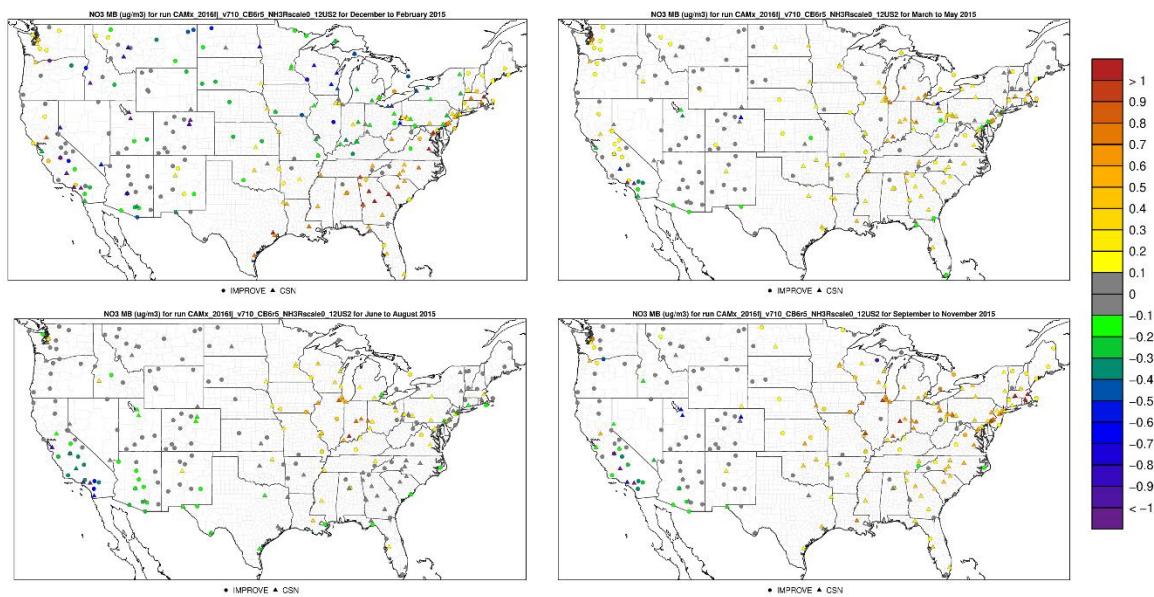


Figure 9. CAMx nitrate mean bias ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

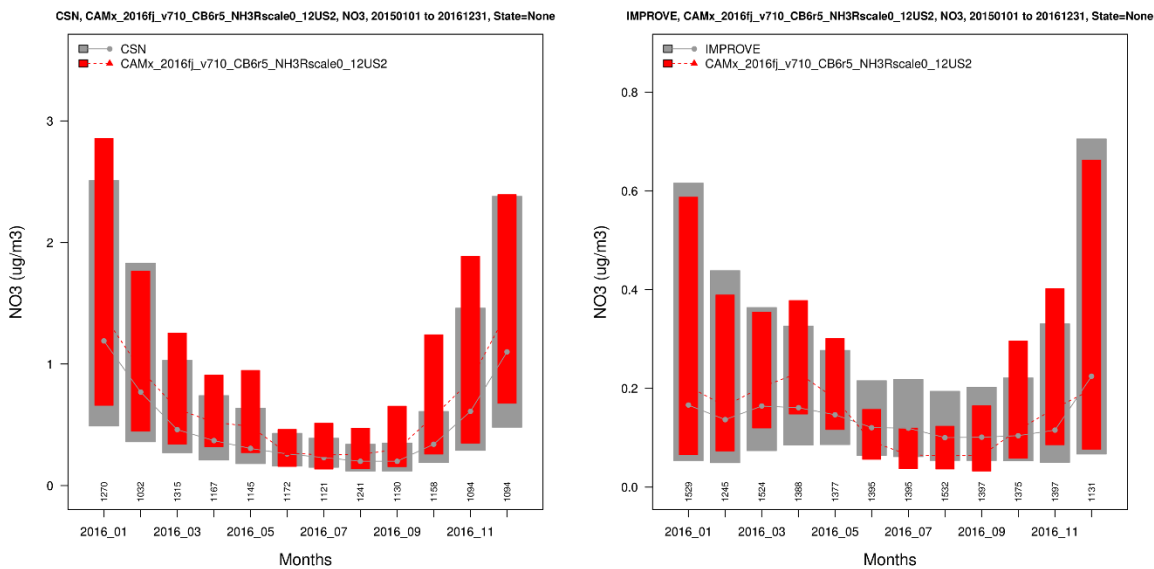


Figure 10: Boxplots of observed and modeled nitrate concentrations ($\mu\text{g}/\text{m}^3$) by month at CSN (right) and IMPROVE (left) monitoring sites. Lines indicate median concentrations across monitors in each month. Boxes delineate the 25th and 75th percentile ranges.

Table 3: nitrate model performance at CSN sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-----------------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 747 | 1.69 | 1.95 | 0.34 | 19.87 | 0.93 | 55.09 | 0.66 |
| | spring | 800 | 0.86 | 1.05 | 0.19 | 22.45 | 0.59 | 68.91 | 0.67 |
| | summer | 813 | 0.32 | 0.40 | 0.05 | 15.88 | 0.20 | 63.34 | 0.50 |
| | fall | 762 | 0.63 | 1.21 | 0.58 | 92.82 | 0.69 | 110.07 | 0.65 |
| | Annual | 3122 | 0.86 | 1.14 | 0.29 | 33.14 | 0.60 | 69.21 | 0.70 |
| Upper Midwest | winter | 326 | 2.59 | 2.32 | -0.27 | -10.39 | 1.15 | 44.27 | 0.71 |
| | spring | 354 | 1.07 | 1.41 | 0.33 | 30.50 | 0.78 | 72.32 | 0.58 |
| | summer | 314 | 0.32 | 0.56 | 0.21 | 64.75 | 0.36 | 110.43 | 0.37 |
| | fall | 310 | 0.75 | 1.28 | 0.42 | 56.15 | 0.59 | 78.24 | 0.77 |
| | Annual | 1304 | 1.19 | 1.40 | 0.17 | 14.40 | 0.72 | 60.49 | 0.73 |
| Ohio River Valley | winter | 547 | 2.38 | 2.18 | -0.14 | -5.90 | 1.27 | 53.27 | 0.42 |
| | spring | 562 | 0.88 | 1.10 | 0.27 | 31.20 | 0.68 | 77.84 | 0.37 |
| | summer | 554 | 0.36 | 0.60 | 0.36 | 99.24 | 0.47 | 131.08 | 0.24 |
| | fall | 541 | 0.79 | 1.16 | 0.51 | 63.88 | 0.72 | 90.69 | 0.58 |
| | Annual | 2204 | 1.10 | 1.25 | 0.25 | 22.63 | 0.78 | 71.28 | 0.54 |
| Southeast | winter | 573 | 0.61 | 1.20 | 0.71 | 117.20 | 0.80 | 131.40 | 0.46 |
| | spring | 643 | 0.34 | 0.49 | 0.18 | 52.59 | 0.28 | 83.49 | 0.28 |
| | summer | 610 | 0.20 | 0.24 | 0.05 | 24.52 | 0.12 | 61.35 | 0.26 |
| | fall | 560 | 0.30 | 0.62 | 0.34 | 112.57 | 0.38 | 127.89 | 0.62 |
| | Annual | 2386 | 0.36 | 0.63 | 0.31 | 86.63 | 0.39 | 108.52 | 0.57 |
| South | winter | 327 | 0.83 | 1.15 | 0.33 | 40.37 | 0.68 | 82.88 | 0.51 |
| | spring | 351 | 0.33 | 0.50 | 0.16 | 50.23 | 0.29 | 87.02 | 0.50 |
| | summer | 336 | 0.25 | 0.28 | 0.03 | 12.72 | 0.19 | 74.06 | 0.17 |
| | fall | 331 | 0.31 | 0.54 | 0.23 | 75.04 | 0.32 | 103.85 | 0.55 |
| | Annual | 1345 | 0.43 | 0.62 | 0.19 | 44.39 | 0.37 | 86.12 | 0.59 |
| Northern Rockies and Plains | winter | 143 | 1.18 | 0.72 | -0.16 | -13.74 | 0.64 | 54.27 | 0.67 |
| | spring | 151 | 0.49 | 0.48 | 0.15 | 29.44 | 0.35 | 71.40 | 0.73 |
| | summer | 153 | 0.16 | 0.23 | 0.08 | 48.39 | 0.14 | 83.58 | 0.52 |
| | fall | 139 | 0.31 | 0.45 | 0.22 | 69.64 | 0.33 | 103.68 | 0.59 |
| | Annual | 586 | 0.53 | 0.47 | 0.07 | 13.25 | 0.36 | 67.64 | 0.69 |
| Southwest | winter | 247 | 2.54 | 0.80 | -1.73 | -68.16 | 1.87 | 73.37 | 0.49 |
| | spring | 255 | 0.44 | 0.33 | -0.09 | -19.70 | 0.24 | 54.75 | 0.56 |
| | summer | 250 | 0.27 | 0.16 | -0.10 | -37.61 | 0.17 | 63.06 | 0.07 |
| | fall | 260 | 0.54 | 0.30 | -0.22 | -41.09 | 0.36 | 65.40 | 0.53 |
| | Annual | 1012 | 0.94 | 0.39 | -0.53 | -56.16 | 0.65 | 69.22 | 0.58 |
| Northwest | winter | 157 | 1.20 | 0.97 | -0.28 | -23.55 | 0.92 | 77.11 | 0.39 |

| | | | | | | | | | |
|----------|--------|-------|------|------|-------|--------|------|--------|------|
| | spring | 161 | 0.41 | 0.65 | 0.43 | 104.89 | 0.49 | 119.89 | 0.46 |
| | summer | 166 | 0.27 | 0.33 | 0.14 | 50.66 | 0.21 | 78.19 | 0.46 |
| | fall | 161 | 0.51 | 0.67 | 0.29 | 57.84 | 0.53 | 104.49 | 0.29 |
| | Annual | 645 | 0.59 | 0.66 | 0.15 | 24.95 | 0.53 | 90.52 | 0.31 |
| West | winter | 341 | 3.28 | 1.80 | -1.36 | -41.45 | 1.96 | 59.90 | 0.60 |
| | spring | 352 | 1.57 | 1.00 | -0.43 | -27.08 | 0.83 | 52.69 | 0.64 |
| | summer | 349 | 1.25 | 0.56 | -0.64 | -51.37 | 0.81 | 64.64 | 0.56 |
| | fall | 332 | 1.96 | 1.01 | -0.83 | -42.45 | 1.24 | 63.15 | 0.65 |
| | Annual | 1374 | 2.01 | 1.08 | -0.81 | -40.38 | 1.20 | 59.98 | 0.64 |
| National | winter | 3408 | 1.80 | 1.64 | -0.10 | -5.79 | 1.12 | 62.16 | 0.50 |
| | spring | 3629 | 0.74 | 0.86 | 0.14 | 19.07 | 0.52 | 70.36 | 0.58 |
| | summer | 3545 | 0.38 | 0.40 | 0.04 | 9.70 | 0.30 | 78.75 | 0.38 |
| | fall | 3396 | 0.69 | 0.91 | 0.25 | 36.85 | 0.60 | 88.18 | 0.52 |
| | Annual | 13978 | 0.89 | 0.95 | 0.08 | 9.18 | 0.63 | 70.56 | 0.57 |

Table 4: nitrate model performance at IMPROVE sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 431 | 0.52 | 0.77 | 0.19 | 36.27 | 0.39 | 73.49 | 0.62 |
| | spring | 477 | 0.32 | 0.41 | 0.06 | 18.88 | 0.21 | 64.34 | 0.67 |
| | summer | 486 | 0.15 | 0.16 | 0.00 | 0.31 | 0.10 | 63.93 | 0.50 |
| | fall | 456 | 0.25 | 0.47 | 0.18 | 71.22 | 0.27 | 109.48 | 0.55 |
| | Annual | 1850 | 0.31 | 0.45 | 0.10 | 33.74 | 0.24 | 76.88 | 0.65 |
| Upper Midwest | winter | 200 | 1.43 | 1.28 | -0.36 | -25.22 | 0.69 | 48.36 | 0.71 |
| | spring | 208 | 0.58 | 0.74 | 0.04 | 6.90 | 0.40 | 70.04 | 0.57 |
| | summer | 210 | 0.12 | 0.32 | 0.19 | 159.89 | 0.21 | 176.11 | 0.53 |
| | fall | 215 | 0.38 | 0.70 | 0.22 | 57.34 | 0.41 | 108.80 | 0.53 |
| | Annual | 833 | 0.62 | 0.76 | 0.03 | 4.40 | 0.43 | 69.23 | 0.66 |
| Ohio River Valley | winter | 220 | 1.34 | 1.14 | -0.21 | -16.04 | 0.84 | 62.82 | 0.45 |
| | spring | 244 | 0.52 | 0.54 | 0.03 | 5.40 | 0.35 | 66.31 | 0.53 |
| | summer | 239 | 0.19 | 0.30 | 0.12 | 60.95 | 0.19 | 97.26 | 0.39 |
| | fall | 227 | 0.49 | 0.53 | 0.06 | 11.18 | 0.35 | 70.89 | 0.53 |
| | Annual | 930 | 0.62 | 0.63 | 0.00 | 0.06 | 0.42 | 67.89 | 0.58 |
| Southeast | winter | 342 | 0.49 | 0.66 | 0.13 | 26.76 | 0.35 | 70.85 | 0.49 |
| | spring | 379 | 0.34 | 0.34 | 0.01 | 2.98 | 0.21 | 62.32 | 0.36 |
| | summer | 394 | 0.19 | 0.17 | -0.01 | -5.63 | 0.13 | 69.29 | 0.19 |
| | fall | 366 | 0.29 | 0.35 | 0.07 | 23.86 | 0.22 | 76.96 | 0.51 |
| | Annual | 1481 | 0.32 | 0.38 | 0.05 | 14.75 | 0.22 | 69.69 | 0.52 |
| South | winter | 240 | 0.89 | 0.81 | -0.03 | -3.56 | 0.60 | 66.85 | 0.50 |
| | spring | 273 | 0.34 | 0.35 | 0.01 | 3.57 | 0.21 | 61.88 | 0.53 |

| | | | | | | | | | |
|-----------------------------|--------|-------|------|------|-------|--------|------|--------|------|
| | summer | 252 | 0.22 | 0.15 | -0.06 | -29.56 | 0.15 | 68.67 | 0.14 |
| | fall | 264 | 0.25 | 0.31 | 0.06 | 23.30 | 0.18 | 69.61 | 0.59 |
| | Annual | 1029 | 0.42 | 0.40 | 0.00 | -1.08 | 0.28 | 66.44 | 0.60 |
| Northern Rockies and Plains | winter | 542 | 0.39 | 0.26 | -0.14 | -36.75 | 0.27 | 69.28 | 0.62 |
| | spring | 573 | 0.16 | 0.22 | 0.05 | 33.53 | 0.13 | 81.15 | 0.56 |
| | summer | 603 | 0.08 | 0.08 | 0.01 | 7.11 | 0.04 | 57.58 | 0.29 |
| | fall | 574 | 0.11 | 0.16 | 0.05 | 46.09 | 0.10 | 94.55 | 0.56 |
| | Annual | 2292 | 0.18 | 0.18 | -0.01 | -3.60 | 0.13 | 74.39 | 0.58 |
| Southwest | winter | 910 | 0.27 | 0.18 | -0.09 | -34.26 | 0.19 | 70.66 | 0.48 |
| | spring | 991 | 0.18 | 0.17 | 0.00 | 0.11 | 0.09 | 51.23 | 0.39 |
| | summer | 985 | 0.15 | 0.05 | -0.10 | -65.15 | 0.10 | 67.78 | 0.32 |
| | fall | 962 | 0.12 | 0.08 | -0.05 | -38.39 | 0.07 | 56.41 | 0.53 |
| | Annual | 3848 | 0.18 | 0.12 | -0.06 | -33.13 | 0.11 | 62.71 | 0.48 |
| Northwest | winter | 427 | 0.32 | 0.24 | -0.07 | -23.17 | 0.31 | 97.40 | 0.37 |
| | spring | 505 | 0.15 | 0.26 | 0.11 | 73.67 | 0.15 | 99.05 | 0.54 |
| | summer | 519 | 0.14 | 0.10 | -0.03 | -24.31 | 0.09 | 69.05 | 0.47 |
| | fall | 499 | 0.16 | 0.21 | 0.04 | 27.18 | 0.16 | 100.69 | 0.41 |
| | Annual | 1950 | 0.19 | 0.20 | 0.01 | 7.95 | 0.17 | 92.95 | 0.36 |
| West | winter | 565 | 0.47 | 0.41 | -0.04 | -8.10 | 0.31 | 65.79 | 0.78 |
| | spring | 608 | 0.38 | 0.41 | 0.03 | 8.98 | 0.23 | 60.33 | 0.77 |
| | summer | 603 | 0.32 | 0.11 | -0.21 | -64.87 | 0.24 | 72.89 | 0.36 |
| | fall | 576 | 0.41 | 0.26 | -0.15 | -36.03 | 0.26 | 63.70 | 0.84 |
| | Annual | 2352 | 0.39 | 0.30 | -0.09 | -22.80 | 0.26 | 65.37 | 0.76 |
| National | winter | 3877 | 0.53 | 0.50 | -0.06 | -10.56 | 0.36 | 67.36 | 0.65 |
| | spring | 4258 | 0.28 | 0.33 | 0.04 | 13.33 | 0.18 | 65.54 | 0.63 |
| | summer | 4291 | 0.17 | 0.13 | -0.04 | -25.85 | 0.13 | 73.96 | 0.24 |
| | fall | 4139 | 0.24 | 0.27 | 0.02 | 10.22 | 0.19 | 79.50 | 0.64 |
| | Annual | 16565 | 0.30 | 0.31 | -0.01 | -2.98 | 0.21 | 70.29 | 0.65 |

Organic Carbon:

Observed organic carbon concentrations are shown in Figure 11. The spatial and temporal patterns of organic carbon reflect its varied sources and formation mechanisms including primary emissions from wildfires in the summer and woodsmoke in the winter along with secondary formation from biogenic precursors which are prevalent in the Southeastern US and from anthropogenic precursors such as vehicles and cooking emissions in urban areas. Organic carbon is highest in California, in the Southeastern US and along the mid-Atlantic coast. In addition, there are a few organic carbon hotspots in western mountain valleys in Oregon, Washington, Idaho, Utah, and Montana during winter due to woodsmoke emissions and in Idaho and Montana during summer due to wildfires. Elevated organic carbon in the southeastern US is present year-round but peaks during the fall with concentrations reaching above 5 $\mu\text{g}/\text{m}^3$ at some monitoring locations. The spatial and seasonal patterns of organic carbon predicted by CAMx (Figure 12) are similar to observed patterns although the model underpredicts the wintertime concentrations in California, and Utah but overestimates the

concentrations in Washington and the Eastern US. The organic carbon concentrations in the Southeast and along the Atlantic coast tend to be overpredicted in spring, summer, and fall while in the Western US there is no consistency in terms of model performance with a mix of underprediction and overprediction at various monitoring sites during these seasons. As shown in Tables 5 and 6, CAMx organic carbon estimates were within $\pm 30\%$ of monitored values for the majority of region/season combinations. CAMx OC concentrations were more often overpredicted than underpredicted. Overpredictions were most notable in the Northwest (fall, spring, and summer) and in the eastern US during winter. Underpredictions occurred more frequently in the Western half of the US and in the Southeast during fall. Nationally, the organic carbon NMB was 40% in winter, 34% in spring, 14% in summer and 17% in fall at CSN monitoring locations and 36% in winter, -26% in spring, -5% in summer and 9% in fall at IMPROVE monitoring locations.

Monthly 25th-75th percentile concentrations of observed and modeled organic carbon at monitor locations are shown in Figure 14. At the more urban CSN monitors, observed and modeled concentrations are highest during winter months when colder temperatures lead to less dispersion of local pollution, with a peak in November in both the model and observations. Conversely, organic carbon concentrations peak during summer at the more rural IMPROVE monitor locations due to secondary formation in the atmosphere and as seen in both the monitor values and the model predictions.

Correlations between CAMx modeled OC and observed OC (Tables 5 and 6) were higher at CSN monitoring sites than at IMPROVE monitoring sites. Correlation at CSN monitoring sites was above 0.5 in all regions and seasons except in the Upper Midwest in spring/summer, the Ohio Valley in summer, the Northern Rockies and Plains in winter/summer/fall, the Northwest in winter/spring/fall and the Southwest in all seasons. Correlations at IMPROVE sites tended to be somewhat lower with the best performance in the Northeast, South and West regions.

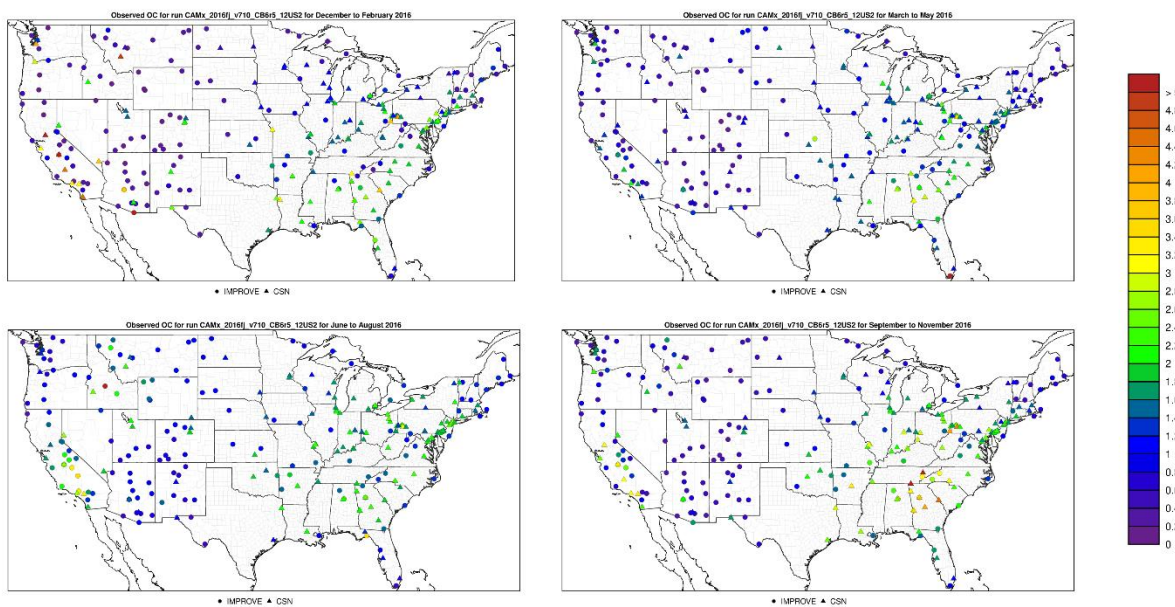


Figure 11. Observed organic carbon concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

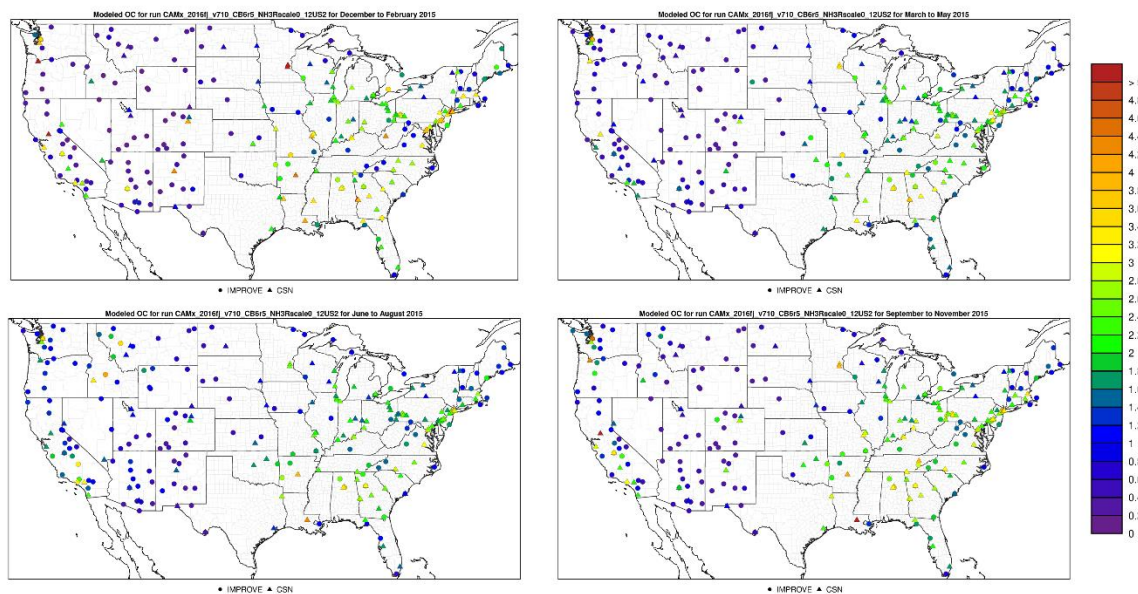


Figure 12. Modeled organic carbon concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter, spring, summer, and fall 2015.

monitoring sties during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

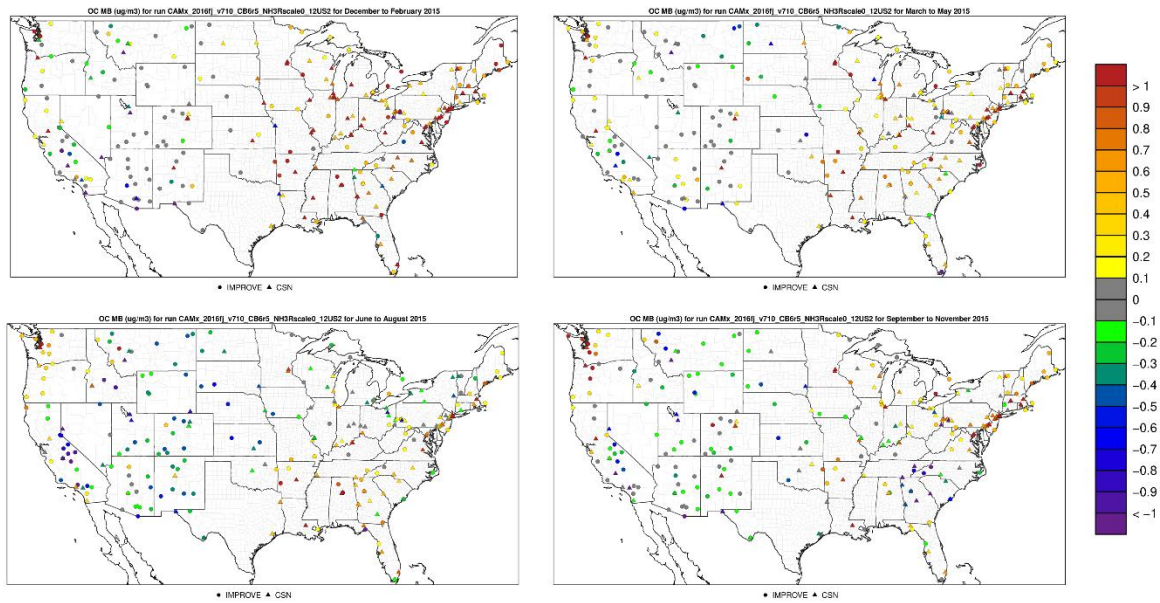


Figure 13. CAMx organic carbon mean bias ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sties during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

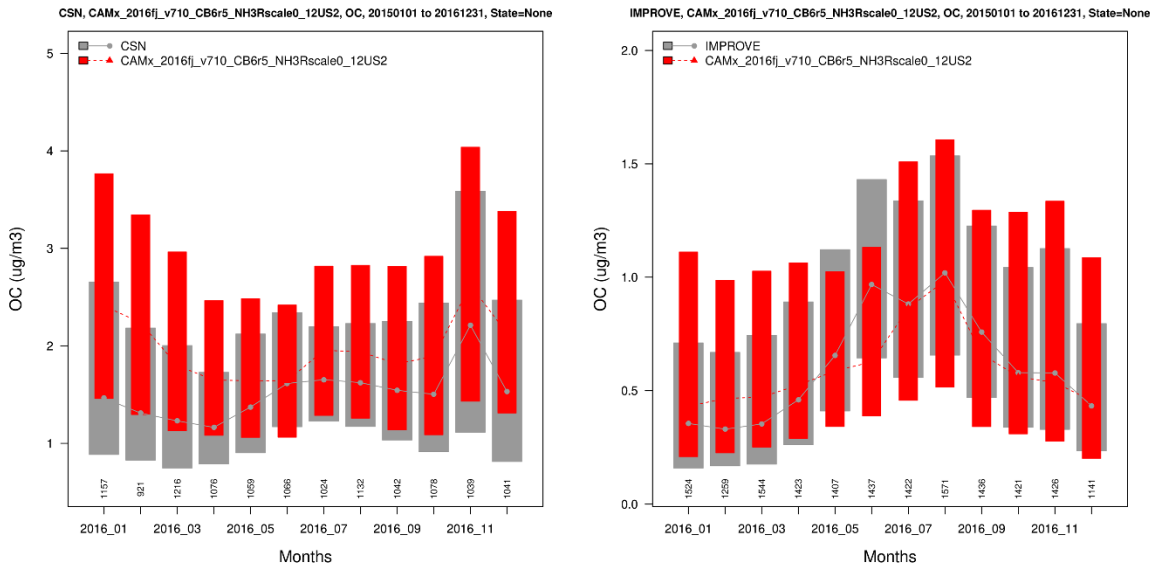


Figure 14: Boxplots of observed and modeled organic carbon concentrations ($\mu\text{g}/\text{m}^3$) by month at CSN (right) and IMPROVE (left) monitoring sites. Lines indicate median concentrations across monitors in each month. Boxes delineate the 25th and 75th percentile ranges.

Table 5: OC model performance at CSN sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 751 | 1.79 | 2.92 | 1.33 | 74.01 | 1.54 | 85.73 | 0.65 |
| | spring | 815 | 1.57 | 2.33 | 0.79 | 50.01 | 0.96 | 61.36 | 0.61 |
| | summer | 819 | 1.95 | 2.33 | 0.36 | 18.47 | 0.71 | 36.31 | 0.58 |
| | fall | 805 | 1.85 | 2.64 | 0.85 | 46.10 | 1.09 | 58.61 | 0.65 |
| | Annual | 3190 | 1.79 | 2.55 | 0.82 | 45.83 | 1.06 | 59.38 | 0.62 |
| Upper Midwest | winter | 334 | 1.13 | 2.54 | 1.38 | 122.01 | 1.41 | 124.92 | 0.54 |
| | spring | 347 | 1.47 | 1.90 | 0.53 | 36.00 | 0.96 | 65.25 | 0.41 |
| | summer | 332 | 1.61 | 1.74 | 0.19 | 11.97 | 0.58 | 35.94 | 0.48 |
| | fall | 338 | 1.50 | 2.03 | 0.54 | 35.61 | 0.77 | 51.44 | 0.68 |
| | Annual | 1351 | 1.43 | 2.05 | 0.66 | 46.06 | 0.93 | 65.17 | 0.43 |
| Ohio River Valley | winter | 535 | 1.62 | 2.51 | 0.87 | 53.61 | 1.09 | 67.46 | 0.56 |
| | spring | 571 | 1.57 | 2.12 | 0.40 | 25.33 | 0.74 | 47.21 | 0.60 |
| | summer | 532 | 1.85 | 2.08 | 0.17 | 9.27 | 0.58 | 31.39 | 0.47 |

| | | | | | | | | | |
|-----------------------------|--------|--------|------|------|-------|--------|-------|--------|-------|
| | fall | 535 | 2.44 | 2.62 | 0.09 | 3.67 | 0.85 | 34.75 | 0.75 |
| | Annual | 2173 | 1.86 | 2.33 | 0.38 | 20.51 | 0.81 | 43.69 | 0.64 |
| Southeast | winter | 436 | 2.00 | 2.57 | 0.72 | 36.12 | 1.05 | 52.32 | 0.66 |
| | spring | 478 | 2.01 | 2.34 | 0.51 | 25.18 | 0.78 | 38.81 | 0.75 |
| | summer | 445 | 1.90 | 2.50 | 0.64 | 33.73 | 0.84 | 44.01 | 0.71 |
| | fall | 430 | 2.85 | 2.80 | -0.14 | -4.94 | 1.02 | 35.86 | 0.67 |
| | Annual | 1789 | 2.18 | 2.55 | 0.44 | 20.03 | 0.92 | 42.04 | 0.60 |
| | South | winter | 272 | 1.98 | 2.35 | 0.47 | 23.74 | 1.16 | 58.52 |
| spring | | 297 | 1.45 | 1.86 | 0.35 | 23.77 | 0.74 | 50.58 | 0.60 |
| summer | | 251 | 1.50 | 1.99 | 0.41 | 26.97 | 0.89 | 58.99 | 0.58 |
| fall | | 238 | 2.11 | 2.50 | 0.37 | 17.58 | 0.99 | 47.14 | 0.62 |
| Annual | | 1058 | 1.75 | 2.17 | 0.40 | 22.74 | 0.94 | 53.67 | 0.60 |
| Northern Rockies and Plains | winter | 141 | 0.95 | 0.85 | -0.04 | -4.25 | 0.82 | 86.15 | 0.12 |
| | spring | 145 | 0.87 | 0.81 | -0.07 | -7.56 | 0.43 | 49.80 | 0.55 |
| | summer | 161 | 1.45 | 1.13 | -0.52 | -35.98 | 0.69 | 47.26 | 0.41 |
| | fall | 146 | 1.01 | 0.95 | -0.27 | -26.44 | 0.49 | 47.90 | 0.25 |
| | Annual | 593 | 1.08 | 0.94 | -0.23 | -21.56 | 0.61 | 56.05 | 0.27 |
| Southwest | winter | 228 | 2.53 | 2.30 | 0.06 | 2.33 | 1.32 | 52.22 | 0.35 |
| | spring | 254 | 1.06 | 1.13 | 0.28 | 26.84 | 0.54 | 51.30 | 0.42 |
| | summer | 237 | 1.41 | 1.15 | -0.13 | -9.26 | 0.50 | 35.79 | 0.45 |
| | fall | 240 | 1.64 | 1.47 | 0.08 | 4.93 | 0.76 | 46.70 | 0.45 |
| | Annual | 959 | 1.64 | 1.50 | 0.08 | 4.71 | 0.77 | 47.20 | 0.46 |
| Northwest | winter | 140 | 2.46 | 3.82 | 1.29 | 52.31 | 2.19 | 88.67 | 0.39 |
| | spring | 150 | 1.41 | 2.38 | 1.41 | 100.38 | 1.50 | 106.57 | 0.46 |
| | summer | 158 | 1.49 | 2.42 | 1.39 | 93.33 | 1.46 | 97.75 | 0.66 |
| | fall | 155 | 1.95 | 3.04 | 1.53 | 78.20 | 1.87 | 95.87 | 0.47 |
| | Annual | 603 | 1.82 | 2.92 | 1.41 | 77.59 | 1.75 | 96.07 | 0.46 |
| West | winter | 286 | 3.66 | 3.12 | -0.35 | -9.48 | 1.63 | 44.39 | 0.51 |
| | spring | 294 | 1.54 | 1.75 | 0.22 | 14.03 | 0.60 | 38.82 | 0.61 |
| | summer | 290 | 2.47 | 2.19 | -0.37 | -15.17 | 0.89 | 36.15 | 0.52 |
| | fall | 277 | 2.82 | 2.48 | -0.06 | -2.00 | 1.07 | 37.94 | 0.57 |
| | Annual | 1147 | 2.61 | 2.38 | -0.14 | -5.33 | 1.04 | 39.90 | 0.59 |
| National | winter | 3123 | 1.96 | 2.61 | 0.79 | 40.17 | 1.34 | 68.29 | 0.52 |
| | spring | 3351 | 1.53 | 2.01 | 0.52 | 33.74 | 0.82 | 53.22 | 0.58 |
| | summer | 3225 | 1.82 | 2.08 | 0.26 | 14.25 | 0.74 | 40.89 | 0.54 |
| | fall | 3164 | 2.10 | 2.42 | 0.36 | 17.21 | 0.98 | 46.67 | 0.59 |
| | Annual | 12863 | 1.85 | 2.27 | 0.48 | 25.96 | 0.96 | 52.22 | 0.55 |

Table 6: OC model performance at IMPROVE sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-----------------------------|--------|------|---|--|--|--------------------------|---|---------------------------|--------|
| Northeast | winter | 429 | 429 | 0.75 | 1.50 | 0.85 | 113.11 | 0.87 | 115.77 |
| | spring | 478 | 478 | 0.75 | 1.18 | 0.45 | 60.07 | 0.52 | 69.64 |
| | summer | 482 | 482 | 1.20 | 1.41 | 0.22 | 18.33 | 0.45 | 37.23 |
| | fall | 459 | 459 | 0.92 | 1.41 | 0.51 | 56.03 | 0.63 | 68.56 |
| | Annual | 1848 | 1848 | 0.91 | 1.37 | 0.50 | 54.90 | 0.61 | 67.09 |
| Upper Midwest | winter | 228 | 228 | 0.60 | 1.14 | 0.59 | 99.46 | 0.62 | 103.53 |
| | spring | 239 | 239 | 0.90 | 1.14 | 0.24 | 26.56 | 0.63 | 69.87 |
| | summer | 237 | 237 | 1.18 | 1.08 | -0.10 | -8.18 | 0.39 | 32.84 |
| | fall | 245 | 245 | 0.89 | 1.03 | 0.14 | 15.72 | 0.36 | 40.30 |
| | Annual | 949 | 949 | 0.90 | 1.10 | 0.21 | 23.99 | 0.50 | 55.47 |
| Ohio River Valley | winter | 217 | 217 | 1.00 | 1.79 | 0.92 | 92.64 | 1.10 | 109.94 |
| | spring | 242 | 242 | 1.11 | 1.79 | 0.71 | 63.42 | 0.93 | 83.67 |
| | summer | 242 | 242 | 1.34 | 1.61 | 0.27 | 20.45 | 0.49 | 36.79 |
| | fall | 232 | 232 | 1.80 | 2.04 | 0.19 | 10.41 | 0.81 | 44.92 |
| | Annual | 933 | 933 | 1.32 | 1.81 | 0.52 | 39.18 | 0.83 | 62.74 |
| Southeast | winter | 398 | 398 | 1.18 | 1.58 | 0.51 | 42.82 | 0.89 | 74.95 |
| | spring | 447 | 447 | 6.23 | 1.82 | -4.38 | -70.38 | 5.52 | 88.65 |
| | summer | 455 | 455 | 1.49 | 1.55 | 0.14 | 9.18 | 0.71 | 47.72 |
| | fall | 423 | 423 | 1.95 | 1.80 | -0.08 | -4.35 | 0.83 | 42.63 |
| | Annual | 1723 | 1723 | 2.76 | 1.69 | -1.01 | -36.38 | 2.03 | 73.47 |
| South | winter | 240 | 240 | 0.86 | 1.22 | 0.44 | 51.32 | 0.63 | 73.14 |
| | spring | 273 | 273 | 1.06 | 1.29 | 0.23 | 21.40 | 0.70 | 65.77 |
| | summer | 250 | 250 | 1.16 | 1.09 | -0.02 | -1.43 | 0.57 | 49.21 |
| | fall | 264 | 264 | 1.17 | 1.18 | 0.00 | 0.24 | 0.50 | 42.52 |
| | Annual | 1027 | 1027 | 1.07 | 1.19 | 0.16 | 15.01 | 0.60 | 56.21 |
| Northern Rockies and Plains | winter | 565 | 565 | 0.30 | 0.34 | 0.03 | 11.16 | 0.20 | 66.79 |
| | spring | 603 | 603 | 0.61 | 0.54 | -0.12 | -19.21 | 0.37 | 60.44 |
| | summer | 631 | 631 | 1.22 | 1.04 | -0.15 | -12.03 | 0.71 | 58.68 |
| | fall | 602 | 602 | 0.62 | 0.48 | -0.13 | -21.54 | 0.35 | 56.40 |
| | Annual | 2401 | 2401 | 0.70 | 0.60 | -0.09 | -13.40 | 0.41 | 59.37 |
| Southwest | winter | 910 | 910 | 0.65 | 0.45 | -0.17 | -26.93 | 0.37 | 57.14 |
| | spring | 994 | 994 | 0.44 | 0.46 | 0.02 | 5.28 | 0.23 | 52.83 |
| | summer | 979 | 979 | 0.87 | 0.64 | -0.22 | -25.81 | 0.48 | 54.60 |
| | fall | 964 | 964 | 0.63 | 0.54 | -0.08 | -11.98 | 0.34 | 54.98 |
| | Annual | 3847 | 3847 | 0.64 | 0.52 | -0.11 | -17.25 | 0.35 | 54.98 |
| Northwest | winter | 447 | 447 | 0.35 | 0.59 | 0.24 | 67.88 | 0.41 | 117.31 |
| | spring | 513 | 513 | 0.52 | 0.75 | 0.22 | 42.60 | 0.38 | 71.62 |
| | summer | 519 | 519 | 1.26 | 1.42 | 0.17 | 13.16 | 0.90 | 70.95 |

| | | | | | | | | | |
|----------|--------|--------|-------|------|------|-------|--------|-------|--------|
| | fall | 500 | 500 | 0.74 | 1.32 | 0.58 | 77.61 | 0.85 | 114.31 |
| | Annual | 1979 | 1979 | 0.74 | 1.02 | 0.30 | 41.02 | 0.64 | 87.18 |
| West | winter | 562 | 562 | 0.61 | 0.52 | -0.07 | -11.27 | 0.33 | 55.14 |
| | spring | 605 | 605 | 0.61 | 0.59 | -0.02 | -3.13 | 0.27 | 44.44 |
| | summer | 611 | 611 | 1.71 | 1.29 | -0.43 | -24.90 | 0.92 | 53.81 |
| | fall | 576 | 576 | 1.07 | 1.01 | -0.08 | -7.78 | 0.49 | 45.58 |
| | Annual | 2354 | 2354 | 1.01 | 0.85 | -0.15 | -15.10 | 0.51 | 50.41 |
| | | winter | 3996 | 3996 | 0.65 | 0.86 | 0.23 | 35.94 | 0.52 |
| National | spring | 4394 | 4394 | 1.22 | 0.91 | -0.32 | -26.11 | 0.93 | 76.39 |
| | summer | 4406 | 4406 | 1.24 | 1.16 | -0.06 | -5.09 | 0.64 | 51.84 |
| | fall | 4265 | 4265 | 0.98 | 1.07 | 0.09 | 8.83 | 0.54 | 55.25 |
| | Annual | 17061 | 17061 | 1.03 | 1.00 | -0.02 | -2.12 | 0.66 | 64.25 |

Elemental Carbon:

Spatial and temporal patterns of observed elemental carbon concentrations are more heterogeneous than sulfate, nitrate, or organic carbon with localized hotspots rather than regional patterns. As shown in Figure 15, the highest elemental carbon concentrations are generally observed in winter and fall when mixing of local pollution is minimized. At most monitors elemental carbon concentrations are less than $0.5 \mu\text{g}/\text{m}^3$ but concentrations of $1\text{-}2 \mu\text{g}/\text{m}^3$ in winter and fall are observed in the San Joaquin Valley and in certain urban areas such as Los Angeles, Atlanta, Denver, Pittsburgh and along the Northeast corridor from Philadelphia to New York City. CAMx predictions of elemental carbon concentrations shown in Figure 16 generally follow the same spatial and seasonal patterns as the corresponding observations. Model over and under predictions of seasonal elemental carbon concentrations shown in Figure 17 are with $\pm 0.2 \mu\text{g}/\text{m}^3$ at most monitoring sites with a few isolated locations with larger biases. As shown in Tables 7 and 8, those elemental carbon biases correspond to normalized mean bias values within $\pm 20\%$ of observations in most regions and seasons at both CSN and IMPROVE sites.

The higher fall/winter elemental carbon concentrations in both the model and observations are also depicted in Figure 18 which shows monthly distributions. The highest observed and modeled concentrations both occur in November.

As shown in Tables 7, correlation between the model and the observation at CSN sites were generally between 0.45-0.74 in most seasons/regions with the exception of some lower correlations in the Northern Rockies (all seasons), the Southwest (summer), and the Northwest (winter/summer/fall). Correlations were somewhat higher at IMPROVE sites (Table 8), generally between 0.5 and 0.86 in most regions and seasons except for some lower values in the Ohio River Valley (winter/spring), the Southeast (spring), The Northern Rockies and Plains (all seasons), the Northwest (summer), and the West (summer).

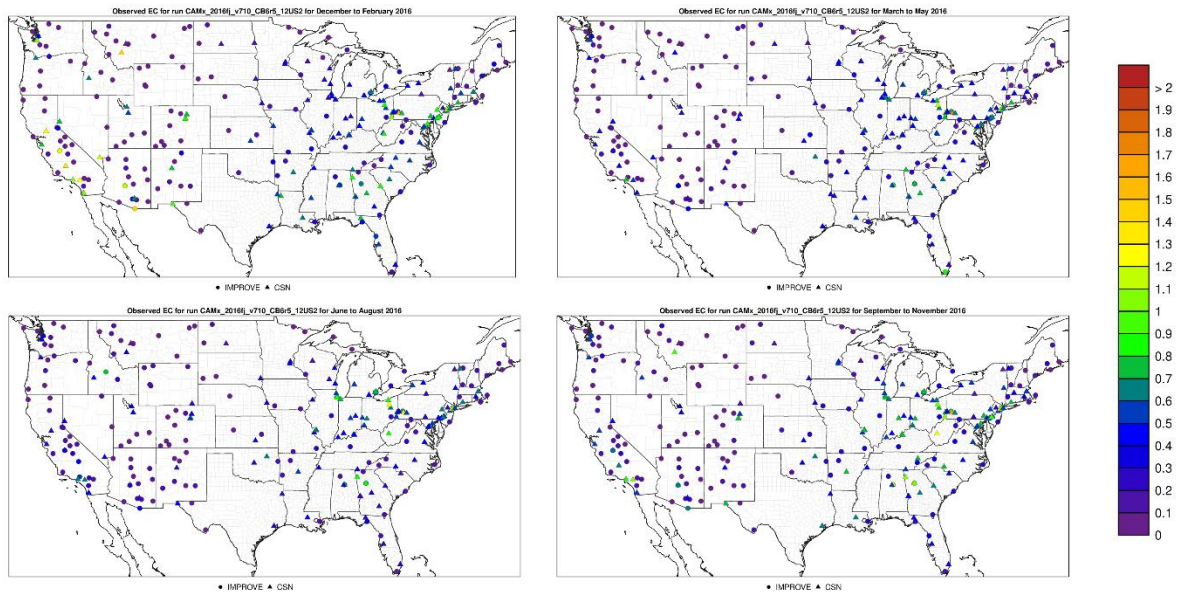


Figure 15. Observed elemental carbon concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

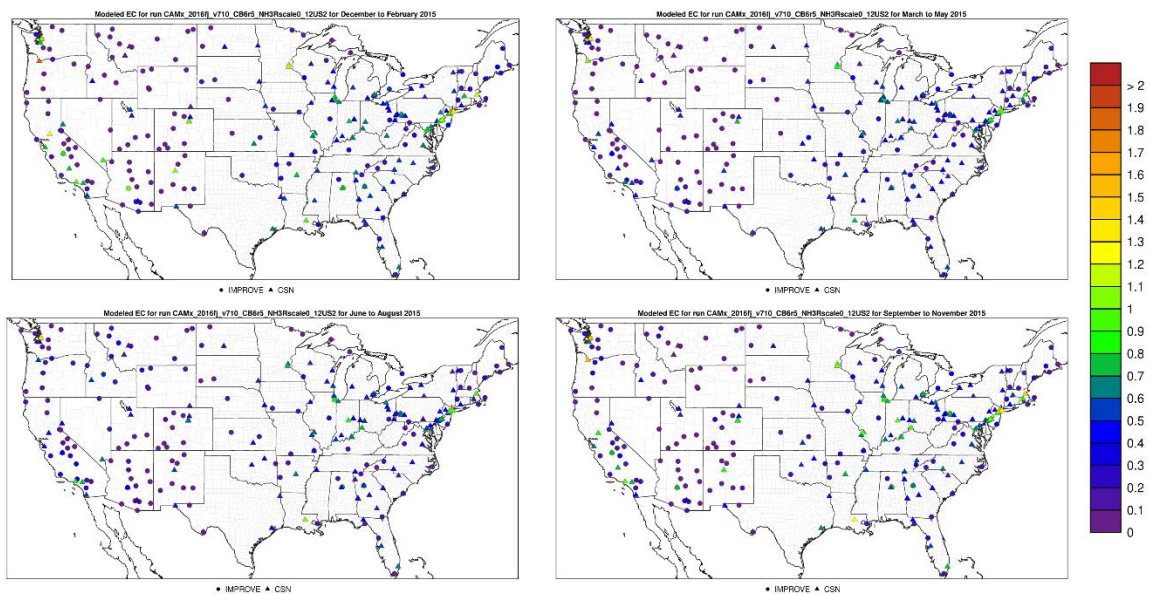


Figure 16. Modeled elemental carbon concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles)

monitoring sties during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

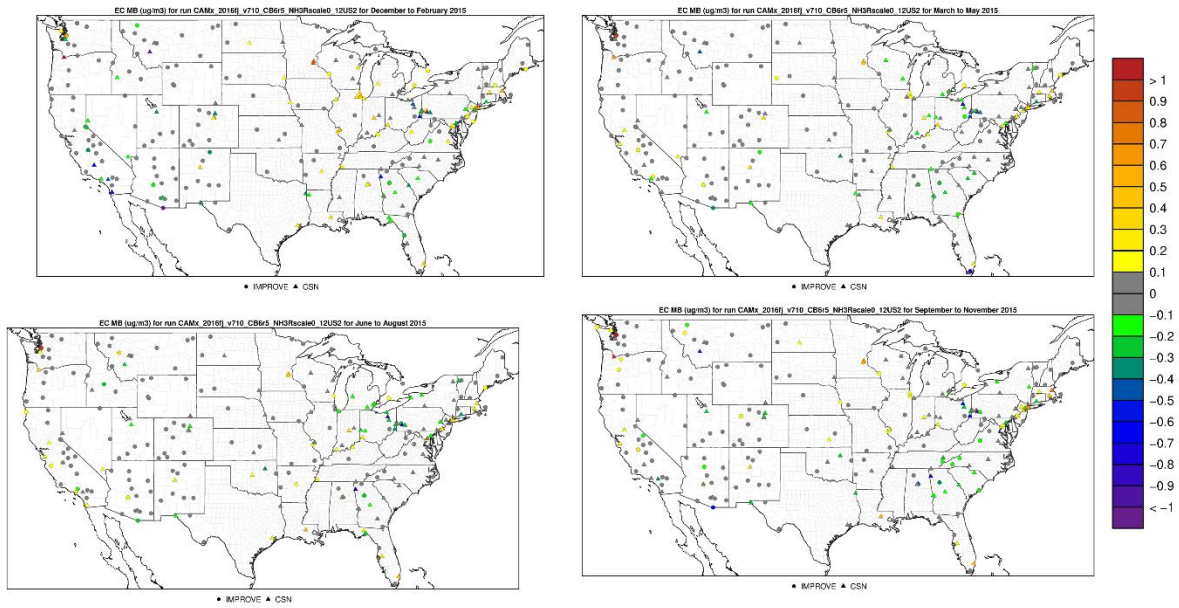


Figure 17. CAMx elemental carbon mean bias ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sties during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

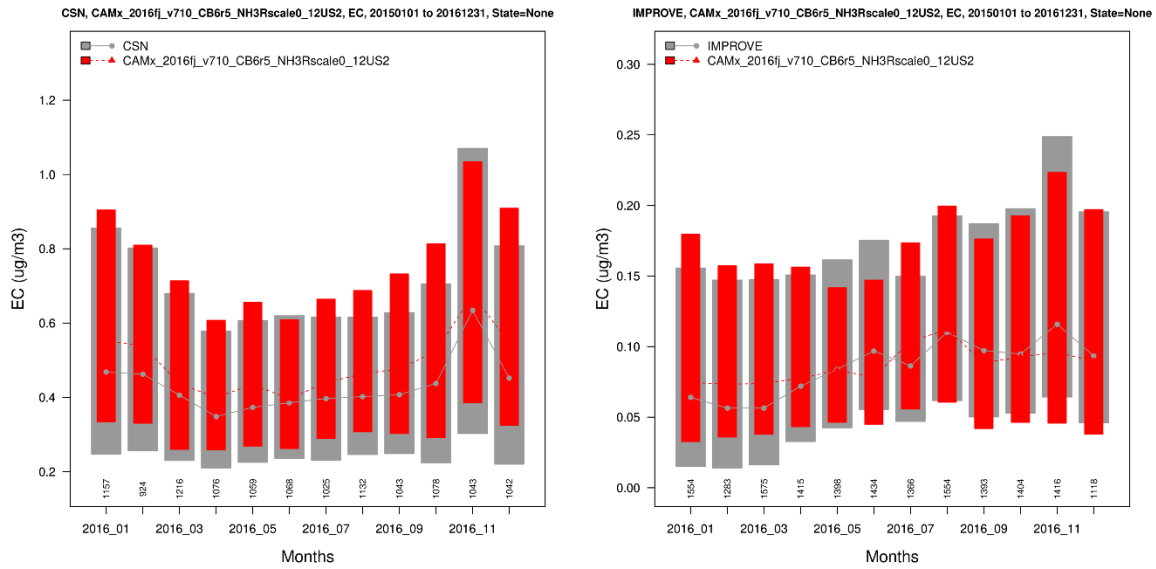


Figure 18: Boxplots of observed and modeled elemental carbon concentrations ($\mu\text{g}/\text{m}^3$) by month at CSN (right) and IMPROVE (left) monitoring sites. Lines indicate median concentrations across monitors in each month. Boxes delineate the 25th and 75th percentile ranges.

Table 7: EC model performance at CSN sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 751 | 0.67 | 0.74 | 0.15 | 23.00 | 0.37 | 55.48 | 0.58 |
| | spring | 815 | 0.58 | 0.61 | 0.06 | 9.92 | 0.28 | 48.75 | 0.53 |
| | summer | 819 | 0.58 | 0.59 | 0.04 | 6.91 | 0.25 | 42.99 | 0.56 |
| | fall | 805 | 0.63 | 0.75 | 0.17 | 26.77 | 0.35 | 55.76 | 0.54 |
| | Annual | 3190 | 0.61 | 0.67 | 0.10 | 16.92 | 0.31 | 50.91 | 0.55 |
| Upper Midwest | winter | 334 | 0.33 | 0.51 | 0.20 | 60.33 | 0.25 | 76.58 | 0.54 |
| | spring | 347 | 0.43 | 0.42 | 0.01 | 3.16 | 0.20 | 47.12 | 0.54 |
| | summer | 332 | 0.40 | 0.40 | 0.02 | 4.39 | 0.18 | 44.27 | 0.48 |
| | fall | 338 | 0.45 | 0.50 | 0.08 | 17.01 | 0.23 | 50.76 | 0.65 |
| | Annual | 1351 | 0.40 | 0.46 | 0.08 | 18.89 | 0.22 | 53.40 | 0.52 |
| Ohio River Valley | winter | 535 | 0.48 | 0.57 | 0.11 | 22.04 | 0.24 | 50.65 | 0.59 |
| | spring | 571 | 0.53 | 0.50 | -0.03 | -4.94 | 0.21 | 40.56 | 0.55 |
| | summer | 532 | 0.58 | 0.53 | -0.04 | -6.50 | 0.22 | 38.49 | 0.45 |

| | | | | | | | | | |
|-----------------------------|--------|--------|------|------|-------|--------|-------|--------|-------|
| | fall | 535 | 0.66 | 0.63 | 0.00 | 0.60 | 0.25 | 37.85 | 0.60 |
| | Annual | 2173 | 0.56 | 0.56 | 0.01 | 1.94 | 0.23 | 41.37 | 0.56 |
| Southeast | winter | 436 | 0.57 | 0.53 | 0.00 | 0.81 | 0.26 | 44.76 | 0.56 |
| | spring | 478 | 0.54 | 0.43 | -0.08 | -14.74 | 0.23 | 42.29 | 0.56 |
| | summer | 445 | 0.44 | 0.42 | 0.02 | 3.43 | 0.22 | 49.37 | 0.49 |
| | fall | 430 | 0.66 | 0.53 | -0.11 | -16.42 | 0.29 | 43.36 | 0.66 |
| | Annual | 1789 | 0.55 | 0.47 | -0.04 | -7.71 | 0.25 | 44.62 | 0.58 |
| | South | winter | 272 | 0.57 | 0.56 | 0.00 | -0.85 | 0.25 | 43.92 |
| spring | | 297 | 0.43 | 0.43 | -0.02 | -3.63 | 0.18 | 41.06 | 0.56 |
| summer | | 251 | 0.37 | 0.45 | 0.05 | 13.78 | 0.22 | 58.42 | 0.48 |
| fall | | 238 | 0.54 | 0.57 | 0.02 | 3.65 | 0.25 | 46.72 | 0.56 |
| Annual | | 1058 | 0.48 | 0.50 | 0.01 | 2.31 | 0.22 | 46.60 | 0.57 |
| Northern Rockies and Plains | winter | 141 | 0.25 | 0.20 | -0.03 | -11.10 | 0.22 | 88.76 | 0.09 |
| | spring | 145 | 0.20 | 0.16 | -0.02 | -11.35 | 0.11 | 54.45 | 0.44 |
| | summer | 161 | 0.22 | 0.20 | -0.02 | -7.81 | 0.10 | 45.54 | 0.39 |
| | fall | 146 | 0.24 | 0.21 | -0.04 | -15.94 | 0.16 | 67.03 | 0.15 |
| | Annual | 593 | 0.23 | 0.19 | -0.03 | -11.55 | 0.15 | 64.21 | 0.20 |
| Southwest | winter | 228 | 0.88 | 0.73 | -0.07 | -7.69 | 0.34 | 38.56 | 0.53 |
| | spring | 254 | 0.31 | 0.38 | 0.14 | 46.02 | 0.19 | 60.12 | 0.69 |
| | summer | 237 | 0.30 | 0.35 | 0.11 | 35.61 | 0.17 | 55.46 | 0.41 |
| | fall | 240 | 0.56 | 0.52 | 0.06 | 10.79 | 0.25 | 45.14 | 0.58 |
| | Annual | 959 | 0.51 | 0.49 | 0.06 | 12.63 | 0.23 | 46.42 | 0.66 |
| Northwest | winter | 140 | 0.75 | 0.95 | 0.26 | 35.43 | 0.61 | 81.29 | 0.34 |
| | spring | 150 | 0.46 | 0.70 | 0.43 | 94.57 | 0.51 | 111.90 | 0.57 |
| | summer | 158 | 0.40 | 0.68 | 0.51 | 125.70 | 0.53 | 130.71 | 0.43 |
| | fall | 155 | 0.58 | 0.89 | 0.59 | 101.23 | 0.71 | 122.23 | 0.39 |
| | Annual | 603 | 0.54 | 0.81 | 0.45 | 83.53 | 0.59 | 108.61 | 0.42 |
| West | winter | 286 | 1.06 | 0.84 | -0.24 | -22.46 | 0.43 | 40.74 | 0.53 |
| | spring | 294 | 0.41 | 0.51 | 0.09 | 22.40 | 0.19 | 47.11 | 0.74 |
| | summer | 290 | 0.44 | 0.57 | 0.10 | 22.96 | 0.17 | 38.52 | 0.74 |
| | fall | 277 | 0.68 | 0.71 | 0.04 | 5.26 | 0.25 | 37.41 | 0.63 |
| | Annual | 1147 | 0.64 | 0.66 | 0.00 | -0.31 | 0.26 | 40.55 | 0.67 |
| National | winter | 3123 | 0.61 | 0.62 | 0.06 | 9.87 | 0.32 | 51.64 | 0.54 |
| | spring | 3351 | 0.48 | 0.48 | 0.04 | 7.38 | 0.23 | 48.64 | 0.54 |
| | summer | 3225 | 0.46 | 0.49 | 0.05 | 11.31 | 0.22 | 47.97 | 0.52 |
| | fall | 3164 | 0.59 | 0.61 | 0.07 | 12.37 | 0.30 | 50.28 | 0.53 |
| | Annual | 12863 | 0.54 | 0.55 | 0.06 | 10.28 | 0.27 | 49.77 | 0.55 |

Table 8: EC model performance at IMPROVE sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-----------------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 429 | 0.19 | 0.26 | 0.09 | 46.35 | 0.12 | 61.28 | 0.81 |
| | spring | 478 | 0.15 | 0.19 | 0.04 | 28.44 | 0.07 | 46.50 | 0.86 |
| | summer | 482 | 0.16 | 0.20 | 0.04 | 24.68 | 0.07 | 42.84 | 0.81 |
| | fall | 459 | 0.20 | 0.24 | 0.05 | 25.24 | 0.10 | 49.89 | 0.78 |
| | Annual | 1848 | 0.17 | 0.22 | 0.05 | 31.19 | 0.09 | 50.30 | 0.81 |
| Upper Midwest | winter | 228 | 0.14 | 0.19 | 0.06 | 40.29 | 0.08 | 52.98 | 0.82 |
| | spring | 239 | 0.19 | 0.18 | -0.02 | -9.41 | 0.08 | 43.15 | 0.54 |
| | summer | 237 | 0.18 | 0.16 | -0.02 | -10.06 | 0.07 | 37.68 | 0.82 |
| | fall | 245 | 0.20 | 0.20 | -0.01 | -3.52 | 0.08 | 39.14 | 0.83 |
| | Annual | 949 | 0.18 | 0.18 | 0.00 | 1.62 | 0.08 | 42.50 | 0.70 |
| Ohio River Valley | winter | 217 | 0.21 | 0.23 | 0.03 | 12.91 | 0.09 | 43.54 | 0.45 |
| | spring | 242 | 0.21 | 0.20 | -0.01 | -6.43 | 0.09 | 42.45 | 0.27 |
| | summer | 242 | 0.18 | 0.17 | -0.02 | -11.52 | 0.05 | 27.29 | 0.67 |
| | fall | 232 | 0.30 | 0.26 | -0.05 | -17.91 | 0.09 | 31.04 | 0.67 |
| | Annual | 933 | 0.23 | 0.21 | -0.02 | -7.18 | 0.08 | 35.71 | 0.47 |
| Southeast | winter | 398 | 0.27 | 0.25 | -0.01 | -2.19 | 0.14 | 52.60 | 0.50 |
| | spring | 447 | 0.36 | 0.22 | -0.13 | -35.35 | 0.20 | 56.02 | 0.18 |
| | summer | 455 | 0.22 | 0.18 | -0.03 | -12.00 | 0.10 | 45.12 | 0.61 |
| | fall | 423 | 0.35 | 0.24 | -0.09 | -24.55 | 0.14 | 39.08 | 0.83 |
| | Annual | 1723 | 0.30 | 0.22 | -0.06 | -20.76 | 0.14 | 48.33 | 0.40 |
| South | winter | 240 | 0.17 | 0.16 | 0.00 | -2.82 | 0.07 | 39.30 | 0.70 |
| | spring | 273 | 0.17 | 0.18 | 0.00 | 2.26 | 0.09 | 51.62 | 0.60 |
| | summer | 250 | 0.12 | 0.10 | -0.01 | -9.28 | 0.05 | 41.67 | 0.64 |
| | fall | 264 | 0.19 | 0.14 | -0.04 | -22.59 | 0.07 | 35.60 | 0.71 |
| | Annual | 1027 | 0.16 | 0.15 | -0.01 | -8.39 | 0.07 | 42.11 | 0.64 |
| Northern Rockies and Plains | winter | 565 | 0.06 | 0.06 | 0.01 | 12.71 | 0.04 | 73.96 | 0.39 |
| | spring | 603 | 0.08 | 0.08 | -0.01 | -8.33 | 0.06 | 72.72 | 0.48 |
| | summer | 631 | 0.10 | 0.15 | 0.05 | 46.72 | 0.09 | 86.82 | 0.28 |
| | fall | 602 | 0.09 | 0.08 | -0.01 | -14.89 | 0.05 | 59.26 | 0.30 |
| | Annual | 2401 | 0.08 | 0.09 | 0.01 | 11.24 | 0.06 | 73.79 | 0.33 |
| Southwest | winter | 910 | 0.18 | 0.11 | -0.06 | -35.06 | 0.11 | 58.68 | 0.62 |
| | spring | 994 | 0.09 | 0.09 | 0.01 | 8.20 | 0.06 | 68.82 | 0.56 |
| | summer | 979 | 0.11 | 0.10 | -0.01 | -9.21 | 0.06 | 59.29 | 0.50 |
| | fall | 964 | 0.14 | 0.10 | -0.03 | -20.83 | 0.08 | 57.62 | 0.56 |
| | Annual | 3847 | 0.13 | 0.10 | -0.02 | -18.17 | 0.08 | 60.28 | 0.56 |
| Northwest | winter | 447 | 0.08 | 0.12 | 0.04 | 53.70 | 0.08 | 102.20 | 0.83 |
| | spring | 513 | 0.08 | 0.14 | 0.07 | 87.19 | 0.09 | 119.64 | 0.77 |
| | summer | 519 | 0.14 | 0.22 | 0.08 | 57.63 | 0.16 | 114.54 | 0.48 |

| | | | | | | | | | |
|--------|----------|--------|------|------|-------|--------|------|--------|-------|
| | fall | 500 | 0.12 | 0.23 | 0.11 | 97.37 | 0.16 | 135.94 | 0.71 |
| | Annual | 1979 | 0.11 | 0.18 | 0.08 | 73.54 | 0.13 | 119.28 | 0.57 |
| West | winter | 562 | 0.13 | 0.10 | -0.02 | -18.48 | 0.08 | 63.47 | 0.78 |
| | spring | 605 | 0.08 | 0.09 | 0.02 | 24.98 | 0.05 | 64.13 | 0.73 |
| | summer | 611 | 0.19 | 0.18 | -0.01 | -2.81 | 0.12 | 63.03 | 0.47 |
| | fall | 576 | 0.15 | 0.16 | 0.00 | 1.75 | 0.08 | 54.84 | 0.71 |
| | Annual | 2354 | 0.14 | 0.13 | 0.00 | -1.01 | 0.08 | 61.04 | 0.56 |
| | National | winter | 3996 | 0.15 | 0.15 | 0.00 | 0.86 | 0.09 | 59.18 |
| spring | | 4394 | 0.13 | 0.14 | 0.00 | 1.14 | 0.08 | 60.28 | 0.33 |
| summer | | 4406 | 0.15 | 0.16 | 0.01 | 8.55 | 0.09 | 60.48 | 0.39 |
| fall | | 4265 | 0.17 | 0.17 | 0.00 | -2.32 | 0.09 | 53.64 | 0.63 |
| Annual | | 17061 | 0.15 | 0.15 | 0.00 | 1.94 | 0.09 | 58.18 | 0.47 |

Soil

Concentrations of crustal material (or soil) are calculated based on concentrations of 5 key crustal elements with mass adjustment factors that account for oxygen and other elements commonly bonded to those metals:

$$\text{Soil} = 2.20 \times \text{Al} + 2.49 \times \text{Si} + 1.63 \times \text{Ca} + 2.42 \times \text{Fe} + 1.94 \times \text{Ti}$$

Maps of observed soil concentrations are shown in Figure 19. During winter and spring concentrations are largest in the Southwestern US ($1\text{-}3 \mu\text{g}/\text{m}^3$) due to windblown dust at that time of year. Winter and spring concentrations in other parts of the US generally remain below $0.5 \mu\text{g}/\text{m}^3$. During summer and fall, concentrations between $1\text{-}3 \mu\text{g}/\text{m}^3$ are also observed across the Southern US, the plains states and in California in addition to in the Southwest. CAMx model predictions are shown in Figure 20 and generally overpredict soil concentrations over much of the US in all seasons (Figure 21) except in the Southwest and West because windblown dust emissions are not included in the simulation. Soil mean biases are in the range of $\pm 0.2\text{-}0.8$ at CSN sites and $\pm 0.1\text{-}0.4 \mu\text{g}/\text{m}^3$ at IMPROVE sites for most regions and seasons (Table 9 and Table 10) with the exception of Ohio River Valley (summer/fall), the Upper Midwest (fall), the South (summer/fall), the Northwest (all seasons), and the West (summer). Underpredictions of soil in the summer across the South, Southwest, and West range from -0.5 to $-0.9 \mu\text{g}/\text{m}^3$.

The monthly boxplots for soil show that similar to other primary PM components (i.e. elemental carbon) the urban (CSN) concentrations peaked in November in both the observations and the model with a consistent bias of around $0.5 \mu\text{g}/\text{m}^3$ across all months. At the rural IMPROVE sites, the observed concentrations peak in summer while the modeled concentrations peak during spring months leading to overestimates for most of the year averaging around $0.1\text{-}0.2 \mu\text{g}/\text{m}^3$ except for summer months for which the model average underestimates are in the range of $0.1\text{-}0.2 \mu\text{g}/\text{m}^3$.

Correlation between model and monitored values shown in Tables 9 and 10 for soil are somewhat lower than for other PM species and range from $0.2\text{-}0.6$ for most regions and seasons at CSN sites and $0.3\text{-}0.7$ at IMPROVE sites. Correlations below 0.2 at CSN sites are found in the Ohio River Valley in summer, in the South during winter/spring/fall, in the Rockies Mountains and Plains in the winter, in the Southwest during all seasons and in the West during summer/fall. Correlations below 0.3 at IMPROVE sites are

found in the Ohio River Valley in winter/summer, in the Southeast in summer, in the South in winter/fall, in the Southwest in fall, in the Northwest in summer/fall and in the West in summer/fall.

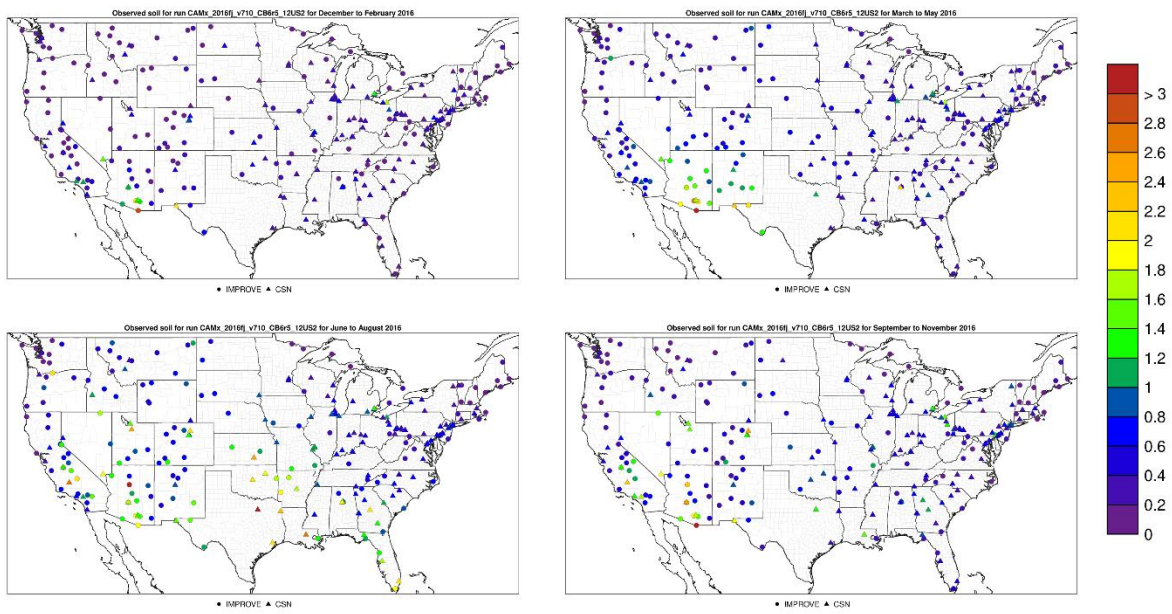


Figure 19. Observed soil concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sites during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

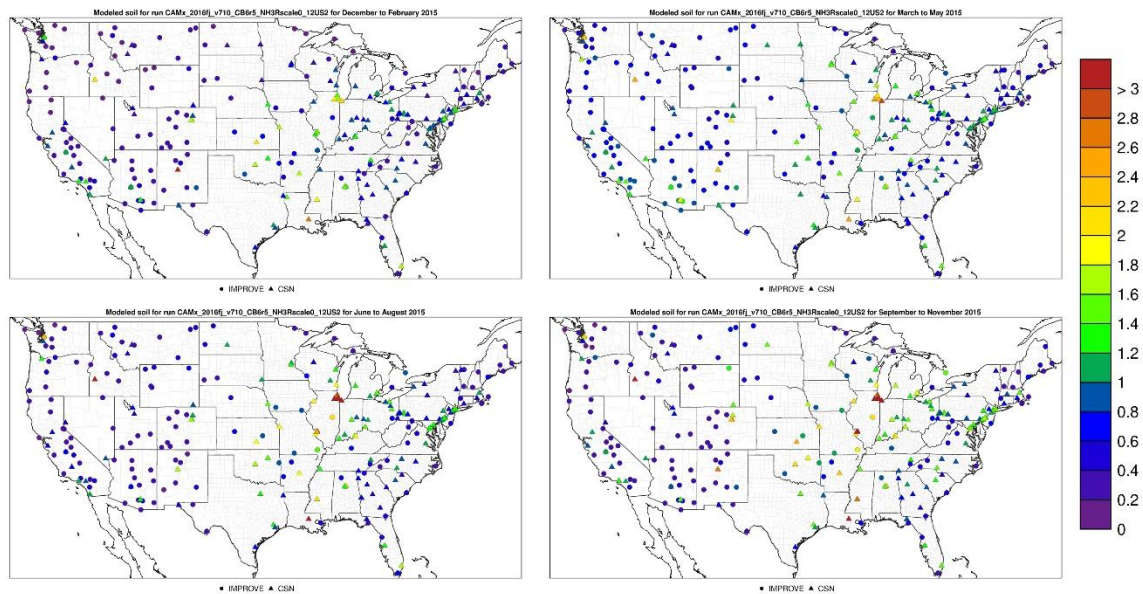


Figure 20. Modeled soil concentrations ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sties during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

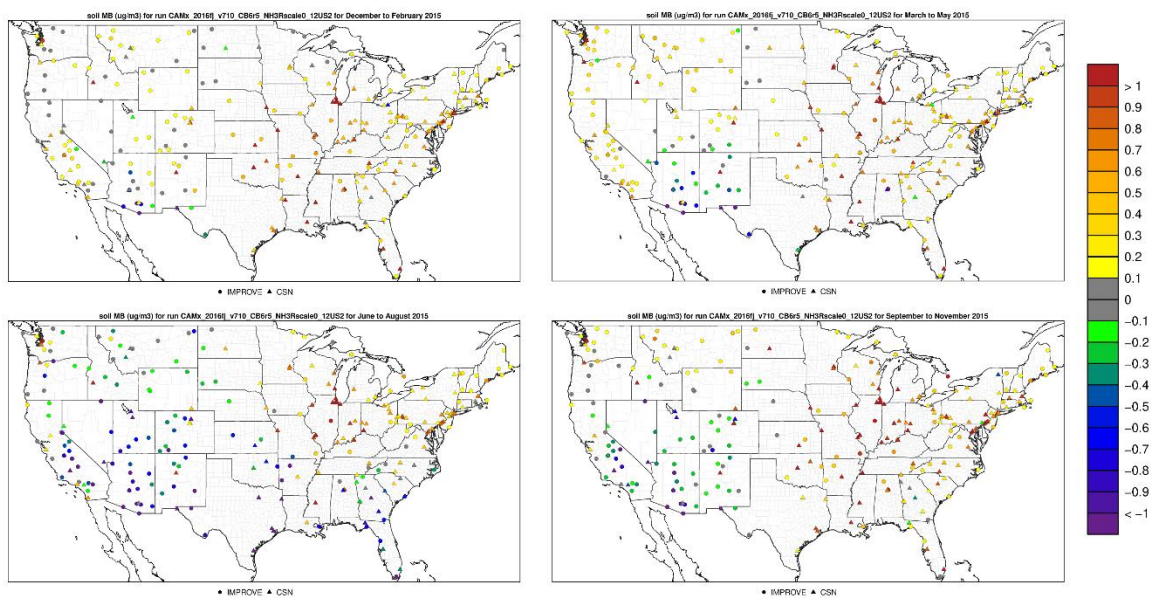


Figure 21. CAMx soil mean bias ($\mu\text{g}/\text{m}^3$) at CSN (triangles) and IMPROVE (circles) monitoring sties during winter (upper left), spring (upper right), summer (lower left) and fall (lower right).

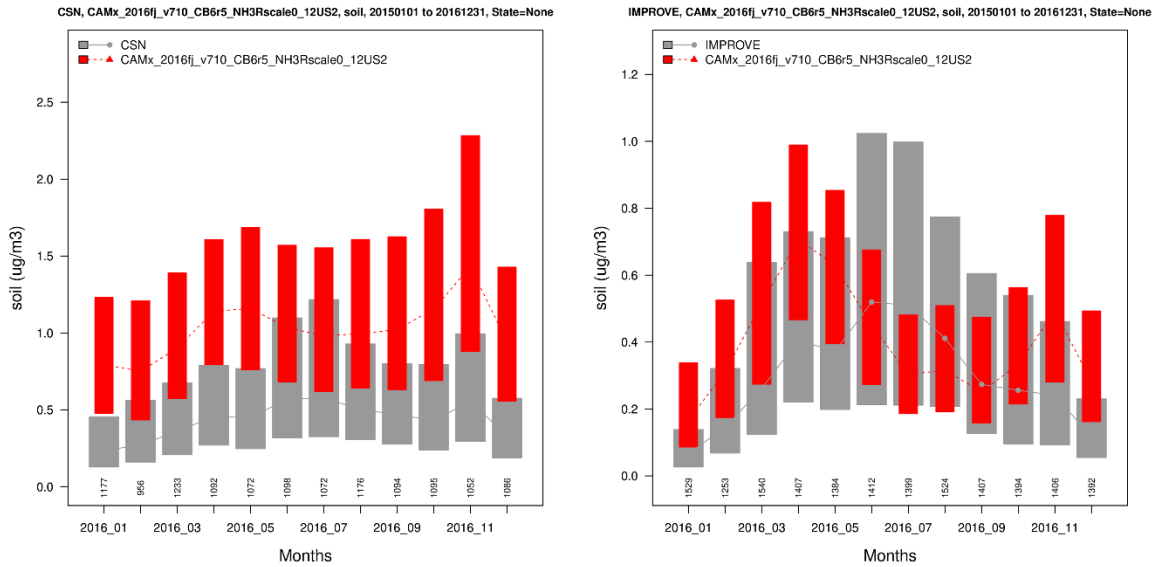


Figure 22: Boxplots of observed and modeled soil concentrations ($\mu\text{g}/\text{m}^3$) by month at CSN (right) and IMPROVE (left) monitoring sites. Lines indicate median concentrations across monitors in each month. Boxes delineate the 25th and 75th percentile ranges.

Table 9: soil model performance at CSN sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 749 | 0.39 | 0.84 | 0.49 | 123.91 | 0.64 | 163.85 | 0.24 |
| | spring | 813 | 0.50 | 0.98 | 0.49 | 99.44 | 0.61 | 122.82 | 0.38 |
| | summer | 802 | 0.50 | 1.03 | 0.50 | 100.51 | 0.63 | 126.35 | 0.30 |
| | fall | 761 | 0.51 | 1.19 | 0.70 | 137.12 | 0.86 | 166.99 | 0.28 |
| | Annual | 3125 | 0.48 | 1.01 | 0.55 | 114.47 | 0.68 | 143.48 | 0.29 |
| Upper Midwest | winter | 306 | 0.31 | 0.74 | 0.41 | 134.76 | 0.49 | 161.35 | 0.34 |
| | spring | 323 | 0.50 | 1.12 | 0.68 | 136.29 | 0.77 | 152.44 | 0.53 |
| | summer | 305 | 0.65 | 1.27 | 0.59 | 90.92 | 0.77 | 117.44 | 0.33 |
| | fall | 310 | 0.58 | 1.48 | 0.86 | 146.94 | 1.00 | 171.77 | 0.30 |
| | Annual | 1244 | 0.51 | 1.15 | 0.64 | 124.88 | 0.76 | 148.28 | 0.40 |
| Ohio River Valley | winter | 546 | 0.47 | 1.06 | 0.65 | 138.79 | 0.82 | 176.47 | 0.25 |
| | spring | 559 | 0.58 | 1.33 | 0.80 | 136.84 | 0.91 | 155.87 | 0.44 |
| | summer | 560 | 0.74 | 1.63 | 1.04 | 141.04 | 1.20 | 162.82 | 0.18 |

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-----------------------------|--------|-------|---|--|--|--------------------------|---|---------------------------|-------|
| | fall | 549 | 0.68 | 1.80 | 1.31 | 191.95 | 1.45 | 211.76 | 0.20 |
| | Annual | 2214 | 0.62 | 1.46 | 0.95 | 153.55 | 1.10 | 177.08 | 0.28 |
| Southeast | winter | 417 | 0.29 | 0.86 | 0.65 | 224.48 | 0.69 | 237.73 | 0.33 |
| | spring | 456 | 0.52 | 1.06 | 0.57 | 111.14 | 0.73 | 140.22 | 0.20 |
| | summer | 435 | 1.04 | 0.98 | -0.02 | -1.50 | 0.80 | 76.43 | 0.31 |
| | fall | 424 | 0.57 | 1.15 | 0.58 | 100.12 | 0.68 | 118.45 | 0.44 |
| | Annual | 1732 | 0.61 | 1.01 | 0.44 | 73.04 | 0.72 | 118.85 | 0.26 |
| South | winter | 327 | 0.58 | 1.32 | 0.79 | 136.38 | 1.10 | 190.38 | 0.03 |
| | spring | 354 | 0.77 | 1.23 | 0.53 | 68.81 | 0.97 | 126.62 | 0.05 |
| | summer | 344 | 1.99 | 1.39 | -0.60 | -30.14 | 1.65 | 82.60 | 0.36 |
| | fall | 330 | 0.84 | 1.70 | 0.86 | 102.24 | 1.33 | 157.28 | 0.09 |
| | Annual | 1355 | 1.05 | 1.41 | 0.39 | 36.69 | 1.26 | 119.89 | 0.17 |
| Northern Rockies and Plains | winter | 147 | 0.27 | 0.54 | 0.29 | 104.81 | 0.45 | 166.17 | 0.16 |
| | spring | 150 | 0.43 | 1.01 | 0.54 | 125.46 | 0.56 | 130.55 | 0.60 |
| | summer | 149 | 0.69 | 0.95 | 0.26 | 38.11 | 0.48 | 70.33 | 0.40 |
| | fall | 140 | 0.53 | 1.18 | 0.62 | 115.65 | 0.76 | 142.10 | 0.40 |
| | Annual | 586 | 0.48 | 0.92 | 0.42 | 88.12 | 0.56 | 116.74 | 0.41 |
| Southwest | winter | 249 | 1.00 | 1.14 | 0.27 | 26.94 | 0.79 | 78.92 | 0.03 |
| | spring | 253 | 1.40 | 1.33 | 0.09 | 6.43 | 0.87 | 61.89 | 0.12 |
| | summer | 247 | 1.57 | 0.90 | -0.57 | -36.28 | 0.96 | 61.14 | -0.15 |
| | fall | 258 | 1.86 | 1.25 | -0.42 | -22.62 | 1.35 | 72.81 | -0.05 |
| | Annual | 1007 | 1.46 | 1.16 | -0.16 | -10.83 | 1.00 | 68.13 | -0.01 |
| Northwest | winter | 162 | 0.31 | 0.98 | 0.89 | 291.43 | 0.91 | 296.93 | 0.38 |
| | spring | 162 | 0.47 | 1.58 | 1.54 | 325.48 | 1.55 | 327.66 | 0.60 |
| | summer | 167 | 0.49 | 1.50 | 1.50 | 302.88 | 1.50 | 304.17 | 0.58 |
| | fall | 160 | 0.44 | 1.44 | 1.54 | 352.20 | 1.57 | 359.14 | 0.36 |
| | Annual | 651 | 0.43 | 1.37 | 1.37 | 319.45 | 1.38 | 323.16 | 0.49 |
| West | winter | 345 | 0.73 | 1.04 | 0.32 | 43.89 | 0.49 | 67.08 | 0.57 |
| | spring | 352 | 0.76 | 1.18 | 0.45 | 59.42 | 0.58 | 75.61 | 0.57 |
| | summer | 349 | 1.23 | 0.83 | -0.38 | -30.89 | 0.74 | 60.14 | -0.01 |
| | fall | 329 | 1.35 | 0.99 | -0.31 | -23.33 | 0.75 | 55.76 | 0.18 |
| | Annual | 1375 | 1.01 | 1.01 | 0.03 | 2.47 | 0.64 | 62.98 | 0.20 |
| National | winter | 3248 | 0.48 | 0.95 | 0.53 | 112.50 | 0.71 | 149.56 | 0.23 |
| | spring | 3422 | 0.63 | 1.16 | 0.59 | 93.83 | 0.78 | 124.03 | 0.30 |
| | summer | 3358 | 0.94 | 1.18 | 0.29 | 30.70 | 0.94 | 99.68 | 0.18 |
| | fall | 3261 | 0.78 | 1.38 | 0.67 | 85.57 | 1.05 | 135.52 | 0.12 |
| | Annual | 13289 | 0.71 | 1.17 | 0.52 | 73.47 | 0.87 | 123.15 | 0.20 |

Table 10: soil model performance at IMPROVE sites

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|-----------------------------|--------|------|---|--|--|--------------------------|---|---------------------------|------|
| Northeast | winter | 463 | 0.10 | 0.34 | 0.19 | 189.28 | 0.21 | 200.45 | 0.40 |
| | spring | 481 | 0.23 | 0.49 | 0.22 | 95.21 | 0.23 | 101.37 | 0.68 |
| | summer | 481 | 0.19 | 0.44 | 0.20 | 107.41 | 0.24 | 130.05 | 0.37 |
| | fall | 459 | 0.13 | 0.50 | 0.31 | 247.55 | 0.32 | 251.01 | 0.57 |
| | Annual | 1884 | 0.16 | 0.44 | 0.23 | 142.43 | 0.25 | 153.71 | 0.50 |
| Upper Midwest | winter | 216 | 0.12 | 0.35 | 0.17 | 141.34 | 0.19 | 157.87 | 0.53 |
| | spring | 208 | 0.28 | 0.65 | 0.29 | 102.01 | 0.31 | 109.05 | 0.74 |
| | summer | 210 | 0.39 | 0.61 | 0.15 | 38.27 | 0.28 | 71.72 | 0.62 |
| | fall | 215 | 0.26 | 0.72 | 0.36 | 141.99 | 0.38 | 149.54 | 0.69 |
| | Annual | 849 | 0.26 | 0.58 | 0.24 | 93.02 | 0.29 | 111.06 | 0.62 |
| Ohio River Valley | winter | 203 | 0.14 | 0.58 | 0.42 | 287.55 | 0.43 | 296.54 | 0.26 |
| | spring | 209 | 0.36 | 0.78 | 0.43 | 118.24 | 0.45 | 124.66 | 0.63 |
| | summer | 211 | 0.65 | 0.91 | 0.31 | 47.08 | 0.74 | 113.78 | 0.20 |
| | fall | 198 | 0.39 | 1.10 | 0.76 | 191.96 | 0.84 | 213.11 | 0.34 |
| | Annual | 821 | 0.39 | 0.84 | 0.47 | 121.10 | 0.61 | 157.27 | 0.30 |
| Southeast | winter | 403 | 0.14 | 0.44 | 0.30 | 214.21 | 0.31 | 219.31 | 0.73 |
| | spring | 413 | 0.35 | 0.68 | 0.33 | 94.37 | 0.37 | 105.52 | 0.60 |
| | summer | 419 | 0.85 | 0.58 | -0.27 | -31.95 | 0.64 | 75.24 | 0.29 |
| | fall | 391 | 0.32 | 0.61 | 0.31 | 98.36 | 0.37 | 116.08 | 0.59 |
| | Annual | 1626 | 0.42 | 0.58 | 0.17 | 39.50 | 0.43 | 101.26 | 0.33 |
| South | winter | 250 | 0.32 | 0.58 | 0.27 | 83.35 | 0.45 | 140.87 | 0.02 |
| | spring | 268 | 0.74 | 0.69 | -0.05 | -7.01 | 0.50 | 67.37 | 0.30 |
| | summer | 248 | 1.47 | 0.60 | -0.87 | -59.40 | 1.09 | 74.14 | 0.49 |
| | fall | 265 | 0.54 | 0.74 | 0.20 | 37.48 | 0.54 | 100.27 | 0.11 |
| | Annual | 1031 | 0.76 | 0.65 | -0.11 | -14.08 | 0.64 | 83.95 | 0.25 |
| Northern Rockies and Plains | winter | 558 | 0.13 | 0.25 | 0.12 | 94.82 | 0.16 | 126.47 | 0.50 |
| | spring | 571 | 0.41 | 0.61 | 0.20 | 49.20 | 0.29 | 70.37 | 0.63 |
| | summer | 599 | 0.60 | 0.46 | -0.14 | -23.24 | 0.28 | 46.07 | 0.39 |
| | fall | 574 | 0.36 | 0.54 | 0.18 | 50.85 | 0.34 | 96.52 | 0.48 |
| | Annual | 2302 | 0.38 | 0.47 | 0.09 | 23.44 | 0.27 | 71.12 | 0.49 |
| Southwest | winter | 981 | 0.52 | 0.41 | -0.11 | -21.16 | 0.40 | 77.01 | 0.33 |
| | spring | 1016 | 1.18 | 0.79 | -0.38 | -32.47 | 0.59 | 50.16 | 0.50 |
| | summer | 997 | 1.05 | 0.30 | -0.74 | -70.73 | 0.75 | 71.39 | 0.45 |
| | fall | 984 | 0.85 | 0.36 | -0.48 | -56.99 | 0.57 | 66.83 | 0.28 |
| | Annual | 3978 | 0.90 | 0.47 | -0.43 | -47.69 | 0.58 | 64.05 | 0.37 |
| Northwest | winter | 475 | 0.07 | 0.21 | 0.15 | 231.30 | 0.16 | 246.53 | 0.72 |
| | spring | 513 | 0.32 | 0.68 | 0.35 | 109.85 | 0.43 | 132.33 | 0.49 |
| | summer | 512 | 0.46 | 0.43 | -0.03 | -6.72 | 0.42 | 91.06 | 0.09 |

| Region | season | n | Average observed Concentration ($\mu\text{g}/\text{m}^3$) | Average Modeled Concentration ($\mu\text{g}/\text{m}^3$) | Mean Bias ($\mu\text{g}/\text{m}^3$) | Normalized Mean Bias (%) | Mean Error ($\mu\text{g}/\text{m}^3$) | Normalized Mean Error (%) | cor |
|----------|--------|-------|---|--|--|--------------------------|---|---------------------------|------|
| | fall | 499 | 0.19 | 0.39 | 0.20 | 100.93 | 0.32 | 166.42 | 0.19 |
| | Annual | 1999 | 0.26 | 0.43 | 0.17 | 63.61 | 0.34 | 127.02 | 0.26 |
| West | winter | 623 | 0.20 | 0.33 | 0.13 | 65.13 | 0.21 | 102.88 | 0.54 |
| | spring | 626 | 0.52 | 0.73 | 0.21 | 39.50 | 0.32 | 62.14 | 0.57 |
| | summer | 633 | 0.95 | 0.38 | -0.57 | -60.04 | 0.63 | 66.00 | 0.25 |
| | fall | 605 | 0.72 | 0.33 | -0.39 | -54.47 | 0.53 | 73.93 | 0.14 |
| | Annual | 2487 | 0.60 | 0.44 | -0.16 | -26.07 | 0.42 | 70.56 | 0.19 |
| National | winter | 4172 | 0.24 | 0.37 | 0.12 | 52.32 | 0.28 | 117.52 | 0.30 |
| | spring | 4305 | 0.58 | 0.68 | 0.10 | 16.42 | 0.41 | 69.40 | 0.44 |
| | summer | 4310 | 0.76 | 0.46 | -0.31 | -40.94 | 0.56 | 73.16 | 0.23 |
| | fall | 4190 | 0.48 | 0.51 | 0.01 | 1.80 | 0.46 | 94.60 | 0.14 |
| | Annual | 16977 | 0.52 | 0.51 | -0.02 | -4.29 | 0.42 | 81.98 | 0.27 |

IV. Use of 2016fj PM Modeling as Base Year for Estimating Future EGU Benefits

In this section we examine model performance in terms of the specific ways in which the modeling is applied for the proposed rule RIA. There are two key aspects to consider: 1) the use of modeling as an input into the 2016 and 2026 eVNA surfaces and 2) the use of modeling to determine the contribution of EGU emissions to PM_{2.5} concentrations nationwide.

For calculating benefits, speciated PM_{2.5} model predictions are combined with observed speciated PM_{2.5} data to create a 2016 eVNA surface which is the basis, along with 2026 model predictions, for creating the 2026 eVNA surface. That is, the speciated PM_{2.5} surfaces are adjusted to conform with the magnitude spatial characteristics and of observed concentrations (see US EPA, 2022b for details). For instance, Figure 5 shows that model sulfate concentrations are overpredicted in the range of 0.1-0.5 $\mu\text{g}/\text{m}^3$ throughout much of the US but are underestimated during summer and fall in the Southwest and Texas. Figure 23 compares the 2016 CAMx and 2016 eVNA sulfate surfaces. This figure shows that the eVNA methodology adjusted annual average modeled sulfate concentrations downward by 0.1-0.5 $\mu\text{g}/\text{m}^3$ in the Eastern US and along the West coast but adjusted annual average sulfate concentrations upward by 0.1-0.4 $\mu\text{g}/\text{m}^3$ in Texas. Similarly, Figure 17 shows (1) mostly unbiased EC CAMx predictions across the US with some isolated locations of EC overpredictions which are most pronounced in winter in urban areas and (2) EC underpredictions along the Appalachian Mountains and in the Northwestern US. Figure 24 compares 2016 CAMx and 2016 eVNA EC surfaces. This figure shows that the eVNA methodology did not significantly change modeled EC concentrations through most of the country but adjusted annual average EC downwards by 0.1-1 $\mu\text{g}/\text{m}^3$ in urban areas such as Minneapolis, Chicago, New York and Houston and annual average EC upwards by 0.1-1 $\mu\text{g}/\text{m}^3$ along the Appalachian Mountains and in the Northwest. Therefore, the fused eVNA surfaces minimize differences between the modeled and observed PM_{2.5} concentrations at monitoring locations.

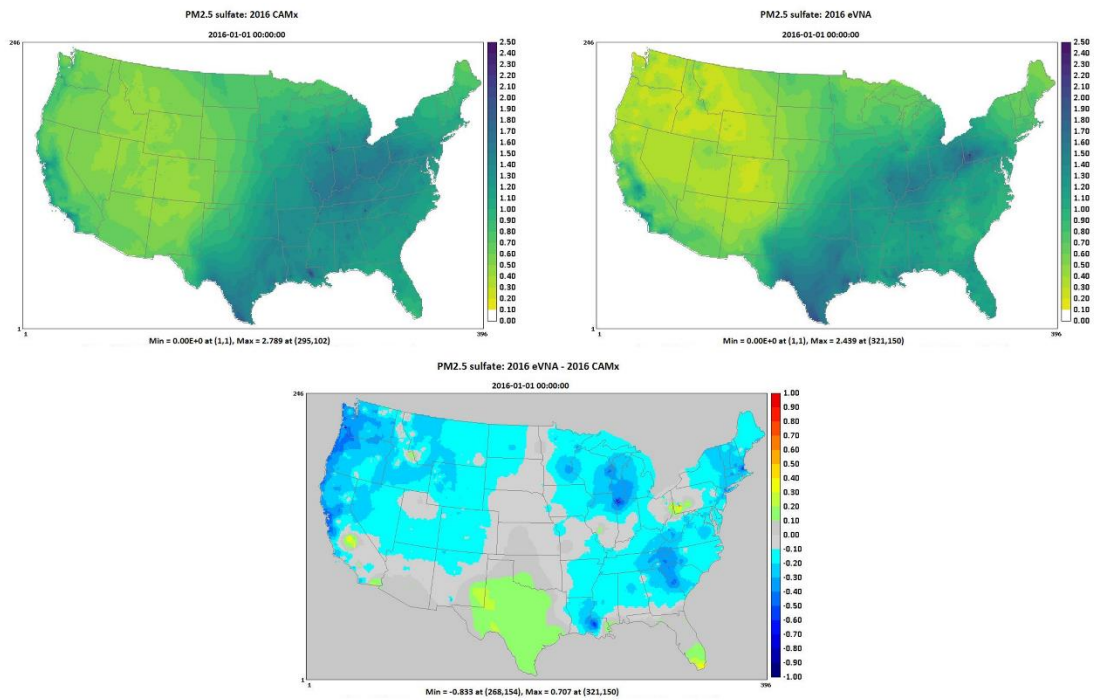


Figure 23: Comparison of annual average PM_{2.5} sulfate ($\mu\text{g}/\text{m}^3$) for 2016 CAMx (left top) and 2016 eVNA (top right) and absolute PM_{2.5} sulfate difference ($\mu\text{g}/\text{m}^3$) between 2016 CAMx and eVNA (bottom). Blue colors on bottom plot represent higher sulfate concentrations in eVNA than in CAMx and green through red colors represent higher sulfate concentrations in CAMx.

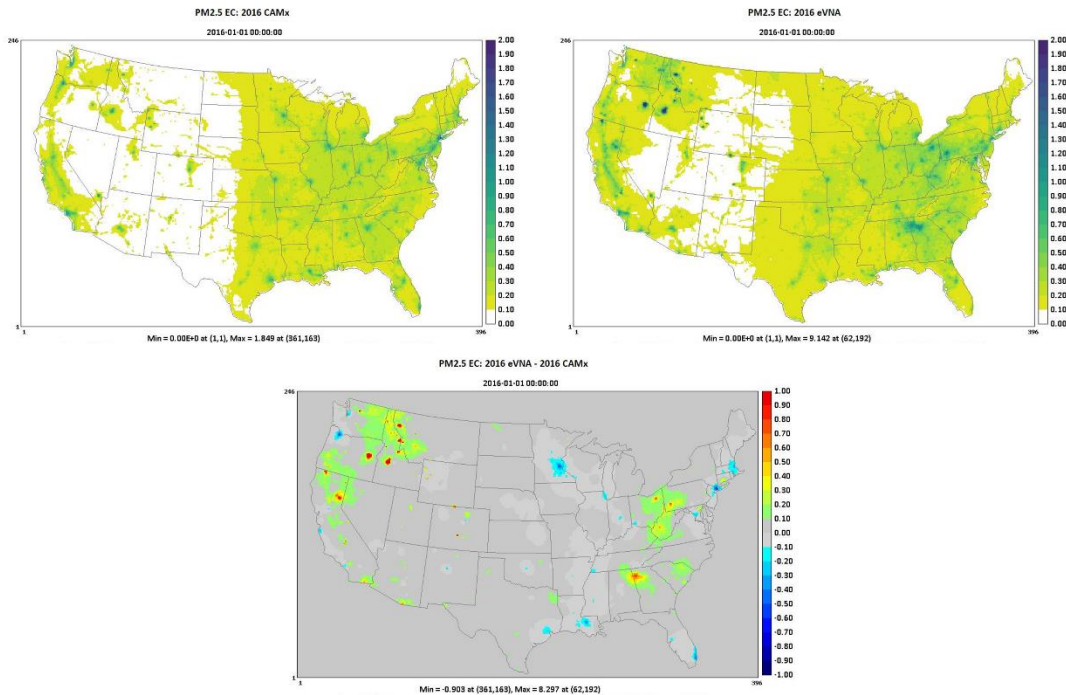


Figure 24: Comparison of annual average PM_{2.5} EC ($\mu\text{g}/\text{m}^3$) for 2016 CAMx (left top) and 2016 eVNA (top right) and absolute PM_{2.5} EC difference ($\mu\text{g}/\text{m}^3$) between 2016 CAMx and eVNA (bottom). Blue colors on bottom plot represent higher EC concentrations in eVNA than in CAMx and green though red colors represent higher EC concentrations in CAMx.

The speciated PM_{2.5} eVNA surfaces for the 2026 baseline are combined with the speciated state-EGU source apportionment contributions to modulate the baseline surfaces to reflect the impact of EGU emissions reductions from the various EGU policies in multiple rulemakings. Figures 25, 26 and 27 show the modeled contributions of EGU emissions to the 2026 eVNA surface for sulfate, nitrate, and primary PM_{2.5}, respectively. Since modulating the PM_{2.5} surfaces to replicate baseline and policy emissions only occur in locations impacted by EGU emissions (i.e. red and purple colors in Figures 25, 26, and 27), model performance in other locations (i.e light yellow in Figures 25, 26, and 27) has little impact on the air quality impacts relevant for EGU policies. For instance, as shown in Figure 25, EGU sulfate contributions are most pronounced in the Eastern half of the US and in urban areas of California. In this respect, model performance for sulfate in other areas of the Western US would not be consequential for estimated the changes in sulfate expected to result from EGU policies. Similarly, EGU nitrate contributions (Figure 26) are highest in the Midwestern US, Salt Lake City, and California, so nitrate model performance in other parts of the country would have little impact on the predicted AQ changes associated with EGU policies. Model biases in the Southeast US caused by not fully capturing large wildfires in the southern Appalachian Mountains (US Department of Agriculture, 2020) are unlikely to affect OC and EGU contributions from EGUs in that region. Primary PM_{2.5} contributions which include organic carbon, elemental carbon, and soil (Figure 27) are more heterogenous with sharper gradients from source locations. Again, model performance for EC, OC, and soil primary PM_{2.5} are not expected to impact AQ changed associated with EGU policies in locations that are distant from EGU sources where EGU contributions are lower (i.e. light yellow areas in Figure 27).

Taken together, the model performance for PM_{2.5} species, as described in the previous section, is acceptable for use in determining EGU impacts when using eVNA surfaces and EGU modeled contributions in a relative manner to estimate the spatial fields of PM_{2.5} concentrations that properly reflect the impact of changes in EGU emissions for the purposes of estimating benefits associated with EGU policies.

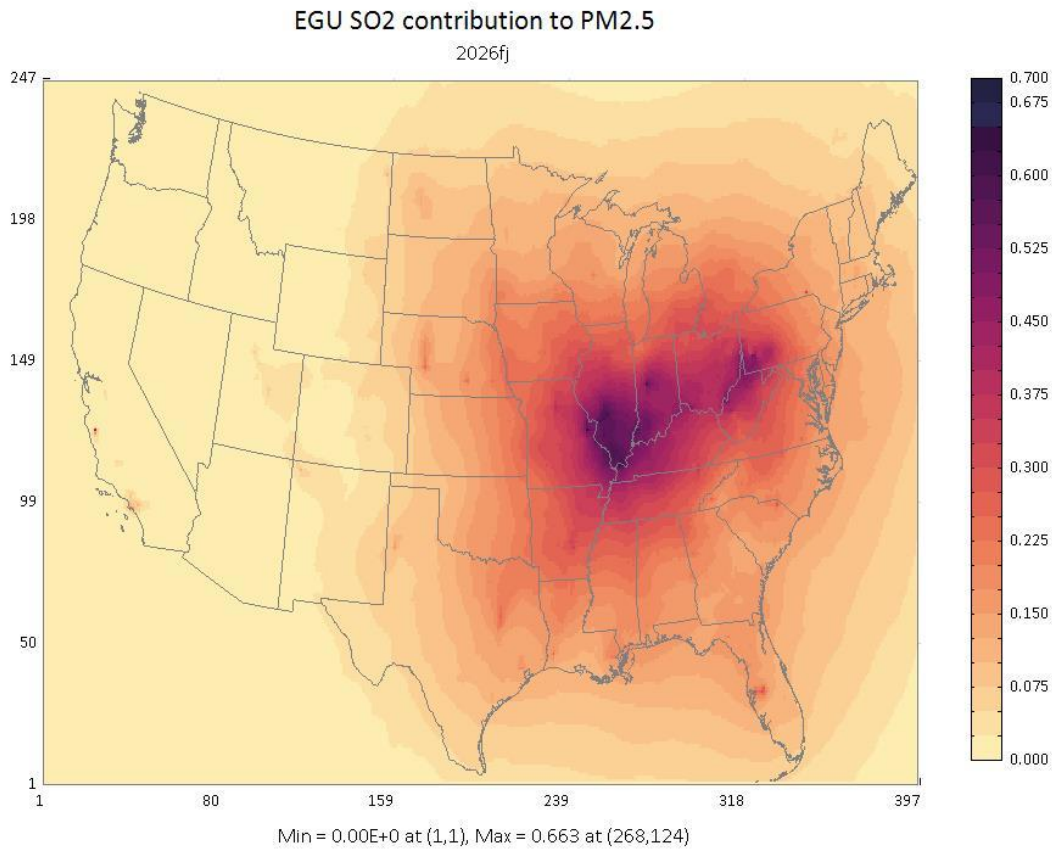


Figure 25: Sulfate concentrations ($\mu\text{g}/\text{m}^3$) from EGU SO₂ emissions in 2026

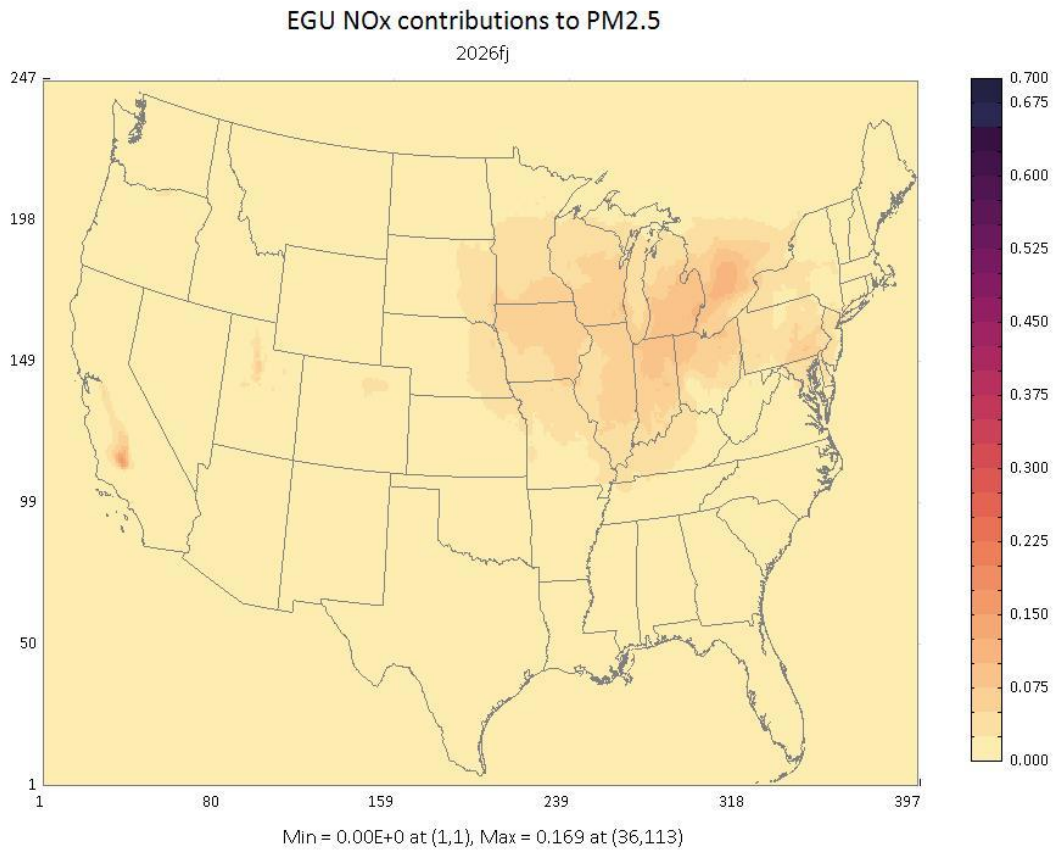


Figure 26: Nitrate concentrations ($\mu\text{g}/\text{m}^3$) from EGU NO_x emissions in 2026

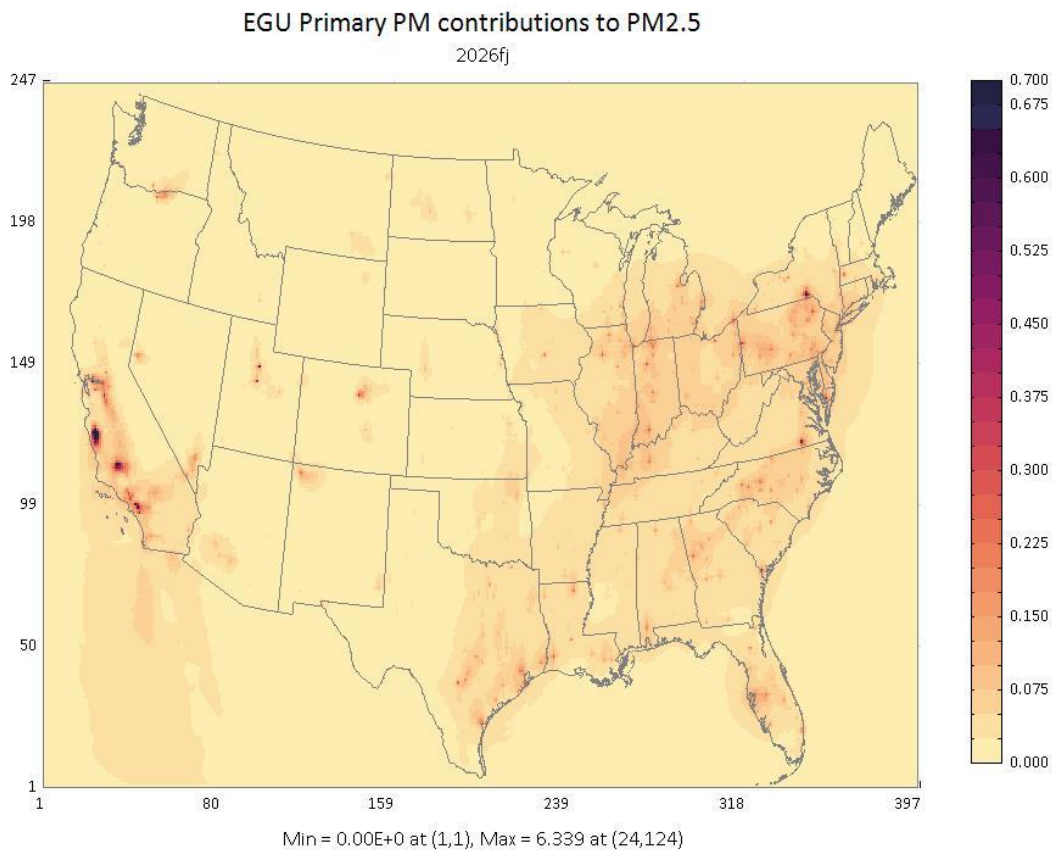


Figure 27: Primary PM_{2.5} concentrations ($\mu\text{g}/\text{m}^3$) from EGU PM_{2.5} emissions in 2026

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