Appendix C. LADCO Documentation

LADCO prepared this Technical Support Document (TSD) to support the development of regional haze state implementation plans (SIPs) for the second haze implementation period. The approaches documented here include emissions inventory processing; chemical transport modeling and evaluation; analysis of ambient monitoring data for haze species; and the calculation of reasonable progress metrics for comparison to regional haze goals. LADCO presents the modeling and analysis results for two base years (2011 and 2016), both projected to 2028, in order to provide robust assessment of expected future year air quality.

The LADCO regional haze TSD and supplemental materials are included below. Additional materials prepared by LADCO in support of the TSD are available at LADCO's webpage for the second regional haze implementation period. The webpage address and list of materials is provided below:

- Webpage
  - https://www.ladco.org/reports/technical-support/ladco-regional-haze-tsd-second-implementation-period/
- TSD Documents
  - LADCO Regional Haze TSD (June 17, 2021; PDF)
  - Supplemental Materials (June 17, 2021; PDF)
  - Response to Comments (Google Doc)
- Q/d Materials
  - LADCO Q/d Memo (October 14, 2020; PDF)
  - Q/d spreadsheet (XLS)
  - Process level report of Q/D sources (Haze_Control_Sheet_7.3.xlsx)
  - Process level report of Q/D sources (Haze_Control_Sheet_6.9.xlsx)
  - Summary of county and sector emissions for 2016 (XLS)
  - Summary of county and sector emissions for 2028 (XLS)
  - Background data and computer code used to generate summaries (zip file)
- CAMx Modeling Results
  - 2016-based 2028 glidepaths and PSAT tracer contributions (XLS)
  - 2011-based 2028 glidepaths and PSAT tracer contributions (XLS)
  - 2011 PSAT nitrate and sulfate tracer footprint plots (Website)
  - 2016 PSAT nitrate and sulfate tracer footprint plots (Website)
  - 2011 CAMx MPE plots (Website)
  - 2016 CAMx MPE plots (Website)
- Emissions Modeling Results
  - 2011 and 2028 emissions tile plots (Website)
  - 2016 and 2028 emissions tile plots (Website)
  - 2016 Emissions Collaborative inventory summary plots for the LADCO region (Website)
- Other Materials
  - Determining Areas of Influence – CenSARA Round 2 Regional Haze report by Ramboll (PDF)
  - CenSARA server with additional trajectory plots

LADCO | LAKE MICHIGAN AIR DIRECTORS CONSORTIUM

Modeling and Analysis for Demonstrating Reasonable Progress for the Regional Haze Rule 2018 - 2028 Planning Period

Technical Support Document

Lake Michigan Air Directors Consortium

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June 17, 2021

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Contents

Document Change Log

Version	Date	Comments/Changes
1	January 11, 2021	First draft to LADCO states
2	January 15, 2021	Updates to sections 2, 4, and 6
3	January 19, 2021	Updates to sections 4, 7, 8, and 8; grammatical/style edits throughout
4	January 27, 2021	Draft for comments to the LADCO regional haze workgroup; incorporated comments from WI DNR and MPCA
5	April 15, 2021	Draft final that integrated comments through March from LADCO states, EPA, and the Federal Land Managers; includes copy editing by LADCO staff
6	May 5, 2021	Removed references to LADCO 2016-based PSAT simulation
7	June 6, 2021	Added results from LADCO 2016abc and 2028abc PSAT simulations
8	June 17, 2021	Added a line to Table 8-1 providing a sum of other lines (contribution to b_{ext} on the most impaired days)

Errata/Known Issues

#	Description

Support Materials

Supplementary Materials

Electronic Docket

Figures

Tables

Executive Summary

LADCO prepared this Technical Support Document to support the development of regional haze state implementation plans (SIPs) for the second haze implementation period. The approaches documented here include emissions inventory processing; chemical transport modeling and evaluation; analysis of ambient monitoring data for haze species; and the calculation of reasonable progress metrics for comparison to regional haze goals. LADCO presents the modeling and analysis results for two base years (2011 and 2016), both projected to 2028, in order to provide robust assessment of expected future year air quality. LADCO also analyzed the stationary point source emission inventory to screen sources for their potential contribution to haze in downwind Class I areas. LADCO calculated distance weighted emissions (Q/d) for the 2028 stationary point inventories.

Analysis of observed ambient fine particle concentrations ($PM_{2.5}$) at surface monitors in the LADCO region in 2019 shows that the 24-hour design values are at least five $\mu g/m^3$ below the level of the NAAQS. The highest concentrations are in the urban areas, and the lowest concentrations are in the far northern parts of the region, including near LADCO's Class I areas, and in the Appalachian portions of Ohio and eastern Kentucky. The annual and 24-hour $PM_{2.5}$ design values for all LADCO states decreased by 33% to 51% between 2002 and 2019. The chemical composition of the $PM_{2.5}$ in the region has changed as concentrations have decreased. Fine particles have transitioned from containing primarily ammonium sulfate aerosols in 2001 to containing similar proportions of ammonium nitrate, ammonium sulfate, and organic carbon at the more rural IMRPOVE monitoring sites in 2018. The reductions in PM concentrations produced significant improvements to regional haze. Total light extinction from haze decreased by roughly 40 percent from 2000-2004 to 2014-2019 at all LADCO-region Class I monitors, with similar reductions on the clearest and most impaired days.

LADCO selected 2011 and 2016 as modeling years because they were available in U.S. EPA modeling platforms that included projections to 2028, the last year of the current regional haze implementation period. The U.S. EPA modeling platforms represented the state-of-the-science for the modeling software, and emissions and meteorology data. U.S. EPA used both platforms for regional haze modeling studies, providing further justification for selecting these years. LADCO chose to model two different base years to provide additional weight of evidence for our member states to use in their RHR reasonable progress SIPs. LADCO used the CAMx regional air quality model to estimate base and future year PM concentrations and haze conditions. We configured CAMx with the Particulate Matter Source Apportionment Tool (PSAT) to calculate emissions tracers for identifying upwind sources of haze at downwind Class I areas.

Starting in March 2018, LADCO produced a series of Q/d analyses for use by the LADCO member states for regional haze planning. LADCO used a cumulative Q/d threshold of 80% to identify sources for possible for-factor analysis. We provided the results of the Q/d analysis to the LADCO-member states in a spreadsheet to use to screen sources for further analysis.

LADCO's projections of haze in 2028 for both modeling platforms show that all of the LADCO-region Class I areas are predicted to be ahead of the uniform rate of progress (URP) toward natural visibility conditions. Predicted 2028 visibility conditions based on the 2016 modeling platform shows that the visibility in the Class I areas in Minnesota and Michigan is about 1 deciview below the unadjusted glidepath line (i.e., URP). Accounting for the adjustment due to international anthropogenic contributions, LADCO estimated 2028 visibility on the 20% most impaired days to be about 2.5 dv below the URP line.

1 Introduction

The Lake Michigan Air Directors Consortium (LADCO) was established by the states of Illinois, Indiana, Michigan, and Wisconsin in 1989. The four states and EPA signed a Memorandum of Agreement (MOA) that initiated the Lake Michigan Ozone Study and identified LADCO as the organization to oversee the study. Additional MOAs were signed by the states in 1991 (to establish the Lake Michigan Ozone Control Program), January 2000 (to broaden LADCO's responsibilities), and June 2004 (to update LADCO's mission and reaffirm the commitment to regional planning). In March 2004, Ohio joined LADCO. Minnesota joined the Consortium in 2012. LADCO consists of a Board of Directors (i.e., the State Air Directors), a technical staff, and various workgroups. The main purposes of LADCO are to provide technical assessments for and assistance to its member states, to provide a forum for its member states to discuss regional air quality issues, and to facilitate training for staff in the member states.

One of LADCO's responsibilities is to provide technical air quality modeling guidance and support to the LADCO states. LADCO prepared this Technical Support Document (TSD) to support our member-states' Regional Haze State Implementation Plans (SIPs) for the second haze implementation period. The approaches documented here include emissions inventory processing; chemical transport modeling and evaluation; analysis of ambient monitoring data for haze species; and the calculation of reasonable progress metrics for comparison to regional haze goals. LADCO presents the modeling and analysis results for two base years (2011 and 2016), both projected to 2028, in order to provide robust assessment of expected future year air quality.

1.1 Regional Haze

Particulate matter (PM) impairs visible light in the atmosphere either as distinct pollution plumes or as more uniformly distributed "regional haze". Regional haze is defined at 40 CFR 51.301 as "visibility impairment that is caused by the emission of air pollutants from numerous anthropogenic sources located over a wide geographic area. Such sources include, but are not limited to, major and minor stationary sources, mobile sources, and area sources." Fine particles less than 2.5 μm in diameter ($PM_{2.5}$) exist in the atmosphere as either primary emitted species or secondary species formed through chemical reactions. When these particles absorb and scatter light they alter the "clarity, color, and visible distance" in the atmosphere. The important PM species for visibility impairment include sulfate, nitrate, ammonium, elemental carbon, organic carbon and soil dust particles. (U.S. EPA 82 FR 3278 January 2017).

Section 169A of the 1977 amendments to the Clean Air Act (CAA) established a visibility protection program for the nation's areas of "great scenic importance", otherwise known as Class I areas. CAA Section 169A established as a national goal the "prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I Federal areas which impairment results from manmade air pollution" (U.S. EPA 82 FR 3278 January 2017).

In 1999, U.S. EPA promulgated the Regional Haze Rule (RHR) to establish more comprehensive visibility protections in the nation's Class I areas (Figure 1-1). There are 156 Class I areas, including four in the LADCO region[1]: Isle Royale National Park and Seney National Wildlife Refuge in Michigan; and Boundary Waters Canoe Area and Voyageurs National Park in Minnesota. EPA's visibility rule (64 FR 35714, July 1, 1999) requires reasonable progress in achieving "natural conditions" in all Class I areas by the year 2064.

For haze SIPs, the Clean Air Act sets "as a national goal the prevention of any future, and the remedying of any existing, impairment of visibility in Class I areas which impairment results from manmade air pollution." The RHR required that all states submit regional haze SIPs every 10 years and review these SIPs every 5 years. Requirements for regional haze SIPs (pursuant to 40 CFR 51.308(d)) include setting reasonable progress goals, determining baseline conditions, determining natural conditions, providing a long-term control strategy, providing a monitoring strategy (air quality and emissions), and establishing best available retrofit technology (BART) emissions limitations and associated compliance schedule. During the first regional haze implementation period, which culminated with regional haze SIPs that were due on December 17, 2007, LADCO effectively served as a Regional Planning Organization (RPO) for its member states[2]. These first regional haze SIPs addressed the initial 10-year implementation period (i.e., reasonable progress by the year 2018).

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[1] Although Rainbow Lake in northern Wisconsin is also a Class I area, the visibility rule does not apply because the Federal Land Manager determined that visibility is not an air quality related value there, meaning that….

[2] A sub-entity of LADCO, known as the Midwest Regional Planning Organization (MRPO), was responsible for the regional haze activities of the multi-state organization during the first RHR planning period.

Figure 1-1. Class I areas by Federal Land Manager

In January 2017, US EPA issued a final rule updating the regional haze program, including revising portions of the visibility protection rule promulgated in 1980 and the Regional Haze Rule promulgated in 1999 (U.S. EPA 82 FR 3278 January 2017). This rule clarifies the obligations of the states and U.S. EPA during the second haze implementation period, which tracks progress in improving visibility out to the year 2028. To aid states in developing second round regional haze SIPs, U.S EPA issued their "Guidance on Regional Haze State Implementation Plans for the Second Implementation Period" (U.S. EPA, 2019a).

LADCO followed the recommendations in the aforementioned Regional Haze SIP guidance document (U.S. EPA, 2019a) and referred to the U.S. EPA (2019b) Technical Support Document for EPA's Updated 2028 Regional Haze Modeling and the U.S. EPA (2018) Modeling Guidance for Demonstrating Air Quality Goals for Ozone, PM2.5, and Regional Haze to inform the development of this document.

1.2 Project Overview

LADCO conducted emission inventory analysis and regional air quality modeling to support the development of Regional Haze SIPs**.** These SIP revisions are plans that describe how states will make reasonable progress toward meeting the visibility goals of the RHR. LADCO used the Comprehensive Air Quality Model with Extensions (CAMx[3]) to simulate PM and haze for two base years, 2011 and 2016. LADCO used CAMx to forecast haze conditions at the end of the second RHR planning period (2028) with emissions inventories projected to 2028 from each of these base years.

LADCO also performed analysis on the stationary point source emission inventory to screen sources for their potential contribution to haze in downwind Class I areas. LADCO calculated distance weighted emissions (Q/d)[4] for the 2028 stationary point inventories. LADCO worked with the states to apply these Q/d estimates for screening sources to subject to the four-factor analysis required by the RHR.

This document describes how LADCO used CAMx modeling to simulate base and future year air quality, and to evaluate if the Class I areas in and near the LADCO region are projected to meet or exceed the uniform rate of progress toward natural visibility conditions in 2064. The CAMx modeling outputs of this work are being provided to the LADCO state air programs to support their RHR SIP revisions that are due to EPA on July 31, 2021.

1.3 Organization of the Technical Support Document

This technical support document (TSD) is organized into the following sections.

- Section 2: Current and historical PM and haze conditions in the LADCO region
- Section 3: CAMx 2011 and 2016 modeling platforms; the platforms include base and future year (2028) emissions inventories, photochemical modeling data and configurations, and model performance evaluation methods
- Section 4: Emissions summaries of the 2011, 2016, and 2028 data used for the modeling in this TSD.
- Section 5: Q/d methods and results used to screen stationary point sources for four factor analysis.

[3] www.camx.com
[4] where Q = emissions in tons/year and d = distance from the Class I areas in km

- Section 6: CAMx model performance evaluation results for both 2011 and 2016.
- Section 7: Second RHR planning period reasonable progress results and analysis.
- Section 8: CAMx source apportionment modeling results and analysis.
- The TSD concludes with a summary of significant findings and observations from the LADCO modeling.

A Supplemental Materials document includes supporting figures and tables for the results presented in this TSD.

An Electronic Docket on the LADCO website includes supporting spreadsheets, memos, and additional figures produced by LADCO during the second regional haze implementation period.

2 Ambient Air Quality Data and Visibility Analysis

In this section LADCO presents an analysis of the historical and current PM and haze conditions at monitors in the Great Lakes region. The goals of this section are to show the current status of ambient PM air quality and haze in the LADCO region and to illustrate the progress with these air quality indicators over time.

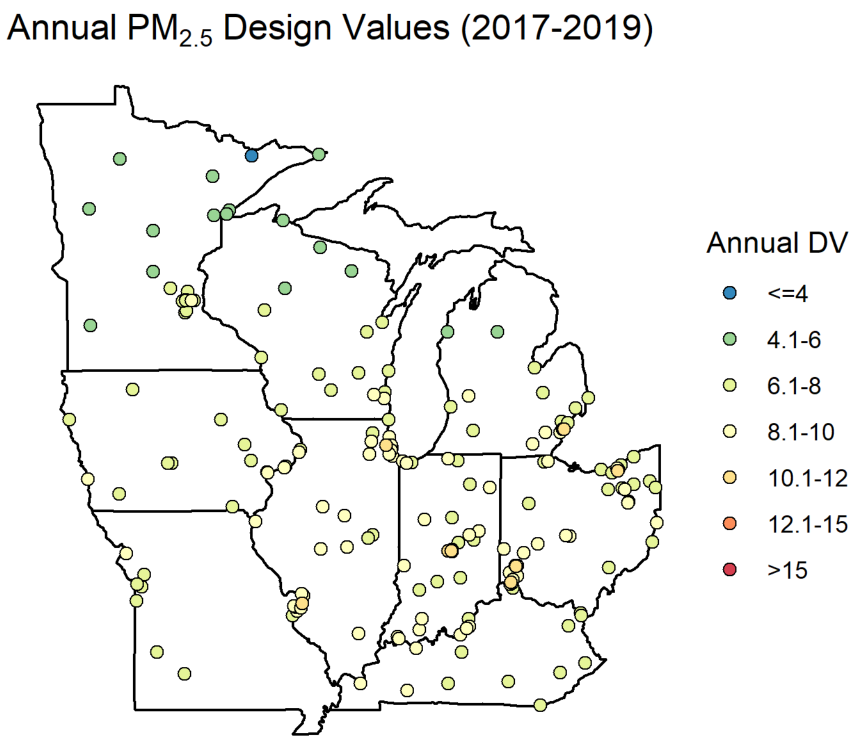
The primary contributor to reduced visibility is $PM_{2.5}$. An extensive network of regulatory and special-purpose monitors around the country measure ambient $PM_{2.5}$ concentrations. Measurements of speciated $PM_{2.5}$ components are made at a smaller network of sites. In particular, $PM_{2.5}$ composition measurements are used to track haze at the mostly rural Class I areas in the Interagency Monitoring of Protected Visual Environments (IMPROVE) network. In this section, we discuss the current status of and trends in both haze and $PM_{2.5}$ in the LADCO region, with a focus on the four Class I areas in the region.

2.1 Current $PM_{2.5}$ Conditions and Historical Trends

Concentrations of $PM_{2.5}$ are frequently reported as design values (DVs), which can be compared with the $PM_{2.5}$ National Ambient Air Quality Standard (NAAQS). These DVs are calculated as annual and daily (24-hour) averages.[5] We present both forms of $PM_{2.5}$ DVs in this section, along with a discussion of trends in DVs and $PM_{2.5}$ composition.

Figure 2-1 shows the annual and 24-hour 2019 $PM_{2.5}$ DVs within the LADCO region and neighboring states. $PM_{2.5}$ DVs at all monitors in the LADCO region are below the levels of both $PM_{2.5}$ NAAQS. In particular, all 24-hour DVs are at least five $\mu g/m^3$ below the level of the NAAQS. The highest concentrations are in the urban areas, and the lowest concentrations are in the far northern parts of the region, including near LADCO's Class I areas, and in the Appalachian portions of Ohio and eastern Kentucky.

[5] The annual $PM_{2.5}$ DV is the three-year average of the annual mean concentration at a monitoring location. The 24-hour $PM_{2.5}$ DV is the three-year average of the 98^{th} percentile of daily average $PM_{2.5}$ at a monitor. Design values are labeled by the last year of the three-year average. For example, the 2019 annual $PM_{2.5}$ DV is the three-year average of the annual average $PM_{2.5}$ concentrations for the years 2017-2019. We downloaded design values from EPA's Air Quality Design Values webpage: https://www.epa.gov/air-trends/air-quality-design-values.



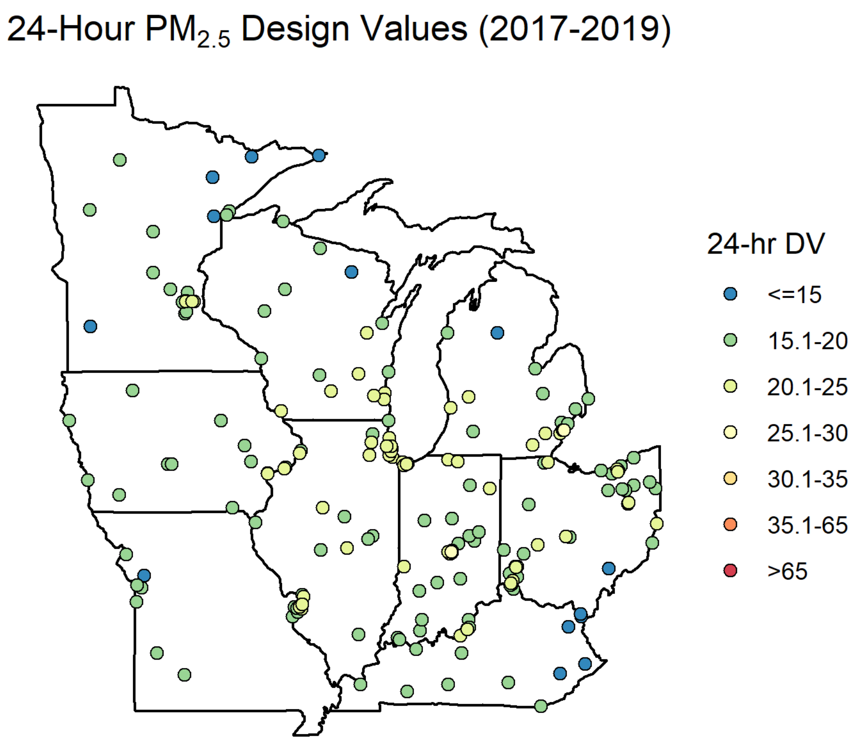


Figure 2-1. 2017-2019 annual (top) and 24-hour (bottom) $PM_{2.5}$ design values (DVs) in μg/m³. For comparison, the annual $PM_{2.5}$ NAAQS is 12 μg/m³, and the 24-hour NAAQS is 35 μg/m³.

$PM_{2.5}$ design values have decreased dramatically in all states in the LADCO region over the last 19 years, as shown in Figure 2-2. The annual and 24-hour $PM_{2.5}$ design values for all states decreased by 33% to 51% since 2002. Ohio started with the highest concentrations and had the largest reductions, whereas Minnesota started with the lowest levels and had the smallest reductions. As a result of these differential changes, $PM_{2.5}$ levels in the six states have converged to much more uniform concentrations among the states. The pace of reduction in $PM_{2.5}$ DVs was especially large after the year 2007. The pace of reductions appears to have decreased somewhat in the last several years. However, state average concentrations are currently at least 14 $\mu g/m^3$ below the level of the 24-hour NAAQS and at least 3 $\mu g/m^3$ below the annual NAAQS.

Figure 2-3 shows how the chemical composition of the $PM_{2.5}$ has changed as its concentrations have decreased. This figure shows the chemical composition of $PM_{2.5}$ at LADCO state monitors in the primarily rural IMPROVE network. Concentrations of all of the major measured $PM_{2.5}$ species have decreased at the regional surface monitors since 2001, with the largest reductions (70%) from ammonium sulfate aerosols and the smallest reductions (7%) from organic carbon.[6] The disproportionately large reductions in ammonium sulfate reflect the dramatic reductions in sulfur dioxide emissions from stationary point sources resulting from regulatory control programs and economically driven shifts away from coal combustion. As a result, the chemical composition of fine particles has transitioned from containing primarily ammonium sulfate aerosols in 2001 to containing similar proportions of ammonium nitrate, ammonium sulfate, and organic carbon at these rural sites in 2018.

[6] The other components had intermediate levels of reduction. Ammonium nitrate concentrations decreased by 20 percent, elemental carbon by 17 percent, and soil by 44 percent. Sea salt was a very small component but increased during this time by 58 percent.

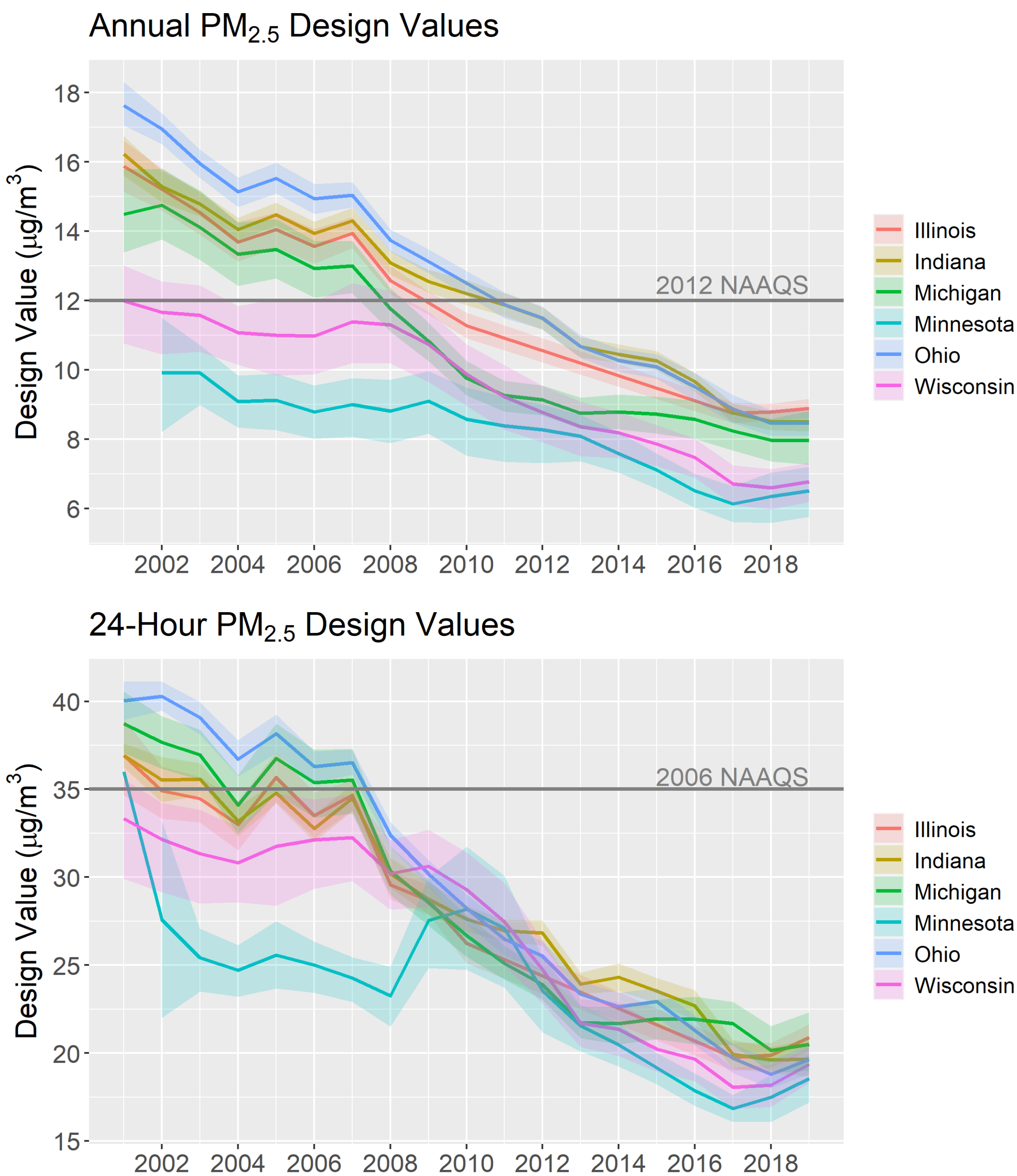


Figure 2-2. Trends in annual (top) and 24-hour (bottom) $PM_{2.5}$ design values in the LADCO states.[7] The levels of the NAAQS are shown for comparison. Dark lines show the state mean, whereas the shaded region shows the 95 percent confidence interval. Plots include monitors with at least six valid design values.

[7] Note that design values were invalidated for Illinois for the years 2011 through 2016. Illinois values in this figure were interpolated between the preceding and subsequent design values.

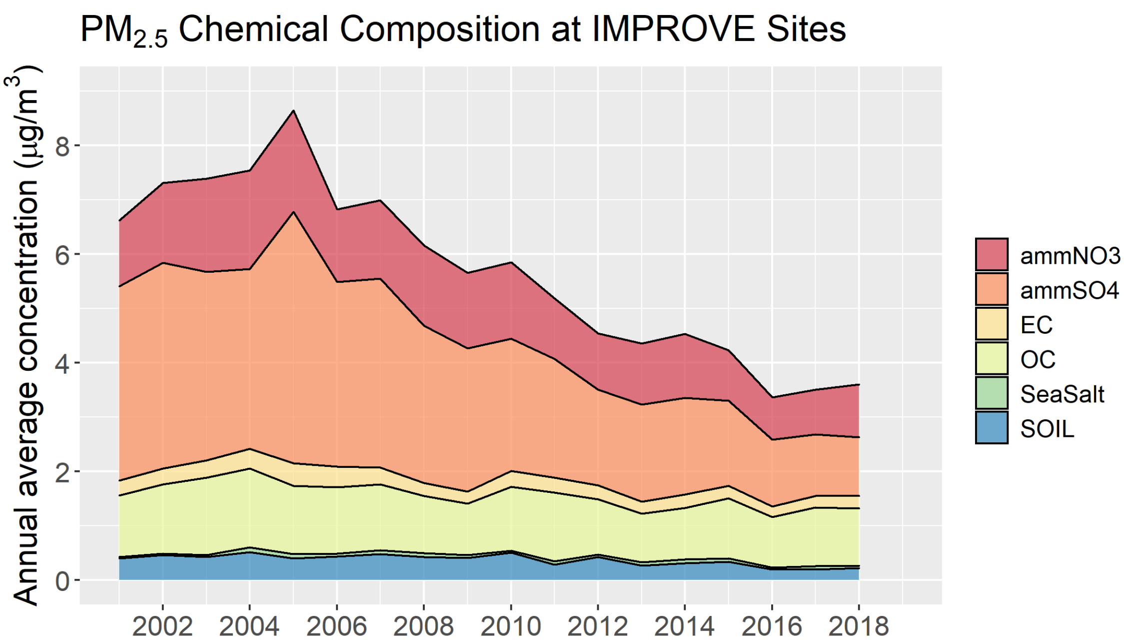


Figure 2-3. Chemical composition of $PM_{2.5}$ at the mostly rural IMPROVE monitoring sites in the LADCO region.[8]

2.2 Current Haze Conditions and Historical Trends

Visibility measurements are reported using either a light extinction coefficient (reported as inverse megameters, Mm^{-1}) or using the deciview haze index. Light extinction represents by how much light is attenuated per unit distance due to a combination of scattering and absorption by gases and particles. The deciview index is a logarithmic transformation of light extinction values[9] and is easier to relate to perceivable changes in visibility. Deciview values would be near zero for a pristine atmosphere and increase with increasing haze. We use both measures in this document. Light extinction is estimated from speciated particle measurements at IMPROVE monitoring sites using the IMPROVE algorithm and then converted to the deciview haze index.[10] We downloaded all visibility data from the Federal Land Manager Environmental Database except as noted.[11]

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[8] Components are: ammNO3 = ammonium nitrate, ammSO4 = ammonium sulfate, EC = elemental carbon, OC = organic carbon, SeaSalt = sea salt, and SOIL = inorganic soil components. Data were downloaded from the Federal Land Manager Environmental Database at http://views.cira.colostate.edu/fed/QueryWizard/.

[9] The relationship is: $dv = 10 \ln (b_{ext} / 10 \text{ Mm-1})$, where dv = deciviews and b_{ext} = the total light extinction coefficient.

[10] These calculations are described in greater detail in Section 7.1.

[11] http://views.cira.colostate.edu/fed/SiteBrowser/Default.aspx?appkey=SBCF_VisSum or http://views.cira.colostate.edu/fed/QueryWizard/.

Visibility at all of the mostly rural IMPROVE monitors in the eastern U.S. improved from 2002 to 2019, as reflected in lower deciview values (Figure 2-4). The haziest areas were located in the middle of this large area, from Iowa and Illinois down to Alabama. The cleanest areas were primarily located along the western and northern parts of this region. The largest reductions in haze over this time period (up to 47%) were found in the southeast and northeast. Reductions at the four LADCO Class I Area monitors were between 27% and 33% during this time. Visibility improvements have been even better than those laid out in the glidepaths for these sites to reach background conditions by 2064, as shown in Section 7.2.

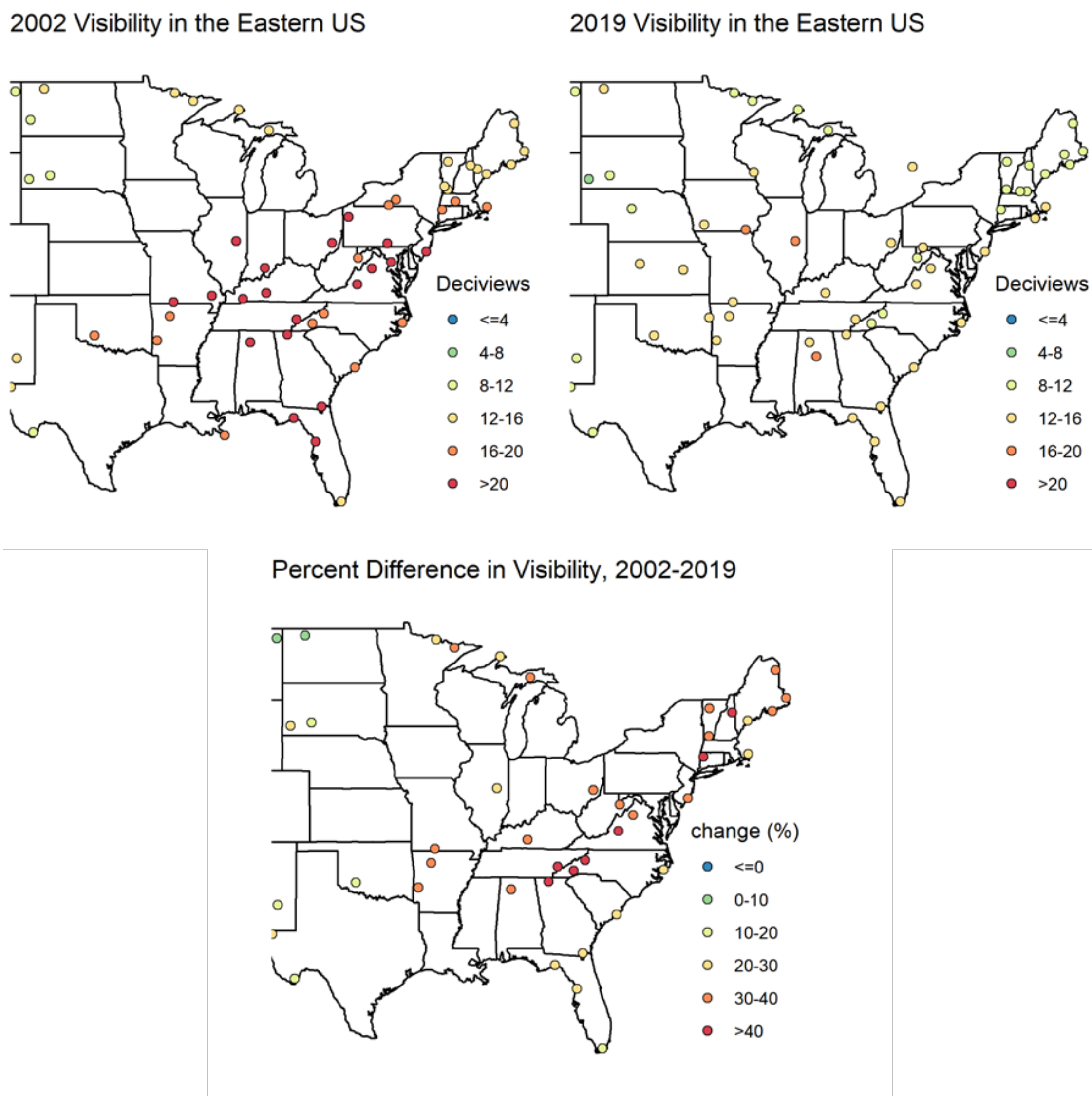


Figure 2-4. Visibility (in deciviews) at sites in the eastern United States in 2002 (left) and 2019 (right), and the percent difference in visibility in these two years (bottom).

Figure 2-5 breaks apart the visibility trends at the four LADCO Class I Area monitors based on the haziness of the day. From 2000 to 2018, visibility on the most impaired days improved by 18% to 26%, with the largest improvements at the Boundary Waters and Seney sites. Visibility improvements were even greater on the clearest days, with improvements of 26% to 34%, with the smallest improvement at Seney.

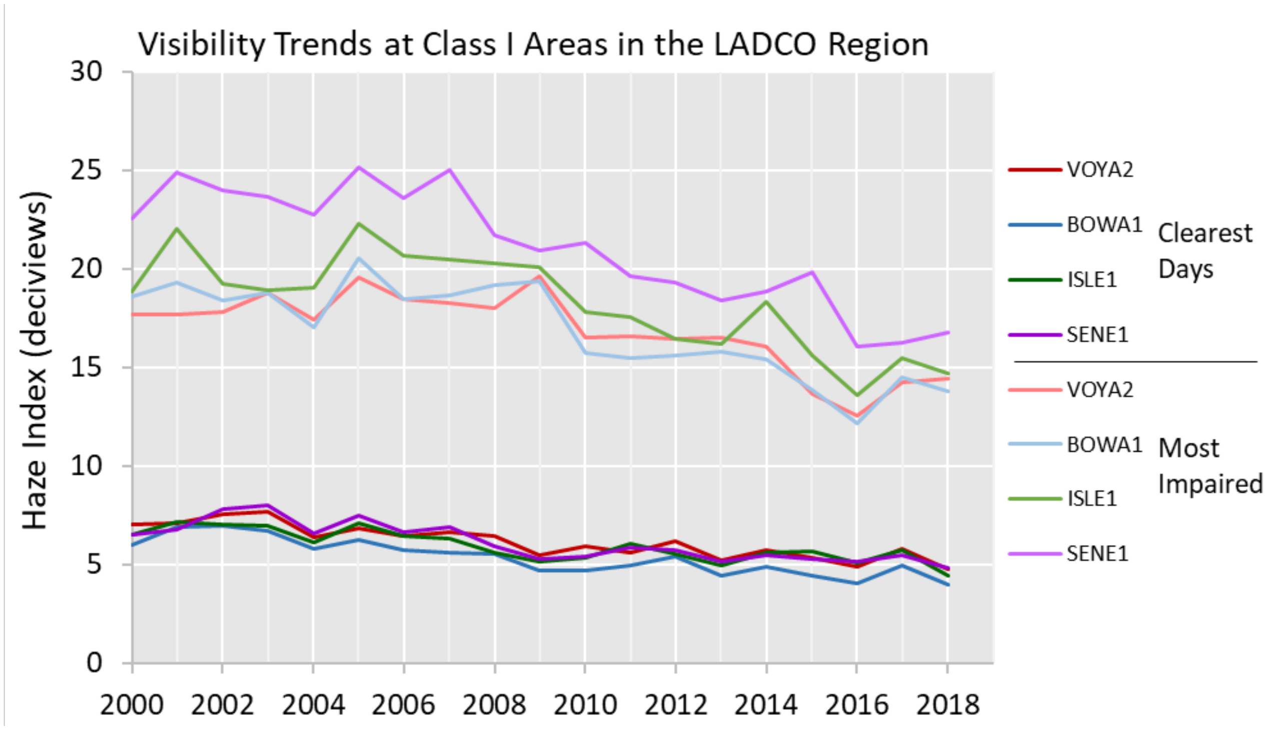


Figure 2-5. Visibility trends (in deciviews) at LADCO Class I Area monitors on the clearest and most impaired days.[12]

Table 2-1 shows the breakdown of the chemical components that contributed to haze at the four LADCO Class I area monitors in the years 2000-2004 and 2014-2019. Figure 2-6 shows the magnitudes and composition of light extinction for every year since 2000 for Minnesota's Voyageurs National Park. Supplemental Materials Section S1 includes comparable figures for the other three LADCO region Class I areas. This chemical speciation of visibility impacts is based upon the $PM_{2.5}$ chemical speciation at these

[12] Site abbreviations are: VOYA2 = Voyageurs National Park (MN), BOWA1 = Boundary Waters Canoe Area (MN), ISLE1 = Isle Royale National Park (MI), and SENE1 = Seney (MI). Data were downloaded from the WRAP Technical Support System at https://views.cira.colostate.edu/tssv2/Express/HazeAnalysisTools.aspx.

sites (similar to that shown in Figure 2-3) but directly indicates the magnitude of the visibility impacts from each chemical component. The composition of light extinction will be somewhat different than the measured chemical composition of $PM_{2.5}$ because different chemical components have different degrees of impact on light and thus on visibility; for example, elemental carbon (soot) has a disproportionate impact on light and thus on haze.

Light extinction on the most impaired days was 6 to 12 times as large as that on the clearest days. On the clearest days, ammonium sulfate has historically been the largest component of haze, as shown in Table 2-1, Figure 2-6 and Section S1. Ammonium nitrate is a much more important component on the most impaired days than it is on the clearest days; in the years 2014-2018, it was the greatest contributor at all LADCO region Class I area sites.

Total light extinction from haze decreased by roughly 40 percent from 2000-2004 to 2014-2019 at all LADCO Class I monitors, with similar reductions on the clearest and most impaired days. However, different components contributed to these reductions on the different types of days. On the clearest days, there were large reductions in light extinction from all of the major components. On the most impaired days, there were large reductions in light extinction from ammonium sulfate, however, reductions from ammonium nitrate were much smaller, particularly at the Michigan sites. The slow pace of ammonium nitrate reductions led to its being the largest contributor to light extinction in recent years, as mentioned above. In general, haze seems to have peaked in the early- to mid-2000s, then steadily decreased. Total light extinction from haze may have plateaued in the last few years.

Analysis of the back-trajectories of polluted air masses provides insight into potential source locations impacting visibility. Figure 2-7 shows the back-trajectory-based residence times for air masses reaching the LADCO Class I monitors on the 20% most impaired days, weighted for distance from the monitor. For all four areas, the most polluted air masses most frequently arrived from the south and west. Supplemental Materials Section S2 includes similar figures that show how residence times vary based on the trajectory end-point altitude and the weighting of the residence time. All of these analyses show the importance of transport from the south on the most impaired days. This analysis suggests that sources in Minnesota, Wisconsin, Iowa, Illinois and Indiana are most likely to contribute to haze in the LADCO Class I areas. The more westerly source regions contribute more to visibility impairment in the Minnesota

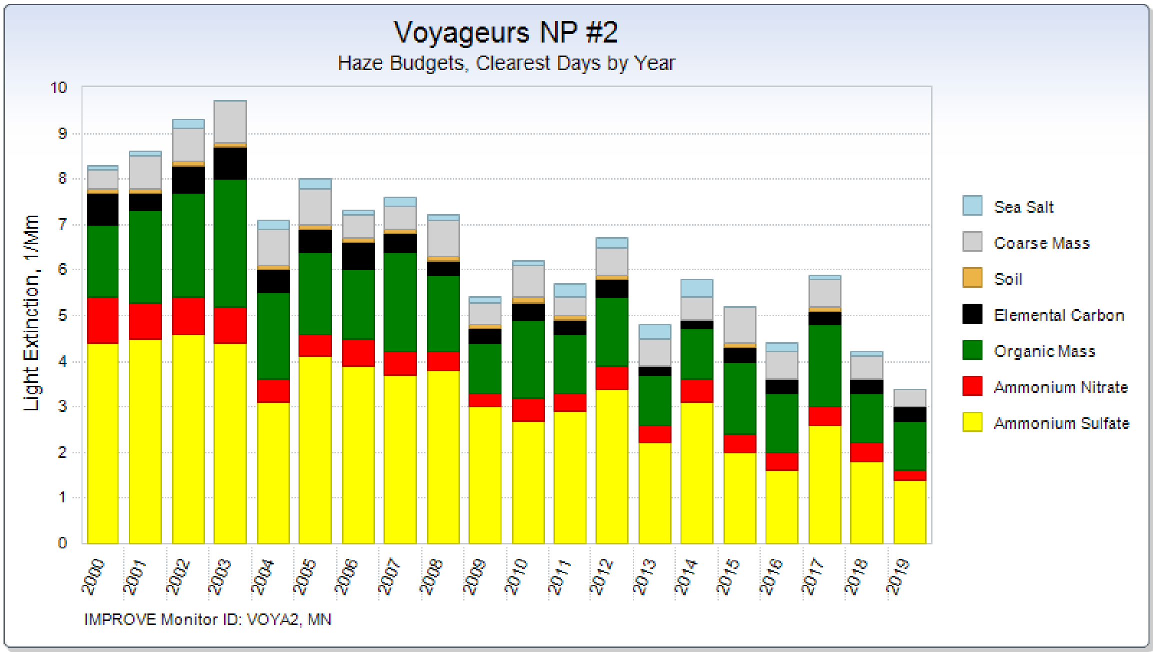
Class I areas, and more easterly source region have a larger contribution to impairment in the Michigan Class I areas.

2.3 Summary

Overall, concentrations of $PM_{2.5}$ and haze have decreased significantly over the last two decades in the LADCO region. As a result, all monitors in the region are meeting the $PM_{2.5}$ NAAQS, and visibility at the regional Class I sites is better than the sites' glide paths. Concentrations of ammonium sulfate, which forms in part from atmospheric sulfur dioxide, have undergone particularly large reductions during this time due to control programs targeting that pollutant. As a result, ammonium nitrate and organic carbon have become relatively more important contributors to fine particulate matter and haze. Air masses on the most impaired days most frequently arrived at LADCO Class I sites from the south, suggesting that emission sources to the south likely contributed most to degraded visibility at these sites.

Table 2-1. Five-year average composition of light extinction (in Mm^{-1}) for LADCO region Class I Area monitors in the years 2000-2004 and 2014-2018.

	Light Extinction (Mm^{-1})											
	Voyageurs NP			Boundary Waters			Isle Royale NP			Seney		
Parameter	2000-2004	2014-2018	Change	2000-2004	2014-2018	Change	2000-2004	2014-2018	Change	2000-2004	2014-2018	Change
Clearest Days												
Ammonium Sulfate	4.2	2.2	-47%	4.1	2.2	-47%	4.6	2.7	-41%	4.8	2.6	-47%
Ammonium Nitrate	0.8	0.4	-46%	0.7	0.4	-42%	0.7	0.4	-41%	0.8	0.5	-40%
Organic Mass	2.1	1.4	-35%	2.0	1.2	-41%	1.2	1.0	-20%	1.6	1.1	-30%
Elemental Carbon	0.6	0.3	-52%	0.6	0.2	-57%	0.4	0.2	-40%	0.5	0.2	-50%
Soil	0.1	0.0		0.1	0.0		0.1	0.1		0.1	0.1	
Coarse Mass	0.7	0.6	-14%	0.7	0.6	-12%	0.7	0.6	-20%	0.7	0.5	-24%
Sea Salt	0.1	0.2		0.1	0.1		0.1	0.2		0.1	0.1	
Total	**8.6**	**5.1**	**-41%**	**8.3**	**4.7**	**-43%**	**7.8**	**5.2**	**-34%**	**8.6**	**5.1**	**-41%**
Most Impaired Days												
Ammonium Sulfate	20.3	11.7	-42%	25.8	11.9	-54%	32.5	15.5	-52%	58.1	18.7	-68%
Ammonium Nitrate	20.7	14.1	-32%	20.1	14.4	-28%	21.3	16.8	-21%	28.1	22.9	-18%
Organic Mass	6.4	3.7	-41%	6.6	3.9	-41%	6.7	4.4	-35%	10.8	5.5	-49%
Elemental Carbon	2.4	1.4	-41%	2.5	1.4	-46%	3.1	1.7	-46%	3.9	2.2	-43%
Soil	0.3	0.2	-33%	0.4	0.2	-53%	0.3	0.2	-33%	0.5	0.2	-57%
Coarse Mass	1.6	1.4	-10%	1.5	1.4	-3%	2.1	1.7	-16%	1.6	1.4	-13%
Sea Salt	0.1	0.3		0.1	0.2		0.1	0.3		0.0	0.2	
Total	**51.7**	**32.9**	**-36%**	**57.0**	**33.4**	**-41%**	**66.1**	**40.6**	**-39%**	**102.9**	**51.2**	**-50%**



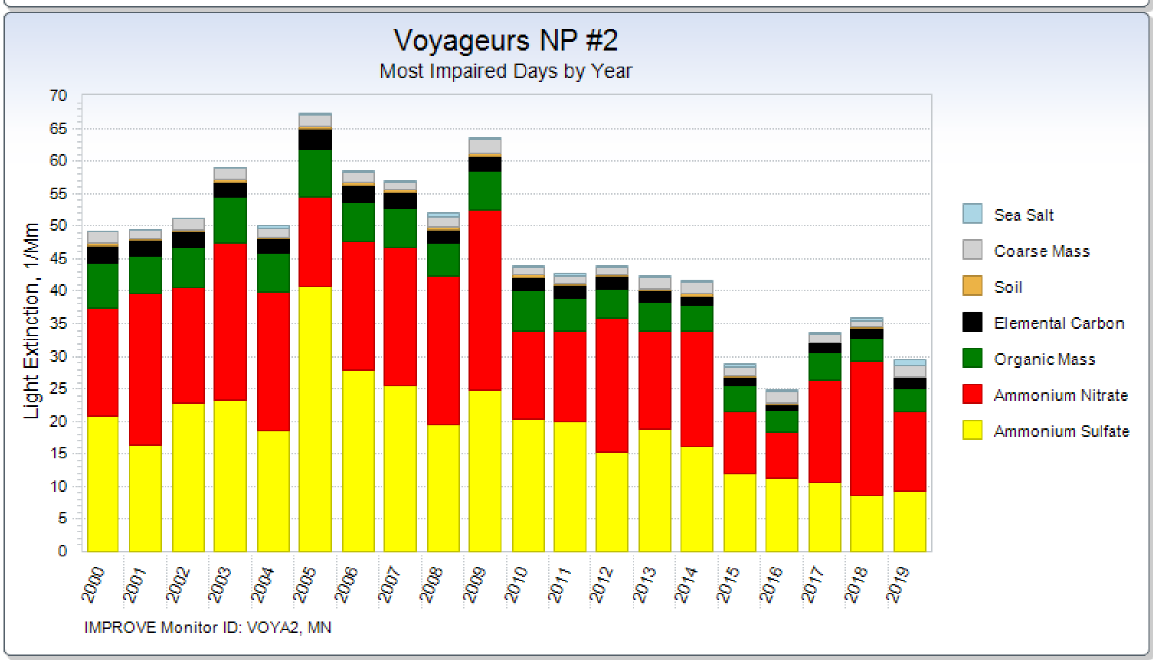


Figure 2-6. Composition of light extinction for Minnesota's Voyageurs National Park, shown for the clearest (top) and most impaired (bottom) days.

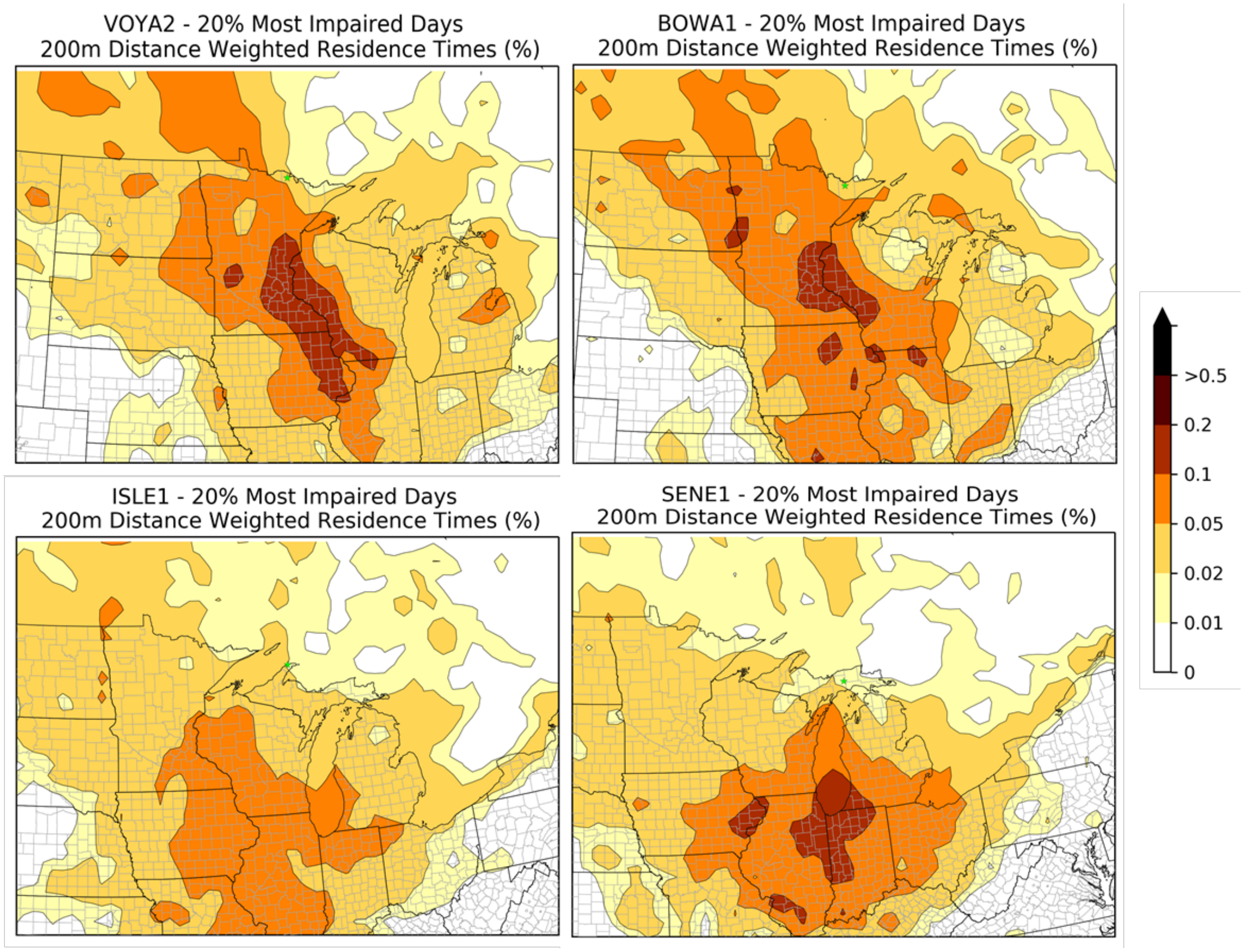


Figure 2-7. Distance weighted residence times for air masses reaching the four LADCO Class I areas on the 20% most impaired days for the years 2012 to 2016. Residence times were determined from 72-hour HYSPLIT back-trajectories ending at 200m altitude.[13]

[13] Residence time is the normalized cumulative time that trajectories reside in a specific geographic area, weighted by the distance from the receptor (end point). Analyses were conducted by Ramboll for the Central States Air Resource Agencies (CenSARA) using the 12-km North American Model (NAM) meteorology for hours 6, 12, 18 and 24. The project report is available in the electronic docket for this TSD. Additional figures for the LADCO Class I areas are available in the Supplemental Materials document. Complete results and figures are available at https://censara.org/ftpfiles/Ramboll/.

3 Air Quality Modeling Platform

This section describes the details of the regional air quality modeling platforms used by LADCO to estimate haze conditions in 2028. The models described in this section are gridded, Eulerian chemistry-transport models designed to simulate, among other things, the PM species that contribute to regional haze. An air quality modeling platform is the complete collection of data, software, and scripts required for conducting regional modeling simulations. Air quality models are a key decision support tool for air quality planning because they integrate our knowledge of air pollution into software to predict future atmospheric conditions based on forecast changes in emissions.

LADCO selected two base modeling years (2011 and 2016) from which to project visibility conditions in 2028. We used two base years for a few different reasons:

1. The 2011 base year modeling platform was the best available option at the start of the second implementation period
2. When the 2016 base year modeling platform became available in 2020 it represented an improvement to the emissions data, particularly for the stationary source projections to 2028
3. Using two meteorology years for modeling provides additional weight of evidence to the states for use in demonstrating progress under the RHR

The goal of this section is to describe the details of the model simulations, including the input data and software used by LADCO to calculate future year visibility. We will present model emissions summaries, model performance and results in subsequent sections of the document.

3.1 Modeling Years Justification

LADCO selected 2011 and 2016 as modeling years because they were available in U.S. EPA modeling platforms that included projections to 2028, the last year of the current regional haze implementation period. The U.S. EPA modeling platforms represented the state-of-the-science for the modeling software, and emissions and meteorology data. U.S. EPA used both platforms for their preliminary (US. EPA, 2017) and updated (U.S. EPA, 2019) regional haze modeling studies, providing further justification for selecting these years. LADCO chose to model two different base years to provide additional weight of evidence for our member states to use in their RHR reasonable progress SIPs.

The availability of emissions inventories with projections to 2028 was a major factor in selecting these two base years. The triennial National Emissions Inventory (NEI) was conducted for the year 2011. Since its first release in 2014, the NEI2011 underwent several revisions, with the final update to version 6.3 released in October 2017 as part of the U.S. EPA's preliminary regional haze modeling platform (US EPA, 2017). Given the use of 2011-based data for evaluating regional haze progress during this implementation period by the U.S. EPA (2017), Metro4/SESARM (2018), and the Ozone Transport Commission (OTC, 2018), LADCO believes that using 2011-based data and emissions projections is justified.

In 2017 a group of multi-jurisdictional organizations (MJOs), states, and EPA established 2016 as the new base year for a national air quality modeling platform[14]. The group concluded that if only one recent year could be selected, then 2016 would serve as a good base year because of fairly typical O_3 conditions and average wildfire conditions. Following from the base year recommendations from that group, several modeling centers, including U.S. EPA and LADCO, developed data and capabilities for simulating and evaluating air quality in 2016.

Following from the selection of 2016 as the base year for a national modeling platform, starting in late 2017, the MJOs, states, and EPA formed the National Emissions Inventory Collaborative to develop a 2016 emissions inventory and modeling platform. Over 200 participants collaborated across 12 workgroups to develop base and future year emissions to support upcoming regulatory modeling applications. This effort was designed to involve a broad group of air pollution emissions experts in the development of a new national emissions modeling platform. LADCO used the 2016 and 2028 inventories developed by the Collaborative for the modeling presented here because they were the most recent inventory data available at the initiation of this project.

LADCO selected 2028 as the future projection year because it aligns with the end of the second regional haze implementation period and is a comparison point in the uniform rate of progress toward natural visibility in 2064.

[14] Base Year Selection Workgroup Final Report

3.2 Electricity Generating Unit (EGU) Emissions Forecasts

LADCO relied upon U.S. EPA's inventory estimates from their 2011 and 2016 modeling platforms for most emissions sectors, as described in Sections 3.3.2 and 3.4.2. However, LADCO replaced the Integrated Planning Model (IPM) EGU inventories in the U.S. EPA 2011 and 2016 modeling platforms with inventories derived from the Eastern Regional Technical Advisory Committee (ERTAC) EGU model (MARAMA, 2012). The ERTAC EGU model for growth was developed around activity pattern matching algorithms designed to provide hourly EGU emissions data for air quality planning. The original goal of the model was to create low-cost software that air quality planning agencies could use for developing EGU emissions projections. States needed a model that did not produce large changes to the emissions forecasts with small changes in inputs. A key feature of the model includes data transparency; all of the inputs to the model are publicly available. The open source software includes documentation and a diverse user community to support new users of the software.

The ERTAC EGU model imports base year Continuous Emissions Monitoring (CEM) data for EGUs from U.S. EPA and sorts the data from the peak to the lowest generation hour. It applies hour specific growth rates that include peak and off-peak generation rates. The model then balances the system for all units and hours that exceed physical or regulatory limits by redistributing the power and associated emissions to underutilized units in the system. ERTAC EGU applies future year controls to the emissions estimates and tests for reserve capacity, generates quality assurance reports, and converts the outputs to Sparse Matrix Operator Kernel Emissions model (SMOKE)-ready files.

ERTAC EGU generates hourly future year emissions estimates. The model does not shutdown or mothball existing units because economics algorithms suggest they are not economically viable. Additionally, alternate control scenarios are easy to simulate with the model. Significant effort has been put into the model to prevent simulations from creating new coal plants to meet forecasted power demand. As an alternative, the model now allows portability of generation to different fuels like renewables and natural gas.

Differences between the IPM and ERTAC EGU emissions forecasts arise from alternative forecast algorithms, and from the data used to inform the model predictions.

3.2.1 2011 EGU Emissions Estimates

The 2011 based ERTAC EGU projections were the first year of estimates available from the ERTAC model. There were five different generations of improvements to the inputs, code, and methods in the model before the release of version 2.7 in 2017, which is the version used by LADCO for this application. Between 2011 and 2017 there were widespread shutdowns of coal EGUs across the country as natural gas and renewable generation integrated more widely into the power markets. During this period combined cycle natural gas plants changed from mostly handling peak loads to serving as base load EGUs. ERTAC EGU 2.7 reflected the transformation in the U.S power sector away from coal to less carbon intensive fuels.

3.2.2 2016 EGU Emissions Estimates

The IPM forecasts used for the U.S. EPA "2016fh" modeling platform were updated based on comments from states and stakeholders received through April 2019. LADCO replaced the IPM EGU forecasts in our modeling with ERTAC EGU version 16.1. The ERTAC EGU 16.1 forecasts used CEM data from 2016 and state-reported changes to EGUs received through September 2020. The LADCO-modified ERTAC EGU 16.1 emissions used for this modeling application represent the best available information on EGU forecasts for the Midwest and Eastern U.S. available in September 2020.

3.2.3 2028 EGU Emissions Forecasts

LADCO used ERTAC 16.1 forecasts to estimate 2028 EGU emissions. Figure 3-1 shows the ERTAC 16.1 2028 emissions projections for NOx and SO_2 as a circle plot. The size of the circles in the plot reflect the magnitude of the annual total future year emissions at individual EGU sources in the LADCO region. Figure 3-2 shows the EGU facility specific SO_2 emissions changes between 2016 and 2028 as forecast by ERTAC EGU 16.1. Red bubbles indicate lower emissions in 2028, while blue bubbles indicate higher emissions in 2028. The emissions increases are projected to occur primarily at natural gas EGUs to offset the lost generation capacity from the coal unit shutdowns. There were no new coal units in the LADCO region forecast by ERTAC EGU from 2016 to 2028.

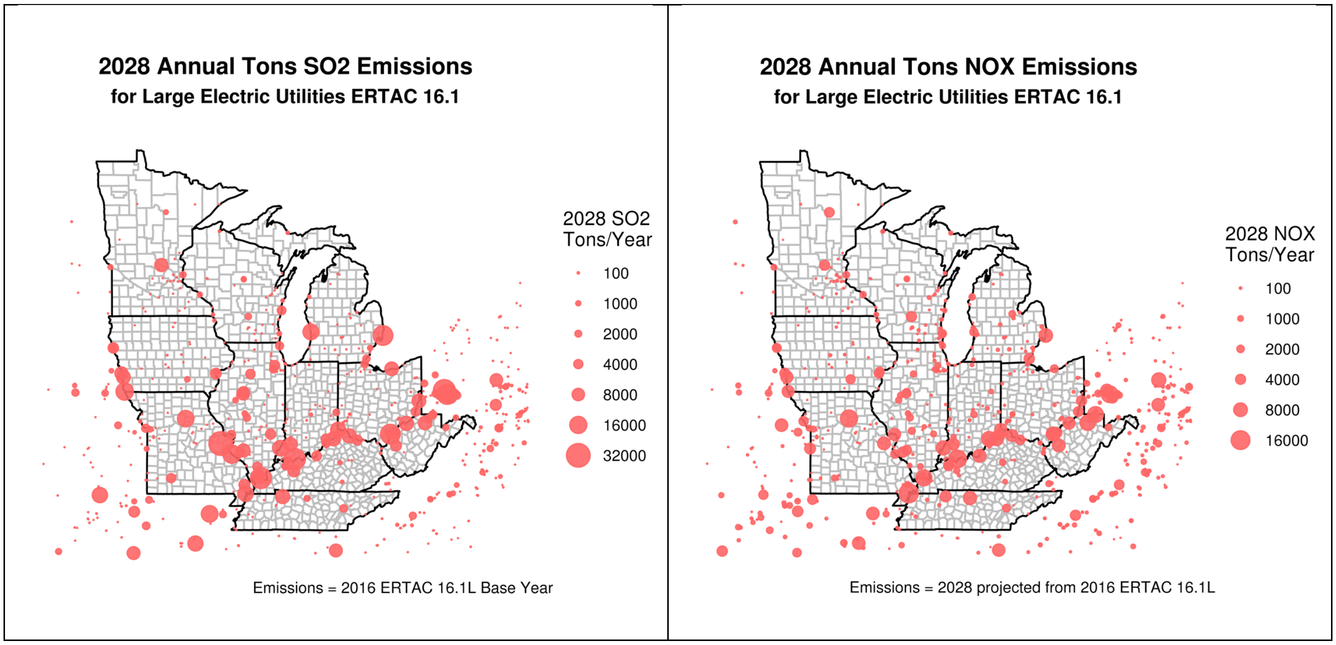


Figure 3-1. ERTAC EGU 16.1 2028 SO_2 (l) and NOx (r) emissions bubble plots

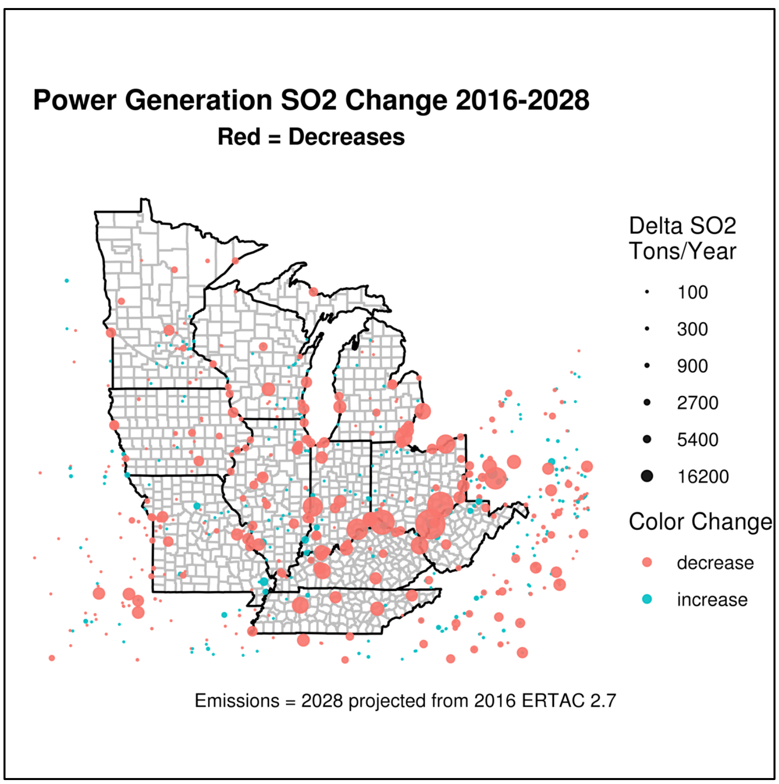


Figure 3-2. ERTAC EGU 16.1 SO_2 emissions difference (2016-2028) bubble plot

3.3 2011 Modeling Platform

LADCO based our 2011 modeling platform on the data and software used by the U.S. EPA for their Preliminary 2028 Regional Haze Modeling (U.S. EPA, 2017). EPA projected the 2011 base year emissions to 2028 to forecast regional haze conditions in the Class I areas. The components of the 2011 modeling platform are described below and in greater detail by U.S. EPA (2016a; 2016b).

3.3.1 Air Quality Model Configuration

LADCO used CAMx 6.40 (Ramboll, 2018) as the photochemical grid model for this application. CAMx is a three-dimensional, Eulerian air quality model that simulates the chemical transformation and physical transport processes of air pollutants in the troposphere. It includes capabilities to estimate the concentrations of primary and secondary gas and particle phase air pollutants, and dry and wet deposition, from urban to continental spatial scales. As CAMx associates source-level air pollution emissions estimates with air pollution concentrations, it can be used to design and assess emissions reduction strategies pursuant to NAAQS attainment goals.

LADCO selected CAMx for this study because it is a component of recent U.S. EPA modeling platforms for investigating the drivers of regional haze in the U.S. As CAMx is a component of U.S. EPA studies with a similar scope to this project (e.g., U.S. EPA, 2017), LADCO was able to leverage the data and software elements that are distributed with recent U.S. EPA regulatory modeling platforms. Using these elements saved LADCO significant resources relative to building a modeling platform from scratch.

Figure 3-3 shows the U.S. EPA modeling domain for the continental U.S. A 12-km uniform grid (12US2) covers all of the continental U.S. and includes parts of Southern Canada and Northern Mexico. The domain has 35 vertical layers with a model top at about 17,550 meters (50 mb). LADCO used the same 12US2 domain for this project because it supported the use of meteorology, initial and boundary conditions, and emissions data that were readily available from U.S. EPA.

Table 3-1 summarizes the CAMx science configurations and options LADCO used for the 2011 and 2028 CAMx modeling for this application. We used the Piecewise Parabolic Method (PPM) advection solver for horizontal transport along with the spatially varying (Smagorinsky) horizontal diffusion approach. We used K-theory for vertical diffusion using the CMAQ-like vertical diffusivities from WRFCAMx. The CB6r4 gas-phase chemical mechanism was selected because it includes the latest chemical kinetic rates and represents improvements over the other alternative CB05 and SAPRC chemical mechanisms as well as active methane chemistry. Additional CAMx inputs were as follows:

Meteorological Inputs: LADCO used the U.S. EPA 2011 WRF data for this study (US EPA, 2014). The U.S. EPA used version 3.4 of the WRF model, initialized with the 12-km North American Model (NAM) from the National Climatic Data Center (NCDC) to simulate 2011 meteorology. U.S. EPA prepared the WRF data for input to CAMx with version 4.3 of the WRFCAMx software.

Initial/Boundary Conditions: LADCO used 2011 initial and boundary conditions for CAMx generated by the U.S. EPA from the GEOS-Chem Global Chemical Transport Model (US EPA, 2017). EPA generated hourly, one-way nested boundary conditions (i.e., global-scale to regional-scale) from a 2011 2.0 degree x 2.5 degree GEOS-Chem simulation. Following the convention of the U.S. EPA regional haze modeling, LADCO used year 2011 GEOS-Chem boundary conditions for modeling 2028 air quality with CAMx.

Photolysis Rates: LADCO prepared the photolysis rate inputs as well as albedo/haze/ozone/snow inputs for CAMx. Day-specific O_3 column data were based on the Total Ozone Mapping Spectrometer (TOMS) data measured using the satellite-based Ozone Monitoring Instrument (OMI). Albedo were based on land use data. For CAMx there is an ancillary snow cover input that will override the land use-based albedo input. LADCO used the TUV photolysis rate processor to prepare clear-sky photolysis rates for CAMx. If there were periods of more than a couple of days where daily TOMS data were unavailable in 2011, the TOMS measurements were interpolated between the days with valid data; in the case where large periods of TOMS data were missing, monthly average TOMS data were used. CAMx was also configured to use the in-line TUV to adjust for cloud cover and account for the effects that modeled aerosol loadings have on photolysis rates; this latter effect on photolysis may be especially important in adjusting the photolysis rates due to the occurrence of particulate matter (PM) concentrations associated with emissions from fires.

Landuse: LADCO used landuse/landcover data from the U.S. EPA WRF simulation.

Spin-Up Initialization: LADCO used a minimum of ten days of model spin up (e.g., December 21-31, 2010) for the 12 km modeling domain. LADCO ran monthly CAMx simulations, initializing each month with a 10-day spin-up period.

LADCO used CAMx to simulate the entire year for 2011 and 2028. LADCO selected a CAMx configuration that was consistent with previous regional haze modeling applications performed by LADCO and U.S. EPA. U.S. EPA (2017) provides complete details of their 2011 CAMx simulation, including a performance evaluation.

Table 3-1. LADCO 2011 and 2016 CAMx modeling platform configurations

Science Options	CAMx 2011 Configuration	CAMx 2016 Configuration
Model Codes	CAMx v6.40	CAMx v7.0
Simulation Period	December 21, 2010 – December 31, 2011	December 21, 2015 – December 31, 2016
Horizontal Grid Mesh	12 km, 396 col x 246 rows	12 km, 396 col x 246 rows
Vertical Grid Mesh	25 CAMx layers collapsed from 35 WRF layers	35 WRF layers (no collapsing)
Grid Interaction	None	None
Initial Conditions	10 day spin-up on 12 km grid	10 day spin-up on 12 km grid
Boundary Conditions	12km from GEOS-Chem	12km from hemispheric CMAQ
Emissions		
Baseline Emissions Processing	Sparse Matrix Operator Kernel Emissions (SMOKE), EPA's MOtor Vehicle Emission Simulator (MOVES) and Biogenic Emission Inventory System (BEIS)	
Emissions Modeling Platform	U.S. EPA 2011 "EN" with ERTAC 2.7 EGU Point and hourly CEMs	U.S. EPA 2016 "FH" Platform with ERTAC 16.1 EGU Point and hourly CEMs
Chemistry		
Gas Phase Chemistry	CB6r4	CB6r4
Aerosol Chemistry	CF + SOAP	CF + SOAP
Meteorology		
Model Codes	WRF v3.4	WRF v3.8
Meteorological Processor	WRFCAMx v4.3	WRFCAMx v4.6
Horizontal Diffusion	Spatially varying	Spatially varying
Vertical Diffusion	CMAQ-like in WRF2CAMx	CMAQ-like in WRF2CAMx
Diffusivity Lower Limit	Kz_min = 0.1 to 1.0 m^2/s or 2.0 m^2/s	Kz_min = 0.1 to 1.0 m^2/s or 2.0 m^2/s
Dry Deposition	Zhang dry deposition scheme (CAMx)	Zhang dry deposition scheme (CAMx)
Wet Deposition	CAMx-specific formulation	CAMx-specific formulation
Gas Phase Chemistry Solver	Euler Backward Iterative (EBI) -- Fast Solver	Euler Backward Iterative (EBI) -- Fast Solver

Science Options	CAMx 2011 Configuration	CAMx 2016 Configuration
Vertical Advection Scheme	Implicit scheme w/ vertical velocity update (CAMx)	Implicit scheme w/ vertical velocity update (CAMx)
Horizontal Advection Scheme	Piecewise Parabolic Method (PPM) scheme	Piecewise Parabolic Method (PPM) scheme
Integration Time Step	Wind speed dependent	Wind speed dependent
Source Apportionment	PSAT with 26 state and region tags	

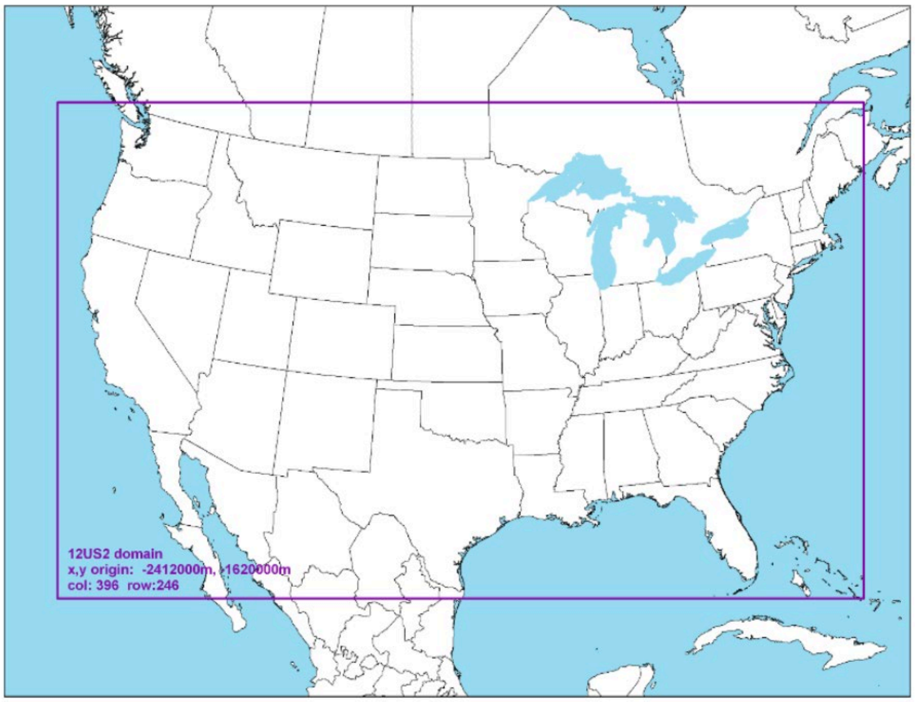


Figure 3-3. CAMx 12-km modeling domain (12US2)

3.3.2 2011 and 2028 Emissions Data

LADCO based the 2011 and 2028 emissions data for this study on the U.S. EPA 2011v6.3 (“EN”) emissions modeling platform (US EPA, 2017b). U.S. EPA generated this platform for their assessment of interstate transport for the 2015 O_3 NAAQS (U.S. EPA, 2016a), and used these data for their preliminary regional haze modeling for Round 2 of the RHR (U.S. EPA, 2017a). LADCO also used these data in support of our member states’ interstate transport SIPs for the 2015 ozone NAAQS (LADCO, 2018). While the U.S. EPA made several changes to the forecasted 2028 emissions in the “EN” platform relative to the earlier “EL” platform, the changes to the base year (2011) model between the two platforms were minor (US EPA, 2017b).

LADCO replaced the EGU emissions in the U.S. EPA EN platform with 2028 EGU forecasts estimated with the ERTAC EGU Tool version 2.7 (MARAMA, 2012), as described in Section 3.2. Since there are differences in the way that EGUs are classified in ERTAC and U.S. EPA's IPM, LADCO used ERTAC's 2028 non-EGU point inventory to replace the same sector in U.S. EPA's 2011 EN modeling platform. We used the U.S. EPA EN platform emissions estimates for all other inventory sectors. Table 3-2 shows the 2011 and 2028 inventory components used by LADCO to forecast regional haze.

Table 3-2. LADCO 2011 emissions modeling platform inventory components

Sector	Abbreviation	Base Year Data Source	Future Year Data Source
Agriculture	ag	U.S. EPA 2011ek	U.S. EPA 2028el
Area and Fugitive Dust	afdust	U.S. EPA 2011ek	U.S. EPA 2028el
Biogenic	beis	U.S. EPA 2011en	U.S. EPA 2011en
C1/C2 Commercial Marine	cmv_c1c2	U.S. EPA 2011en	U.S. EPA 2028en
C3 Commercial Marine	cmv_c2	U.S. EPA 2011en	U.S. EPA 2028en
Nonpoint	nonpt	U.S. EPA 2011en	U.S. EPA 2028en
Offroad Mobile	nonroad	U.S. EPA 2011en	U.S. EPA 2028en
Nonpoint Oil & Gas	np_oilgas	U.S. EPA 2011ek	U.S. EPA 2028en
Onroad Mobile	onroad	U.S. EPA 2011el	U.S. EPA 2028en
Point Oil & Gas	pt_oilgas	U.S. EPA 2011ek	U.S. EPA 2028en
Electricity Generation	ptegu	U.S. EPA 2011el	ERTAC EGU 2.7
Industrial Point	ptnonipm	U.S. EPA 2011en	MARAMA 2011v2[15]
Rail	rail	U.S. EPA 2011ek	U.S. EPA 2028el
Residential Wood Combustion	rwc	U.S. EPA 2011ek	U.S. EPA 2028el
Agricultural Fires	ptagfire	U.S. EPA 2011ek	U.S. EPA 2011ek
Wild and Prescribed Fires	ptfire	U.S. EPA 2011ek	U.S. EPA 2011ek
Mexico Anthropogenic	Multiple	U.S. EPA 2011ek	U.S. EPA 2011ek
Canada Anthropogenic	Multiple	U.S. EPA 2011en	U.S. EPA 2011en

3.4 2016 Modeling Platform

3.4.1 Air Quality Model Configuration

LADCO based our CAMx air quality modeling platform for this application on the configuration that the U.S. EPA used for their updated regional haze modeling (US EPA, 2019b). LADCO used CAMx 7.0 (Ramboll, 2020) as the photochemical grid model for this application. Similar to the 2011 modeling

[15] MARAMA developed a non-EGU point inventory for use with the ERTAC EGU2.7 emissions from the 2011NEIv2

platform, LADCO was able to leverage data and software elements that U.S. EPA distributed for regulatory rulemaking.

The LADCO 2016 CAMx modeling used a similar configuration as the 2011 modeling platform. The horizontal domains are the same between the two simulations (12US2 modeling domain). The 2016 CAMx simulation used all 35 of the WRF vertical layers with no layer collapsing.

Table 3-1 summarizes the CAMx science configurations and options LADCO used for the 2016 and 2028 CAMx modeling for this application. We used the Piecewise Parabolic Method (PPM) advection solver for horizontal transport along with the spatially varying (Smagorinsky) horizontal diffusion approach. We used K-theory for vertical diffusion using the CMAQ-like vertical diffusivities from WRFCAMx. The CB6r4 gas-phase chemical mechanism was selected because it includes the latest chemical kinetic rates and represents improvements over the other alternative CB05 and SAPRC chemical mechanisms as well as active methane chemistry. Additional CAMx inputs were as follows:

Meteorological Inputs: LADCO used the U.S. EPA 2016 WRF data for this study (US EPA, 2019c). The U.S. EPA used version 3.8 of the WRF model, initialized with the 12-km North American Model (NAM) from the National Climatic Data Center (NCDC) to simulate 2016 meteorology. Complete details of the WRF simulation, including the input data, physics options, and four-dimensional data assimilation (FDDA) configuration are detailed in the Meteorology Model Performance for Annual 2016 Simulation WRFv3.8 report (US EPA, 2019c). LADCO prepared the WRF data for input to CAMx with version 4.6 of the WRFCAMx software.

Initial/Boundary Conditions: LADCO used 2016 initial and boundary conditions for CAMx generated by the U.S. EPA from a northern hemisphere simulation of the Community Multiscale Air Quality (CMAQ) model (US EPA, 2019d). EPA generated hourly, one-way nested boundary conditions (i.e., hemispheric-scale to regional-scale) from a 2016 108-km x 108-km polar stereographic CMAQ simulation of the northern hemisphere. Following the convention of the U.S. EPA 2016 regional haze modeling (U.S. EPA, 2019b), LADCO used year 2016 CMAQ boundary conditions for modeling 2016 and 2028 air quality with CAMx.

Photolysis Rates: LADCO prepared the photolysis rate inputs in the same manner as for the 2011 modeling platform described above.

Landuse: LADCO used landuse/landcover data from the U.S. EPA WRF 2016 simulation.

Spin-Up Initialization: A minimum of ten days of model spin up (e.g., December 21-31, 2015) was used for the 12 km modeling domain. LADCO ran quarterly CAMx simulations, initializing each quarter with a 10-day spin-up period.

LADCO used CAMx to simulate the entire year for 2016 and 2028. LADCO selected a CAMx configuration that was consistent with previous regional haze modeling applications performed by U.S. EPA. U.S. EPA (2019b) provides complete details of their 2016 CAMx simulation, including a performance evaluation.

3.4.2 2016 and 2028 Emissions Data

LADCO collected 2016 and 2028 emissions data for this study primarily from the U.S. EPA 2016 v1 ("2016fh_16") emissions modeling platform (U.S. EPA, 2020). U.S. EPA and the 2016 Emissions Inventory Collaborative[16] generated this platform for use in O_3 NAAQS and Regional Haze SIPs.

In addition to a base year emissions estimate for use in a model performance evaluation, LADCO developed a typical-year emissions estimate for comparison with the 2028 forecast (see Section 4.2.3). The typical emissions included three taconite facility industrial point sources. All three sources temporarily shut down in 2016 and restarted operations in 2017, and are included in the 2028 inventory. LADCO also removed an emissions record from the 2016 inventory for the Wisconsin Rapids wastewater treatment facility that incorrectly added 5,000 tons/year of NOx to the inventory for this source. Table 3-3 shows the sources in Minnesota that LADCO included in the typical year emissions that are not included in the 2016 actual base year emissions.

Table 3-3. LADCO typical year inventory sources

Facility	State	NOx Emissions (tons/year)	SO_2 Emissions (tons/year)
US Steel Keetac	MN	5,009	533
Northshore Mining Silver Bay	MN	785	151
United Taconite Fairlane	MN	374	275

[16] http://views.cira.colostate.edu/wiki/wiki/10202

LADCO replaced the 2028 EGU emissions in the U.S. EPA "2016fh" emissions modeling platform with 2028 EGU forecasts estimated with the ERTAC EGU Tool version 16.1 (MARAMA, 2012), as discussed above. LADCO also used the ERTAC non-EGU point inventory in our 2016 modeling platform to ensure consistency with the EGU sector.

Figure 3-4 through Figure 3-9 show 2016 daily total EGU NOx emissions by fuel type for each of the LADCO states. These figures show that in 2016 the NOx emissions from power generation in the LADCO region were primarily emitted by sources that burn coal, that there is significant day to day variation in power plant emissions, and that the summer and winter seasons are the peak periods of EGU NOx emissions.

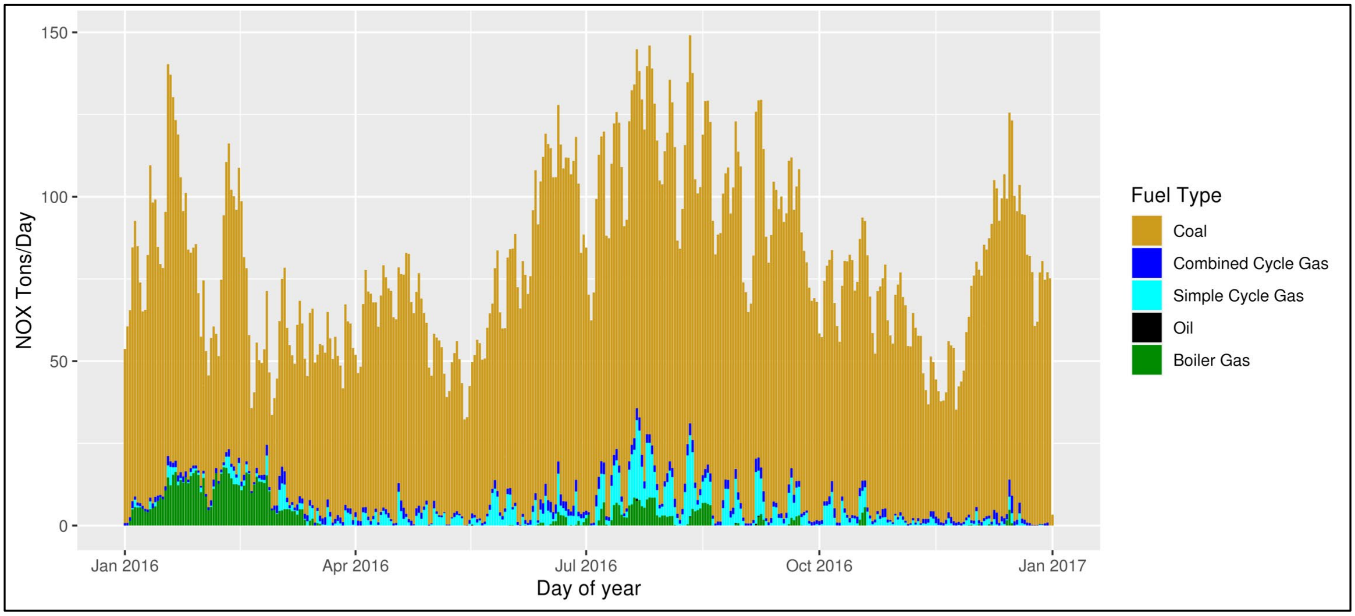


Figure 3-4. Illinois power generation 2016 daily NOx emissions by fuel type

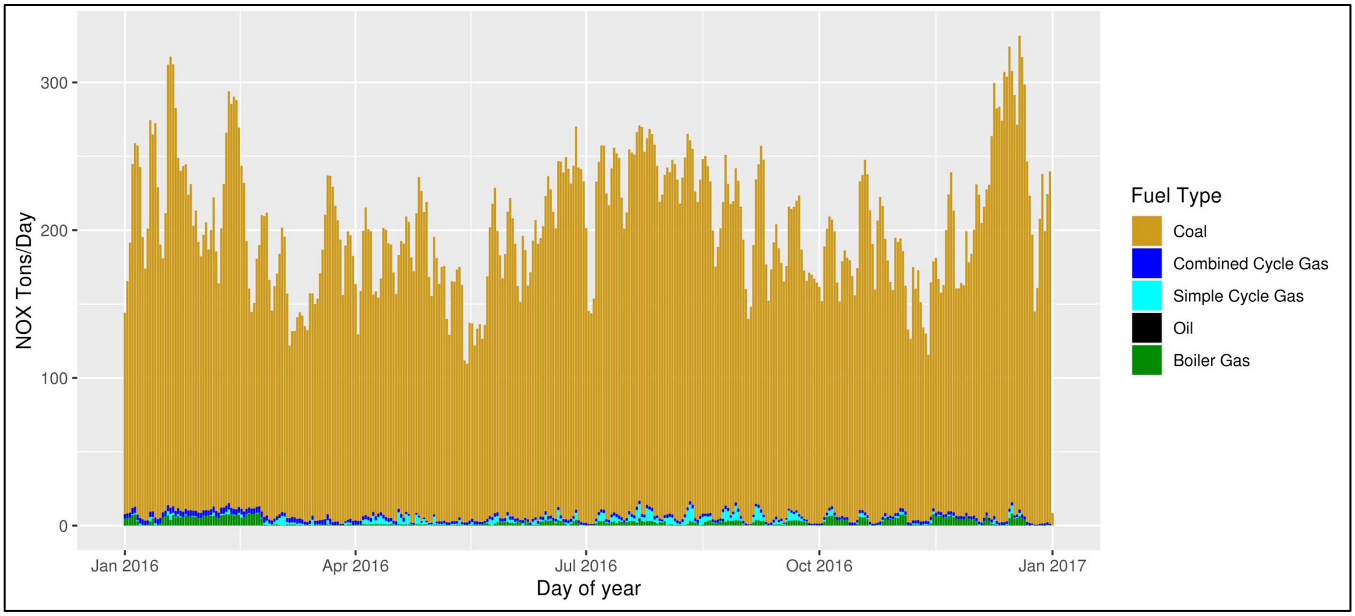


Figure 3-5. Indiana power generation 2016 daily NOx emissions by fuel type

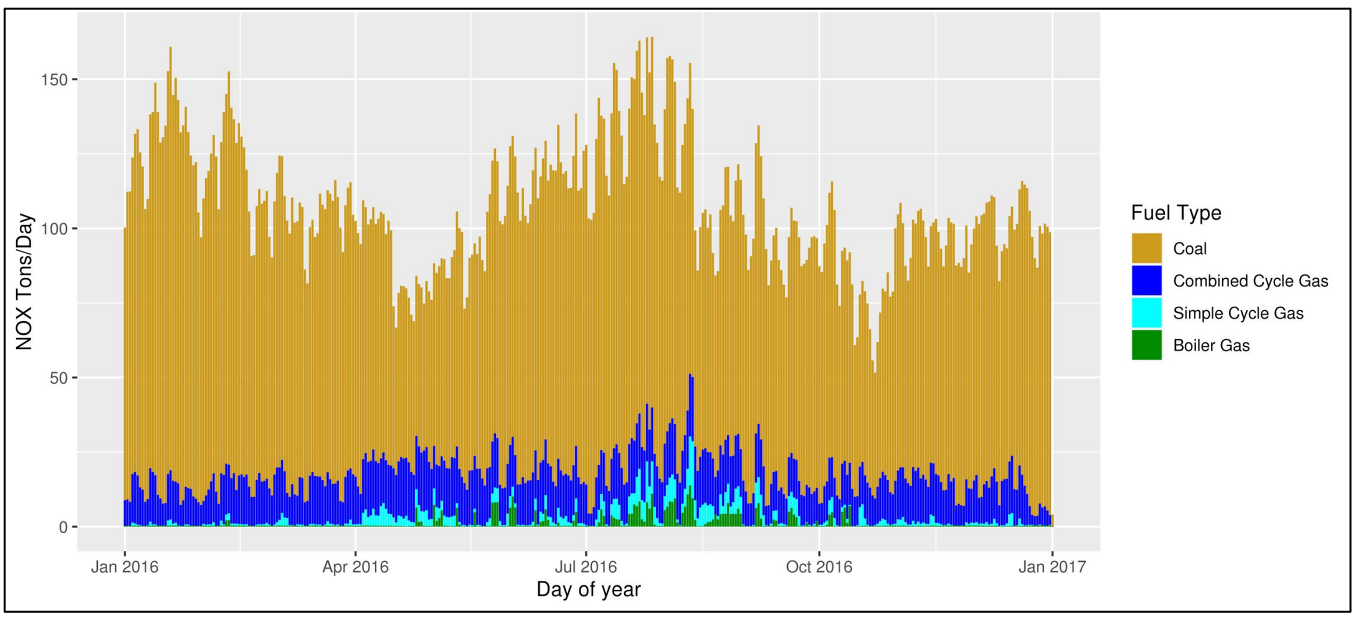


Figure 3-6. Michigan power generation 2016 daily NOx emissions by fuel type

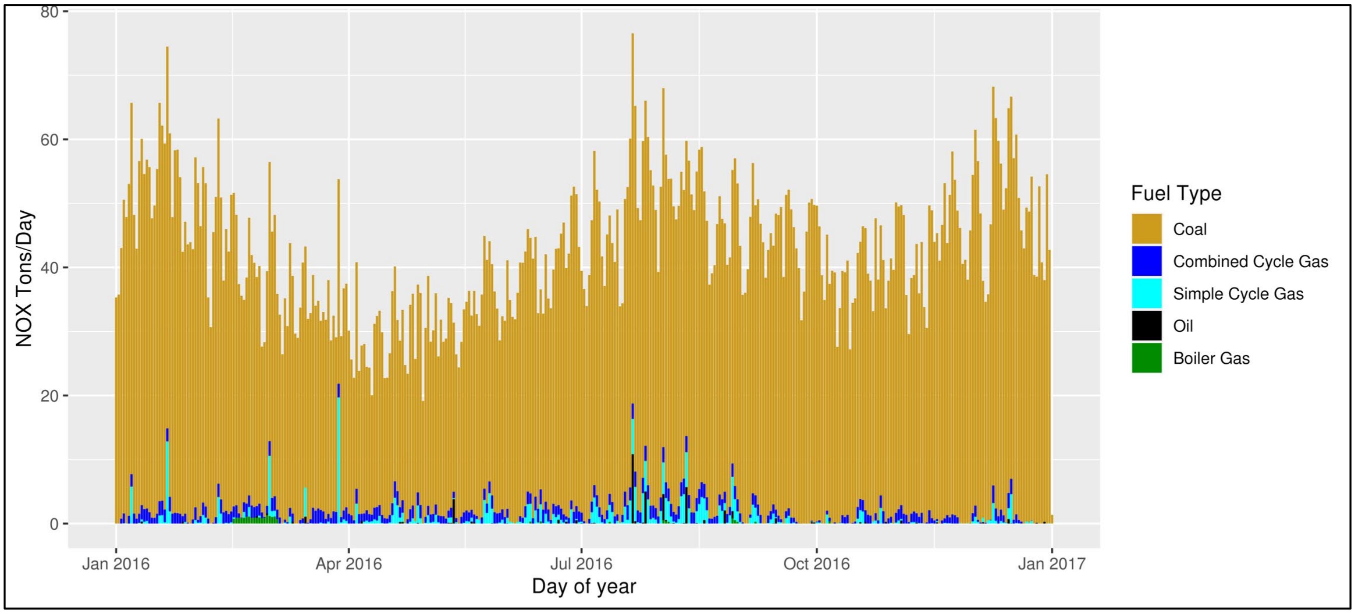


Figure 3-7. Minnesota power generation 2016 daily NOx emissions by fuel type

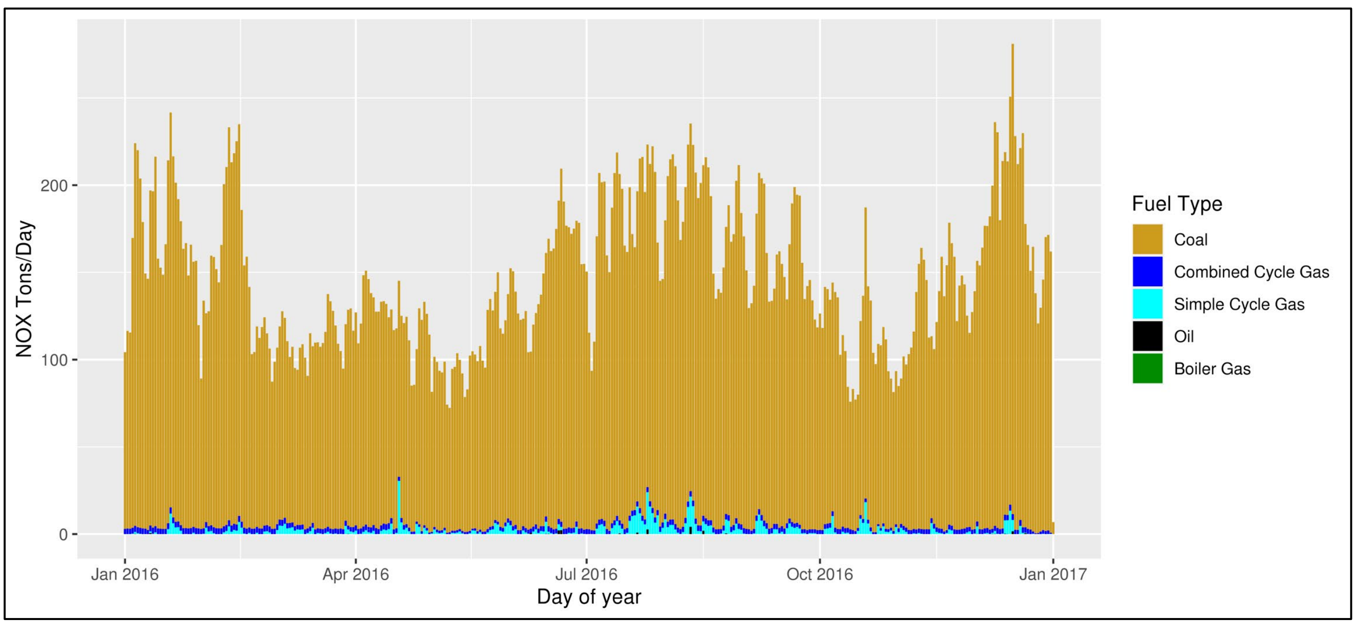


Figure 3-8. Ohio power generation 2016 daily NOx emissions by fuel type

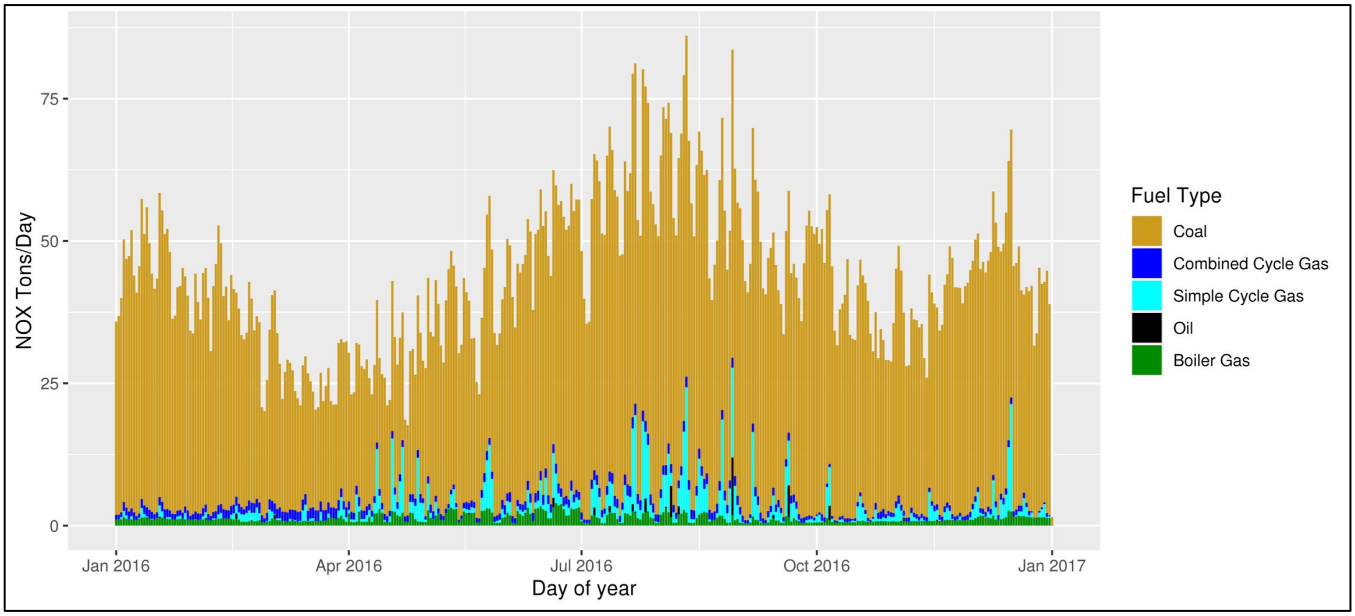


Figure 3-9. Wisconsin power generation 2016 daily NOx emissions by fuel type

LADCO modified the ERTAC EGU 16.1 inventory forecasts for 2028 for the 2016 base year modeling to exclude the emissions from 62 EGU units that announced shutdowns that will occur before 2028. These announcements came after the ERTAC EGU 16.1 emissions were developed. LADCO zeroed out the 2028 emissions from these units in our 2016-based modeling forecasts for 2028. Supplemental materials Section S3 lists the additional units that LADCO removed from our 2016-based 2028 modeling.

Figure 3-10 compares 2016 and 2028 daily total SO_2 emissions from all EGUs in the LADCO region. The two lines in the figure illustrate the daily temporal variability in SO_2 emissions from electricity generating point sources across the LADCO region.

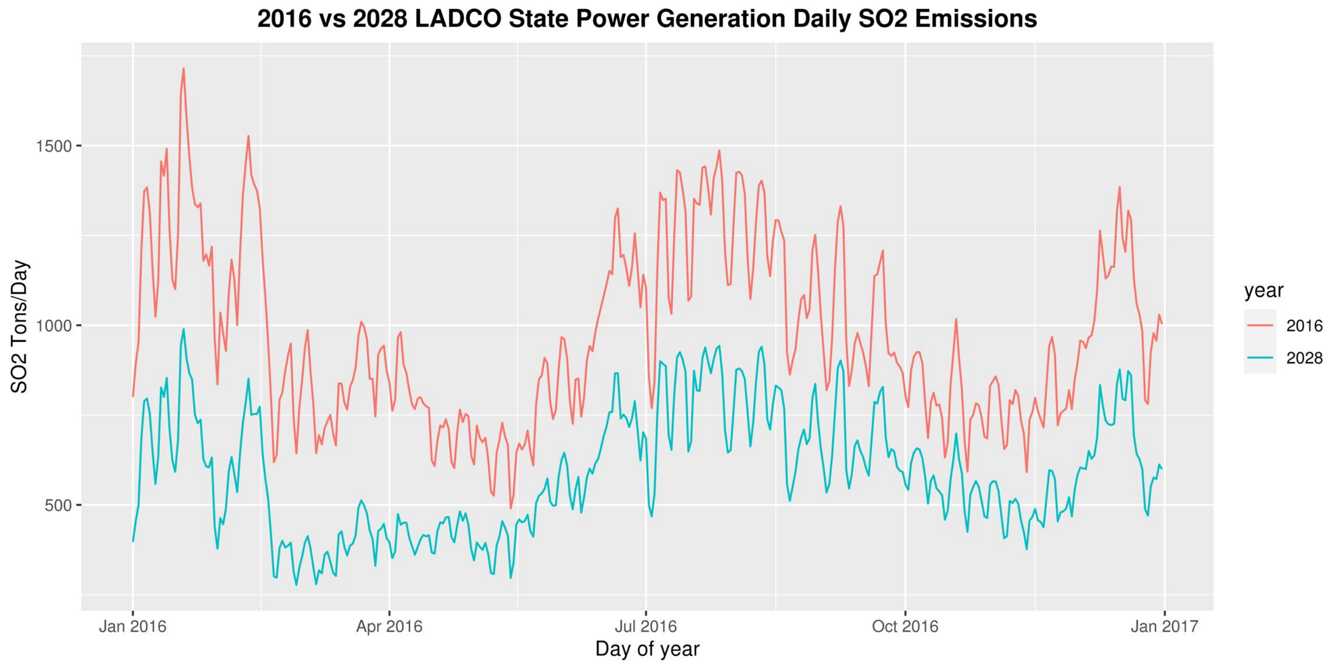


Figure 3-10. Daily total LADCO region SO_2 emissions from EGUs in 2016 and 2028

The Electronic Docket to this TSD includes a spreadsheet with point source facility (EGU and non-EGU) annual emissions totals for 2016 and 2028.

Table 3-4 lists the 2016 base year and 2028 future year inventory components that LADCO used to simulate 2016 and 2028 air quality for this application.

Table 3-4. LADCO 2016 emissions modeling platform inventory components

Sector	Abbreviation	Base Year Data Source	Future Year Data Source
Agriculture	ag	U.S. EPA 2016fh	U.S. EPA 2028fh
Fugitive Dust	afdust	U.S. EPA 2016fh	U.S. EPA 2028fh
Airports	airports	U.S. EPA 2016fi	LADCO 2028v1b
Biogenic	beis	U.S. EPA 2016fh	U.S. EPA 2016fh
C1/C2 Commercial Marine	cmv_c1c2	U.S. EPA 2016fh	U.S. EPA 2028fh
C3 Commercial Marine	cmv_c2	U.S. EPA 2016fh	U.S. EPA 2028fh
Nonpoint	nonpt	U.S. EPA 2016fh	U.S. EPA 2028fh
Offroad Mobile	nonroad	U.S. EPA 2016fh	U.S. EPA 2028fh
Nonpoint Oil & Gas	np_oilgas	U.S. EPA 2016fh	U.S. EPA 2028fh
Onroad Mobile	onroad	U.S. EPA 2016fh	U.S. EPA 2028fh
Point Oil & Gas	pt_oilgas	U.S. EPA 2016fh	U.S. EPA 2028fh
Electricity Generation	ptertac	ERTAC 16.1	ERTAC 16.1
Industrial Point	ptnonertac	U.S. EPA 2016fh	MARAMA 16.1 2028
Minnesota Taconite	ptmntaconite	Provided by MPCA	Provided by MPCA
Rail	rail	U.S. EPA 2016fh	U.S. EPA 2028fh
Residential Wood Combustion	rwc	U.S. EPA 2016fh	U.S. EPA 2028fh
Agricultural Fires	ptagfire	U.S. EPA 2016fh	U.S. EPA 2016fh
Wild and Prescribed Fires	ptfire	U.S. EPA 2016fh	U.S. EPA 2016fh
Mexico Anthropogenic	othar/othpt/	U.S. EPA 2016fh	U.S. EPA 2028fh
Canada Anthropogenic	othar/othpt	U.S. EPA 2016fh	U.S. EPA 2028fh

3.5 Source Apportionment Modeling

LADCO used the CAMx Particulate Matter Source Apportionment Tool (PSAT) to calculate emissions tracers for identifying upwind sources of haze at downwind monitoring sites.

3.5.1 2011 Source Apportionment Configuration

LADCO configured CAMx to use the point source override option in PSAT for tagging states, regions, and inventory sectors for the 2011-based 2028 simulation. LADCO applied state and region tags in the emissions processing sequence rather than using a geographic spatial mask of the emissions data. This approach ensures that the emissions for each source area are accurately apportioned to the state in which they are located. LADCO modified the U.S. EPA 2023en U.S. Source Apportionment (USSA) emissions modeling platform, and applied it to the "EN" 2028 modeling platform to prepare emissions for this simulation. Table 3-5 lists the 26 tags used in the simulation.

For this simulation, LADCO used PSAT to trace the PM and haze impacts from primary and secondary nitrate and sulfate precursors, primary and secondary organic aerosols, and soil dust.

Table 3-5. LADCO CAMx 2028_{2011} PSAT tags

Tag	Description	Tag	Description
1	Biogenic	14	KS
2	IL	15	NE
3	WI	16	ND
4	IN	17	SD
5	OH	18	WV
6	MI	19	KY
7	MN	20	ME, NH, VT, MA, RI, CT, NY, NJ, PA, DE, MD, DC
8	IA	21	VA, NC, SC, TN, GA, AL, MI, FL
9	MO	22	NM, AZ, CO, UT, WY, MT, ID, WA, OR, CA, NV
10	AR	23	Canada/Mexico
11	LA	24	Fire
12	TX	25	Offshore
13	OK	26	Tribes

3.5.2 2016 Source Apportionment Configuration

For the 2016-based 2028 PSAT simulation LADCO used a combination of a geographic spatial mask to tag states and regions, and the CAMx point source override option to tag individual point sources and inventory source groups. Table 3-6 lists the PSAT tags used for the 2016-based 2028 CAMx simulation. PSAT tags 2 through 15 used a geographic spatial mask of the 12-km modeling grid to apportion emissions to the states and regions. Emissions in grid cells with fractional coverage across multiple states were assigned to the state with the dominant coverage in the grid cell. PSAT tags 16 through 25 were used to tag emissions from specific point sources and source groups, including commercial marine, fires, and industrial point sources in Indiana (tags 18-25). Appendix C lists the NAICS and SCC codes associated with each of the PSAT tags for the Indiana point sources.

For this simulation, LADCO used PSAT to trace the PM and haze from primary and secondary nitrate and sulfate precursors, primary carbonaceous aerosols, and soil dust. LADCO used two source groups to distinguish anthropogenic and biogenic sources within each of the tags. LADCO did not use the CAMx PSAT organic aerosol tracer for this simulation.

Table 3-6. LADCO CAMx 2028_{2016} PSAT tags

Tag	Description	Tag	Description
1	Other	14	NM, AZ, CO, UT, WY, MT, ID, WA, OR, CA, NV, ND, SD
2	IL	15	Canada/Mexico
3	WI	16	Commercial Marine (C1/C2/C3)
4	IN	17	Fires
5	OH	18	Rockport EGU (IN)
6	MI	19	Gibson EGU (IN)
7	MN	20	All other IN EGUs
8	IA	21	IN Cement Manufacturing
9	MO	22	IN Iron and Steel
10	TX	23	IN Plastics and Resin
11	LA, OK, KS, NE, AR	24	IN Aluminum Production
12	ME, NH, VT, MA, RI, CT, NY, NJ, PA, DE, MD, DC	25	All other IN point sources
13	WV, KY, VA, NC, SC, TN, GA, AL, MI, FL		

3.6 CAMx Model Performance Evaluation Approach

This section describes the approaches LADCO took to evaluate CAMx model performance. Section 6 describes the results of this evaluation. The CAMx model performance evaluation (MPE) presented here focuses on PM and haze species at surface monitors in and near the LADCO region. As this TSD is focused on regional haze, particular attention is paid to model performance at monitors in the Class I areas. LADCO used the Atmospheric Model Evaluation Tool (AMET) version 1.3 to pair the model results and surface observations in space and time, generate bi-variate statistics of model performance, and to produce MPE plots.

LADCO evaluated the CAMx 2011 and 2016 modeled PM concentrations and reconstructed visibility against concurrent measured surface ambient concentrations using graphical displays of model performance and statistical model performance measures. LADCO compared the statistical measures against established model performance goals and criteria following the procedures recommended in EPA's photochemical modeling guidance documents (e.g., EPA, 2018).

3.6.1 Available Ambient Monitoring Data for the Model Evaluation

LADCO used the following routine air quality measurement data networks operating in in 2011 and 2016 to assess CAMx model performance:

EPA AQS Surface Air Quality Data: Data files containing hourly-averaged concentration measurements at a wide variety of state and EPA monitoring networks are available in the Air Quality System (AQS) database throughout the U.S. The AQS consists of many sites that tend to be mainly located in and near major cities. The standard hourly AQS AIRS monitoring stations typically measure hourly ozone, NO_2, NOx and CO concentration and there are thousands of sites across the U.S. The Federal Reference Method (FRM) network measures 24-hour total $PM_{2.5}$ mass concentrations using a 1:3 day sampling frequency, with some sites operating on an everyday frequency. The Chemical Speciation Network (CSN) measures speciated $PM_{2.5}$ concentrations including sulfate (SO_4), nitrate (NO_3), ammonium (NH_4), elemental carbon (EC), organic carbon (OC), and elements at 24-hour averaging time period using a 1:3 or 1:6 day sampling frequency

IMPROVE Monitoring Network: The Interagency Monitoring of Protected Visual Environments (IMPROVE) network collects 24-hour average $PM_{2.5}$ and PM_{10} mass and speciated $PM_{2.5}$ concentrations (with the exception of ammonium) using a 1:3 day sampling frequency. IMPROVE monitoring sites are mainly located at more rural Class I area sites that correspond to specific National Parks, Wilderness Areas and Fish and Wildlife Refuges across the U.S., with a large number of sites located in the western U.S. There are also some IMPROVE protocol sites in urban areas.

3.6.2 Model Performance Statistics, Goals and Criteria

EPA's modeling guidance (2018) notes that PM models might not be able to achieve the same level of model performance as ozone models. Indeed, $PM_{2.5}$ species are defined by the measurement technology used to measure them and different measurement technologies can produce quite different $PM_{2.5}$ concentrations. To account for the variability in PM measurements, researchers developed PM model performance goals and criteria that are less stringent than ozone model performance goals (Boylan, 2004; Boylan and Russell, 2006; Simon et al., 2012). More recently Emery et al. (2017) conducted a metaanalysis of 38 peer-reviewed articles reporting air quality model performance for PM species. Table 3-7 lists the recommendations of the authors for performance goals and criteria for different PM model species. The MPE metrics recommended by the authors are shown in Table 3-8.

Table 3-7. PM model performance goals and criteria (Emery et al., 2017)

Species	NMB*		NME*		r*	
	Goal	Criteria	Goal	Criteria	Goal	Criteria
24-hr $PM_{2,5}$, SO_4, NH_4	≤±10%	≤30%	≤±35%	≤50%	>0.70	>0.40
24-hr NO_3	≤±15%	≤65%	≤±65%	≤115%	None	None
24-hr OC	≤±15%	≤50%	≤±45%	≤65%	None	None
24-hr EC	≤±20%	≤40%	≤±50%	≤75%	None	None

* NMB = normalized mean bias; NME = normalized mean error; r = correlation coefficient.

These model performance goals are not used to assign passing or failing grades to model performance, but rather to help interpret the model performance and intercompare across locations, species, time periods and model applications. The model inputs to CAMx vary hourly, but tend to represent average conditions that do not account for unusual or extreme conditions. For example, an accident or large event could cause significant increases in congestion and motor vehicle emissions that are not accounted for in the average emissions inputs used in the model.

Emery et al. (2017) compiled and interpreted the PM model performance from 38 air quality modeling studies in the peer-reviewed literature and developed the following recommendations on what should be reported in a model performance evaluation:

- Photochemical modeling studies should report model performance as Normalized Mean Bias (NMB) and Error (NME), and correlation coefficient (*r*). The confidence interval of *r* should be included with the results (Table 3-8).
- Concentration cutoffs should not be used for PM species because of the lower background concentrations of PM
- Temporal scales for 24-hr total and speciated PM should not exceed 3 months (or 1 season); spatial scales should range from urban to ≤1000 km.

- It is important to report processing steps in the model evaluation and how the predicted and observed data were paired and whether data are spatially/temporally averaged before the statistics are calculated.
- Predicted values should be taken from the grid cell that contains the monitoring site, although bilinear interpolation to the monitoring site point can be used for higher resolution modeling (< 12 km).
- Spatial displays should be used in the model evaluation to evaluate model predictions away from the monitoring sites. Time series of predicted and observed concentrations at a monitoring site should also be used.
- Graphical plots are useful for evaluating models in conjunction with statistics. Specifically, time series (either as individual sites, or as means and variability over multiple sites), scatter diagrams (time-paired regression or time-unpaired rank-ordered comparisons), and cumulative distribution plots are particularly useful for understanding model performance and model behavior over entire ranges of concentrations.
- For regulatory applications, extend the general MPE to focus bias and error calculations on the number of modeled days used in developing the relative reduction factors (RRFs) for each PM species.

LADCO incorporated these and the recommendations of U.S. EPA (2018) into the LADCO CAMx model performance evaluation for the 2011 and 2016 modeling platforms used for this TSD. The LADCO evaluation products include qualitative and quantitative evaluation metrics for total $PM_{2.5}$ and PM species.

Table 3-8. Definition of model performance evaluation statistical measures used to evaluate the CTMs.

Statistical Measure	Mathematical Expression	Notes
Correlation Coefficient (r)	$\frac{\sum_{i=1}^{N}[(P_i - \bar{P})x(O_i - \bar{O})]}{\sqrt{\sum_{i=1}^{N}(P_i - \bar{P})^2 x \sum_{i=1}^{N}(O_i - \bar{O})^2}}$	Range: 0,1 r = 1 is perfect correlation r = 0 is totally uncorrelated P = Predicted O = Observed
Normalized Mean Error (NME)	$\frac{\sum_{i=1}^{N}\lvert P_i - O_i \rvert}{\sum_{i=1}^{N} O_i}$	Range: 0%, +∞ Reported as % P = Predicted O = Observed
Normalized Mean Bias (NMB)	$\frac{\sum_{i=1}^{N}(P_i - O_i)}{\sum_{i=1}^{N} O_i}$	Range: -100%, +∞ Reported as % P = Predicted O = Observed

4 Emissions Summaries

In this section we summarize the base and future year emissions modeling results used to forecast haze conditions in 2028. The emissions projections from the base years to 2028 are the foundation of the air quality model forecasts of future year PM concentrations and haze conditions. The emissions plots and tables in this section illustrate and quantify how the U.S. emissions modeling community, including LADCO, U.S. EPA, and state air quality planning agencies forecasted air pollution emissions at the time of the second regional haze implementation period.

4.1 2011 Modeling Platform

As described in Section 3.3.2, LADCO based the 2011 and 2028 emissions data for this study on the U.S. EPA 2011v6.3 (“EN”) emissions modeling platform (US EPA, 2017b). LADCO replaced the EGU emissions in the U.S. EPA EN platform with 2028 EGU forecasts estimated with the ERTAC EGU Tool version 2.7 (MARAMA, 2012). ERTAC EGU 2.7 integrated state-reported information on EGU operations and forecasts as of May 2017. Table 3-2 shows the 2011 and 2028 inventory components used by LADCO to forecast regional haze.

The following sections summarize the 2011 and 2028 emissions used by LADCO for simulating regional haze conditions during these years.

4.1.1 2011 Emissions Summary

LADCO state total emissions for the 2011 modeling platform are shown in Table 4-1. These emissions totals do not include biogenic sources. In Figure 4-1 and Figure 4-2 we show tile plots of daily total 2011 NOx and SO_2 emissions, respectively, gridded to the 12US2 modeling domain. Table 4-2 shows the 2011 emissions for each LADCO state by emissions inventory sector.

Table 4-1. 2011 annual total emissions by state for all anthropogenic sectors (tons/year)

State	NH_3	NOx	$PM_{2.5}$	SO_2	VOC
Illinois	11,490	542,488	55,566	287,832	812,683
Indiana	7,061	464,561	53,483	425,201	570,781
Michigan	10,939	458,442	73,816	273,598	1,027,207
Minnesota	20,332	342,334	139,857	70,655	990,775
Ohio	13,520	565,513	98,549	680,042	732,132
Wisconsin	7,610	283,971	60,426	147,113	768,382

Onroad and nonroad mobile sources are the primary sources of NOx emissions in the LADCO region. The point sector, which include EGUs, is the primary source of SO_2 emissions. Biogenic emissions are the primary source of volatile organic compounds (VOCs) at a regional and annual total level.

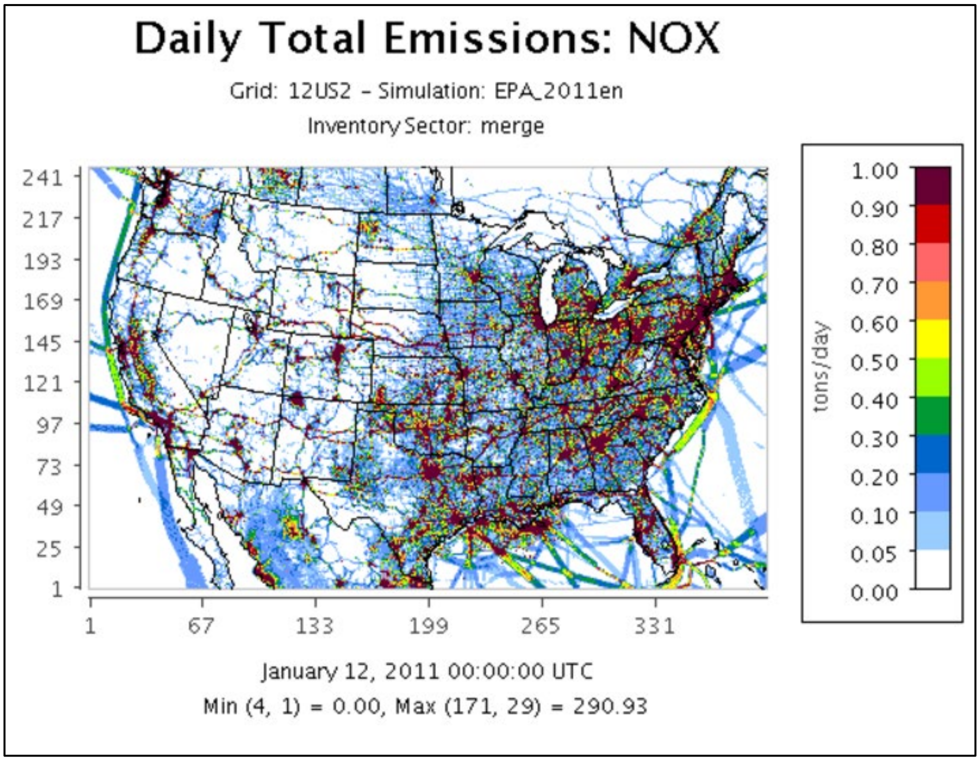


Figure 4-1. Daily total gridded 2011 NOx emissions for an example weekday (tons/day)

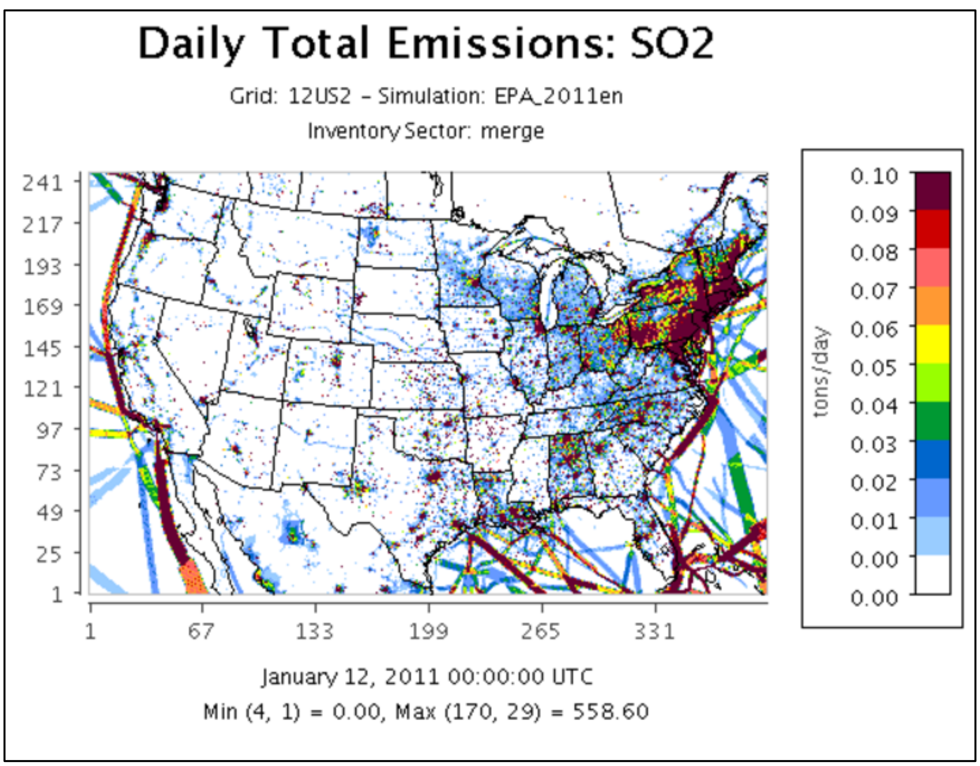


Figure 4-2. Daily total gridded 2011 SO_2 emissions for an example weekday (tons/day)

Table 4-2. 2011 annual emissions totals

State	Group	2011 Emissions (tons/year)				
		NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	Biogenics		35,836			440,546
	Fires	1,041	1,004	5,561	519	14,966
	NonPoint	5,185	43,506	15,770	5,102	145,085
	Nonroad	128	135,410	9,068	1,393	71,976
	Onroad	3,420	176,709	6,174	1,073	67,386
	Point	1,716	150,024	18,992	279,745	72,724
Indiana	Biogenics		21,016			286,402
	Fires	423	445	2,306	225	6,107
	NonPoint	2,087	17,275	18,723	2,453	104,253
	Nonroad	66	67,906	4,707	352	42,212
	Onroad	3,334	171,438	5,403	817	83,362
	Point	1,151	186,481	22,344	421,354	48,445
Michigan	Biogenics		14,351			576,931
	Fires	511	442	2,695	239	7,342
	NonPoint	5,190	32,713	48,181	3,804	157,047
	Nonroad	93	67,127	6,382	2,593	123,697
	Onroad	4,101	194,625	6,186	953	106,140
	Point	1,044	149,184	10,374	266,007	56,050
Minnesota	Biogenics		26,137			516,225
	Fires	13,111	10,924	70,357	6,177	190,325
	NonPoint	3,240	25,065	41,491	5,895	118,203
	Nonroad	76	73,758	5,866	644	76,960
	Onroad	2,445	123,520	4,375	587	68,356
	Point	1,461	82,931	17,768	57,352	20,705
Ohio	Biogenics		17,952			340,817
	Fires	163	165	876	84	2,343
	NonPoint	4,335	38,660	34,226	4,809	147,055
	Nonroad	96	95,195	6,685	912	70,411
	Onroad	4,790	250,433	8,050	1,085	129,619
	Point	4,136	163,108	48,712	673,152	41,886
Wisconsin	Biogenics		15,078			480,085
	Fires	596	566	3,179	294	8,571
	NonPoint	2,930	23,065	39,299	2,987	113,317
	Nonroad	64	53,101	4,559	544	84,430
	Onroad	2,342	127,174	4,585	587	60,066
	Point	1,677	64,987	8,803	142,700	21,911
Grand Total		70,953	2,657,309	481,697	1,884,441	4,901,958

4.1.2 2028_{2011} Emissions Summary

LADCO state total 2028_{2011} emissions[17] projections for the LADCO 2011 modeling platform are shown in Table 4-3. These emissions totals do not include biogenic sources. Figure 4-3 and Figure 4-5 are tile plots of daily total 2028 NOx and SO_2 emissions, respectively, gridded to the 12US2 modeling domain. Figure 4-4 and Figure 4-6 show differences in daily total NOx and SO_2 emissions between 2011 and 2028, respectively. Table 4-4 shows the 2028_{2011} emissions for each LADCO state by emissions inventory sector.

Table 4-3. 2028_{2011} annual total emissions by state for all anthropogenic sectors (tons/year)

State	NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	10,936	292,583	42,154	168,040	705,028
Indiana	5,906	246,805	43,526	196,016	468,536
Michigan	9,663	210,960	62,158	89,274	841,588
Minnesota	20,010	188,083	131,497	42,452	893,958
Ohio	11,503	254,645	70,536	195,434	584,024
Wisconsin	6,234	146,140	52,115	50,233	673,886

As shown in Table 4-5 the U.S. EPA 2011 EN emissions used by LADCO project that in 2028 there will be significant reductions in NOx emissions in the LADCO member states from nonroad mobile (> 50% reductions), onroad mobile (> 70%), and industrial point sources (> 25%) relative to the 2011 base year. Additionally, the shutdowns of large EGUs will result in more than a 40% reduction in total SO_2 emissions. LADCO estimates that the combination of gasoline and diesel onroad vehicles will account for significant decreases in $PM_{2.5}$ (60% reductions) and VOC (70% reductions) emissions across the region.

[17] The subscript with the future year (i.e., 2028_{2011}) indicates the base year from which the future year emissions are projected. We use this convention to distinguish between the two 2028 simulations presented in this TSD.

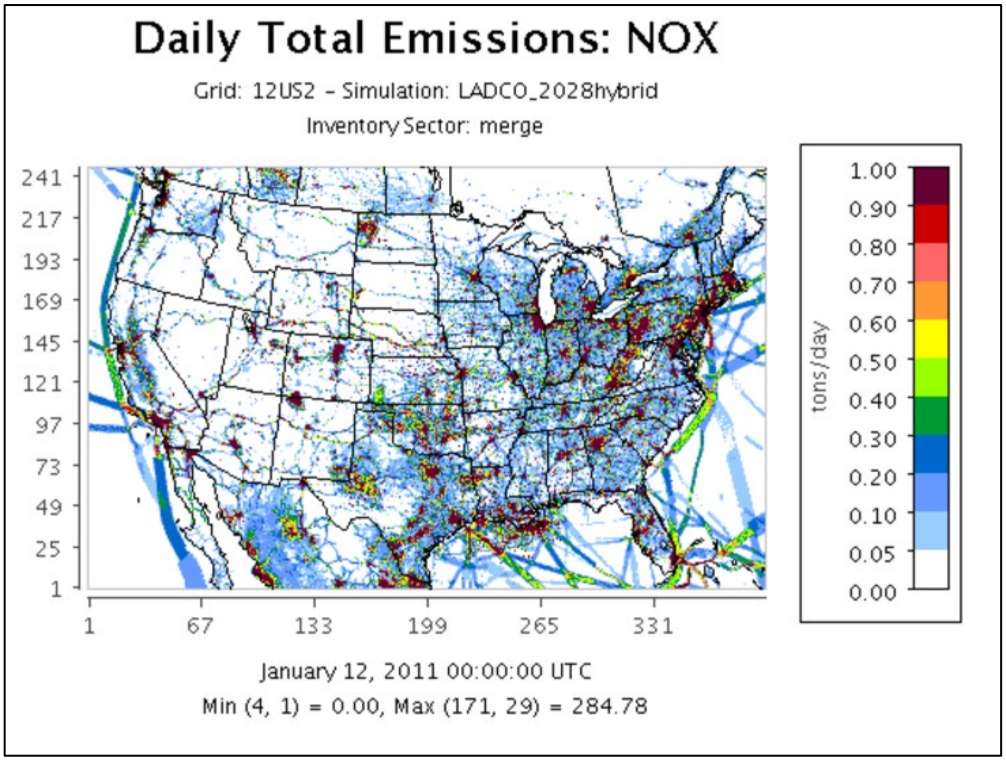


Figure 4-3. Daily total gridded 2028$_{2011}$ NOx emissions for an example weekday (tons/day)

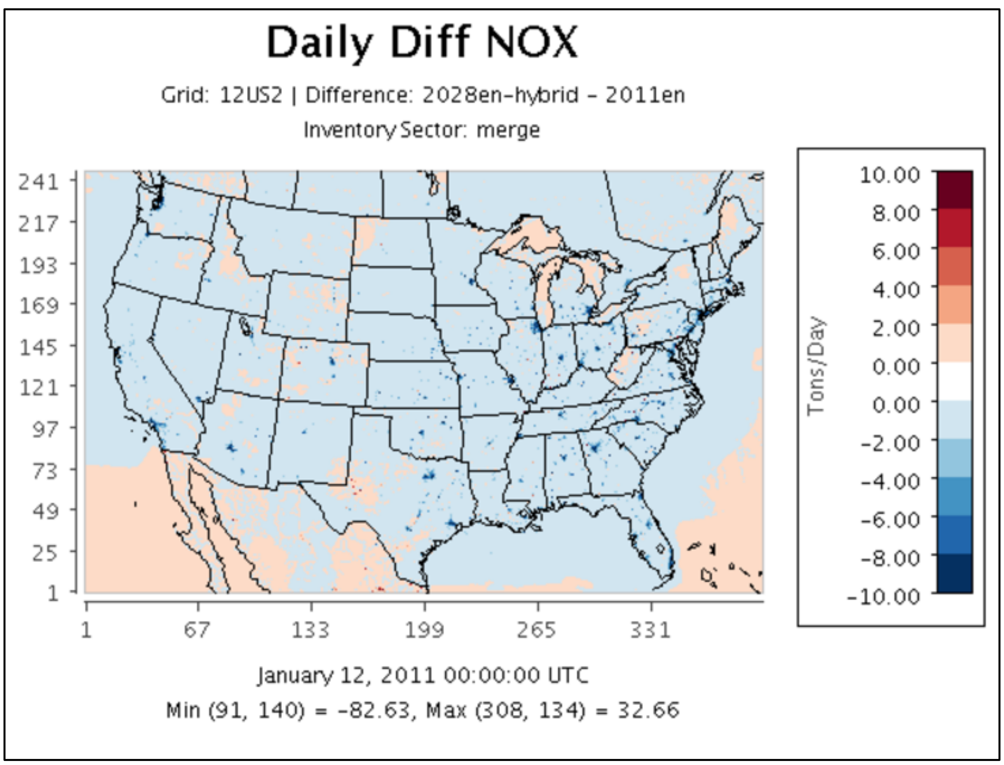


Figure 4-4. Difference (2028-2011) in daily total gridded NOx emissions for an example weekday (tons/day)

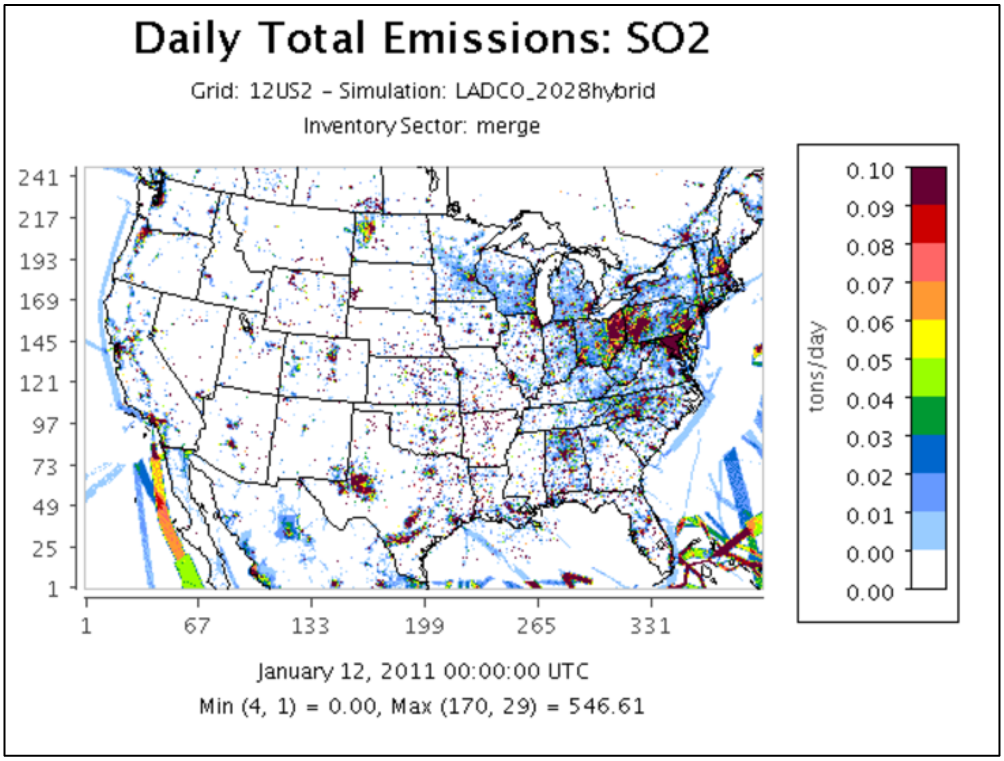


Figure 4-5. Daily total gridded 2028$_{2011}$ SO_2 emissions for an example weekday (tons/day)

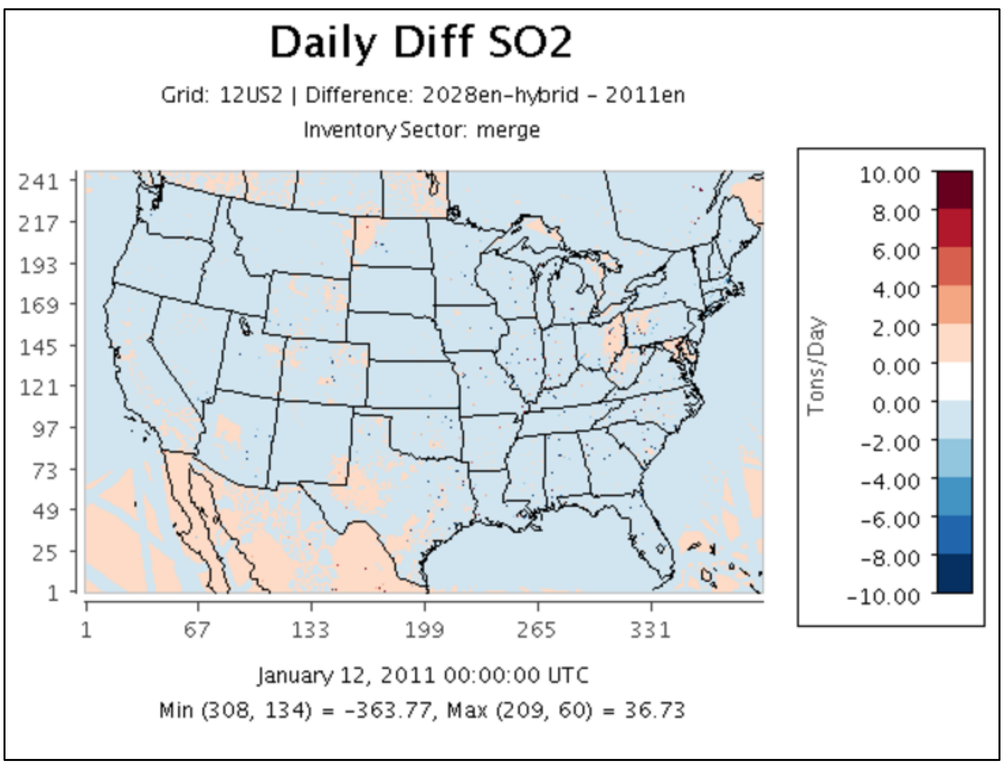


Figure 4-6. Difference (2028-2011) in daily total gridded SO_2 emissions for an example weekday (tons/day)

Table 4-4. 2028$_{2011}$ annual emissions totals

State	Group	2028 Emissions (tons/year)				
		NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	Biogenics		35,836			440,546
	Fires	1,041	1,004	5,561	519	14,966
	NonPoint	5,119	45,490	14,169	3,298	138,366
	Nonroad	163	63,084	3,543	206	43,917
	Onroad	2,830	56,628	2,493	451	23,773
	Point	1,783	90,542	16,388	163,566	43,460
Indiana	Biogenics		21,016			286,402
	Fires	423	445	2,306	225	6,107
	NonPoint	1,959	17,369	16,877	2,313	94,942
	Nonroad	85	31,734	1,858	88	24,757
	Onroad	2,175	38,877	1,812	324	20,251
	Point	1,263	137,364	20,674	193,066	36,077
Michigan	Biogenics		14,351			576,931
	Fires	511	442	2,695	239	7,342
	NonPoint	4,991	33,902	45,334	2,374	139,194
	Nonroad	116	36,261	2,915	209	67,993
	Onroad	2,478	42,030	1,840	316	27,716
	Point	1,567	83,975	9,374	86,135	22,412
Minnesota	Biogenics		26,137			516,225
	Fires	13,111	10,924	70,357	6,177	190,325
	NonPoint	3,205	24,489	41,397	3,083	110,379
	Nonroad	92	34,984	2,162	108	38,569
	Onroad	1,614	27,406	1,420	238	18,409
	Point	1,988	64,143	16,160	32,847	20,053
Ohio	Biogenics		17,952			340,817
	Fires	163	165	876	84	2,343
	NonPoint	4,198	41,237	32,166	4,357	139,121
	Nonroad	116	44,708	3,019	130	42,407
	Onroad	2,844	49,229	2,322	418	29,479
	Point	4,181	101,354	32,153	190,445	29,857
Wisconsin	Biogenics		15,078			480,085
	Fires	596	566	3,179	294	8,571
	NonPoint	2,796	22,581	37,050	2,478	106,033
	Nonroad	77	26,907	1,835	87	38,878
	Onroad	1,659	33,157	1,416	246	18,531
	Point	1,106	47,852	8,634	47,128	21,787
Grand Total		64,250	1,339,217	401,986	741,448	4,167,021

Table 4-5. Base and future year annual emissions percent change (2028-2011)

State	Group	Percent Change 2011 to 2028				
		NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	Biogenics		0.0%			0.0%
	Fires	0.0%	0.0%	0.0%	0.0%	0.0%
	NonPoint	-1.3%	4.6%	-10.2%	-35.4%	-4.6%
	Nonroad	27.1%	-53.4%	-60.9%	-85.2%	-39.0%
	Onroad	-17.2%	-68.0%	-59.6%	-58.0%	-64.7%
	Point	3.9%	-39.6%	-13.7%	-41.5%	-40.2%
Indiana	Biogenics		0.0%			0.0%
	Fires	0.0%	0.0%	0.0%	0.0%	0.0%
	NonPoint	-6.1%	0.5%	-9.9%	-5.7%	-8.9%
	Nonroad	28.3%	-53.3%	-60.5%	-75.0%	-41.4%
	Onroad	-34.8%	-77.3%	-66.5%	-60.4%	-75.7%
	Point	9.8%	-26.3%	-7.5%	-54.2%	-25.5%
Michigan	Biogenics		0.0%			0.0%
	Fires	0.0%	0.0%	0.0%	0.0%	0.0%
	NonPoint	-3.8%	3.6%	-5.9%	-37.6%	-11.4%
	Nonroad	25.5%	-46.0%	-54.3%	-91.9%	-45.0%
	Onroad	-39.6%	-78.4%	-70.3%	-66.8%	-73.9%
	Point	50.0%	-43.7%	-9.6%	-67.6%	-60.0%
Minnesota	Biogenics		0.0%			0.0%
	Fires	0.0%	0.0%	0.0%	0.0%	0.0%
	NonPoint	-1.1%	-2.3%	-0.2%	-47.7%	-6.6%
	Nonroad	20.6%	-52.6%	-63.1%	-83.3%	-49.9%
	Onroad	-34.0%	-77.8%	-67.6%	-59.5%	-73.1%
	Point	36.1%	-22.7%	-9.0%	-42.7%	-3.2%
Ohio	Biogenics		0.0%			0.0%
	Fires	0.0%	0.0%	0.0%	0.0%	0.0%
	NonPoint	-3.2%	6.7%	-6.0%	-9.4%	-5.4%
	Nonroad	21.2%	-53.0%	-54.8%	-85.7%	-39.8%
	Onroad	-40.6%	-80.3%	-71.2%	-61.5%	-77.3%
	Point	1.1%	-37.9%	-34.0%	-71.7%	-28.7%
Wisconsin	Biogenics		0.0%			0.0%
	Fires	0.0%	0.0%	0.0%	0.0%	0.0%
	NonPoint	-4.6%	-2.1%	-5.7%	-17.0%	-6.4%
	Nonroad	19.9%	-49.3%	-59.7%	-84.0%	-54.0%
	Onroad	-29.2%	-73.9%	-69.1%	-58.1%	-69.1%
	Point	-34.1%	-26.4%	-1.9%	-67.0%	-0.6%
Grand Total		-9.4%	-49.6%	-16.5%	-60.7%	-15.0%

4.2 2016 Modeling Platform

As described in Section 3.4.2, LADCO based the 2016 and 2028 emissions data for this study on the U.S. EPA 2016fh_16 ("FH") emissions modeling platform (US EPA, 2020). LADCO replaced the EGU emissions in the U.S. EPA FH platform with 2028 EGU forecasts estimated with a modified version of the ERTAC EGU Tool version 16.1 (MARAMA, 2012). Table 3-4 lists the 2016 base year and 2028 future year inventory components that LADCO used to simulate 2016 and 2028 air quality for this application.

The following sections summarize the 2016 and 2028 emissions used by LADCO for simulating regional haze conditions during these years.

4.2.1 2016 Emissions Summary

The tables and figures in this section summarize the emissions used in the LADCO 2016 CAMx simulation. Table 4-6 shows the LADCO state annual 2016 total emissions for all sectors, and Figure 4-7 and Figure 4-8 are tile plots of the 12-km gridded, daily total NOx and SO_2 emissions, respectively, for a winter weekday (Friday, January 15). The NOx plot illustrates that the highest emissions occur in proximity to urban areas and roadways. The SO_2 plot shows that coal EGU point sources and urban areas are the dominant emissions sources for this pollutant. Table 4-7 shows the 2016 annual emissions totals by LADCO member state and major inventory group.

Table 4-6. 2016 annual total emissions by state for all sectors (tons/year)

State	NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	102,364	387,877	109,474	107,987	800,485
Indiana	86,725	327,142	83,341	129,328	528,217
Michigan	53,366	304,362	66,074	107,265	920,538
Minnesota	208,325	248,879	127,312	35,447	825,120
Ohio	86,354	352,630	106,689	148,912	706,730
Wisconsin	63,286	194,841	68,269	36,468	677,145

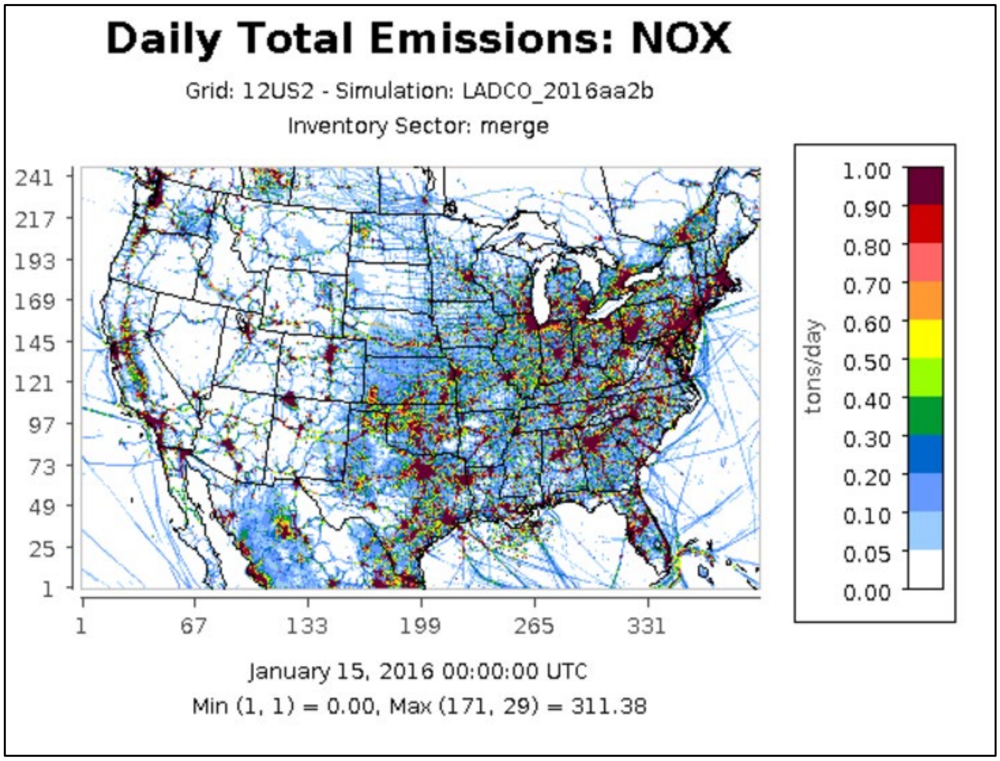


Figure 4-7. Daily total gridded 2016 NOx emissions for an example weekday (tons/day)

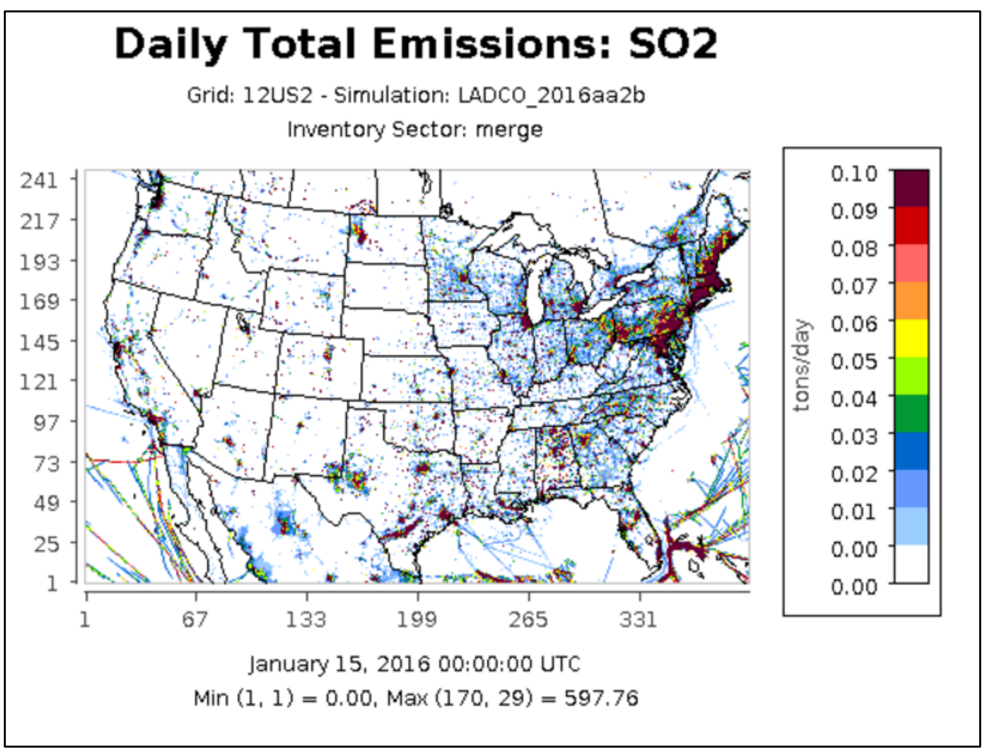


Figure 4-8. Daily total gridded 2016 SO_2 emissions for an example weekday (tons/day)

Table 4-7. 2016 annual emissions totals

State	Group	2016 Emissions (tons/year)				
		NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	Biogenics		38,921			422,736
	Fires	1,434	1,390	7,662	716	20,607
	NonPoint	96,053	102,399	80,406	5,946	211,921
	Nonroad	79	49,234	4,515	94	38,539
	Onroad	3,300	117,837	4,217	705	65,574
	Point	1,498	78,096	12,674	100,526	41,108
Indiana	Biogenics		21,381			279,976
	Fires	720	697	3,849	359	10,356
	NonPoint	81,708	34,816	46,889	1,142	129,207
	Nonroad	56	36,791	3,208	66	20,407
	Onroad	2,737	103,694	3,385	616	55,049
	Point	1,504	129,763	26,010	127,145	33,222
Michigan	Biogenics		14,572			593,916
	Fires	605	435	3,133	256	8,699
	NonPoint	48,254	66,217	47,856	7,480	174,178
	Nonroad	53	25,644	2,919	67	54,091
	Onroad	3,073	97,879	3,053	695	63,809
	Point	1,381	99,615	9,113	98,767	25,845
Minnesota	Biogenics		28,031			510,385
	Fires	4,931	2,606	24,907	1,807	70,882
	NonPoint	200,203	41,001	83,986	4,404	129,706
	Nonroad	73	43,042	4,192	86	52,838
	Onroad	1,915	66,467	2,195	395	41,382
	Point	1,203	67,732	12,032	28,755	19,927
Ohio	Biogenics		18,120			360,156
	Fires	465	459	2,492	235	6,689
	NonPoint	78,786	64,951	71,145	4,061	192,544
	Nonroad	68	40,429	3,692	82	38,405
	Onroad	3,736	122,966	3,931	852	76,612
	Point	3,299	105,705	25,429	143,682	32,324
Wisconsin	Biogenics		16,095			484,780
	Fires	793	709	4,200	378	11,404
	NonPoint	59,119	33,655	53,366	2,075	81,793
	Nonroad	44	23,906	2,431	54	41,548
	Onroad	1,861	80,086	2,845	413	34,837
	Point	1,469	40,390	5,427	33,548	22,783
Grand Total		**600,422**	**1,815,731**	**561,157**	**565,407**	**4,458,233**

4.2.2 2028_{2016} Emissions Summary

The tables and figures in this section summarize the emissions used in the LADCO 2016-based 2028 CAMx simulation. Table 4-8 shows LADCO state total annual emissions, Figure 4-9 and Figure 4-11 show gridded daily total 2016 NOx and SO_2 emissions for a winter weekday (Friday, January 15). The spatial patterns seen in these figures match with the patterns in the 2016 emissions figures shown previously. Figure 4-10 and Figure 4-12 show the locations where emissions are projected to change in 2028 relative to 2016. The emissions differences indicate widespread changes across the region, with larger emissions changes at locations where there are projected to be EGU shutdowns and new controls applied at specific plants. The largest NOx emissions reductions will occur along roadways and in urban areas; emissions increases are projected in oil and gas development regions, in Mexico, and in Canadian offshore sources in the Great Lakes. SO_2 emissions reductions are projected to occur in urban areas and where power plants are located.

Table 4-8. 2028_{2016} annual total emissions by state for all sectors (tons/year)

State	NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	110,871	229,820	103,309	52,788	334,078
Indiana	94,931	175,508	76,884	84,814	214,407
Michigan	55,886	190,164	62,566	53,976	269,661
Minnesota	220,374	146,231	121,290	29,319	274,186
Ohio	94,278	211,025	96,585	109,883	298,719
Wisconsin	65,446	128,962	64,876	26,948	158,065

Table 4-9 shows the LADCO state total 2028_{2016} annual emissions tons for the haze species. Table 4-10 compares 2028 and 2016 annual haze emissions by inventory group for each LADCO state. Negative numbers in these tables indicate percent emissions reductions in 2028 relative to 2016. Comparisons of the EGU and industrial point source emissions changes between 2016 and 2028 is confounded by the different methods used by the U.S EPA and ERTAC EGU projection models for distinguishing EGU from non-EGU industrial point sources. ERTAC only models sources with CEM data while EPA does economic projections of all units that sell power to the grid including facilities with co-generation units like paper mills and aluminum foundries. For the LADCO modeling that used ERTAC to project power plant emissions, we used the EPA 2028 inventory projections for those sources that generate power but do not have CEMs.

LADCO projects that overall both the NOX and SO_2 emissions will decrease in 2028 relative to 2016 in all of the LADCO states. The NOx reductions for the anthropogenic sectors (i.e., excluding biogenics and wildfires) range from 28 to 42%, driven primarily by reductions in onroad and offroad mobile source emissions. We project that the SO_2 emissions reductions will be significant, at around 18 to 51% in each of the LADCO states. These reductions are the result of changes to the power sector, primarily coal-fired EGU shutdowns.

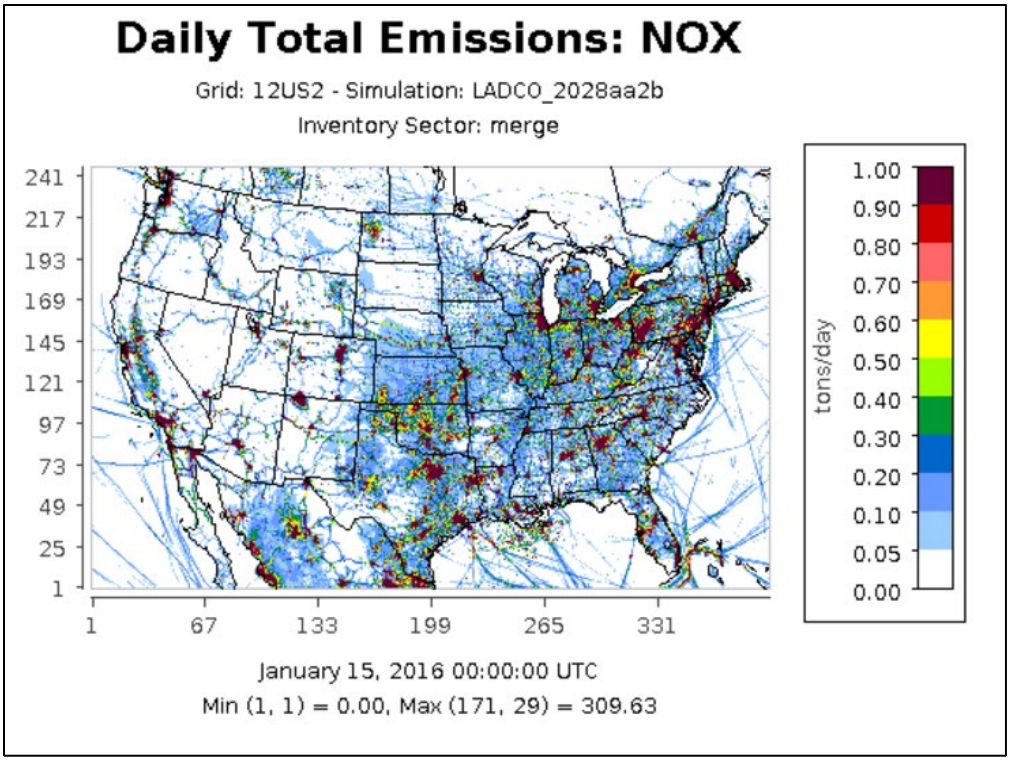


Figure 4-9. Daily total gridded 2028_{2016} NOx emissions for an example weekday (tons/day)

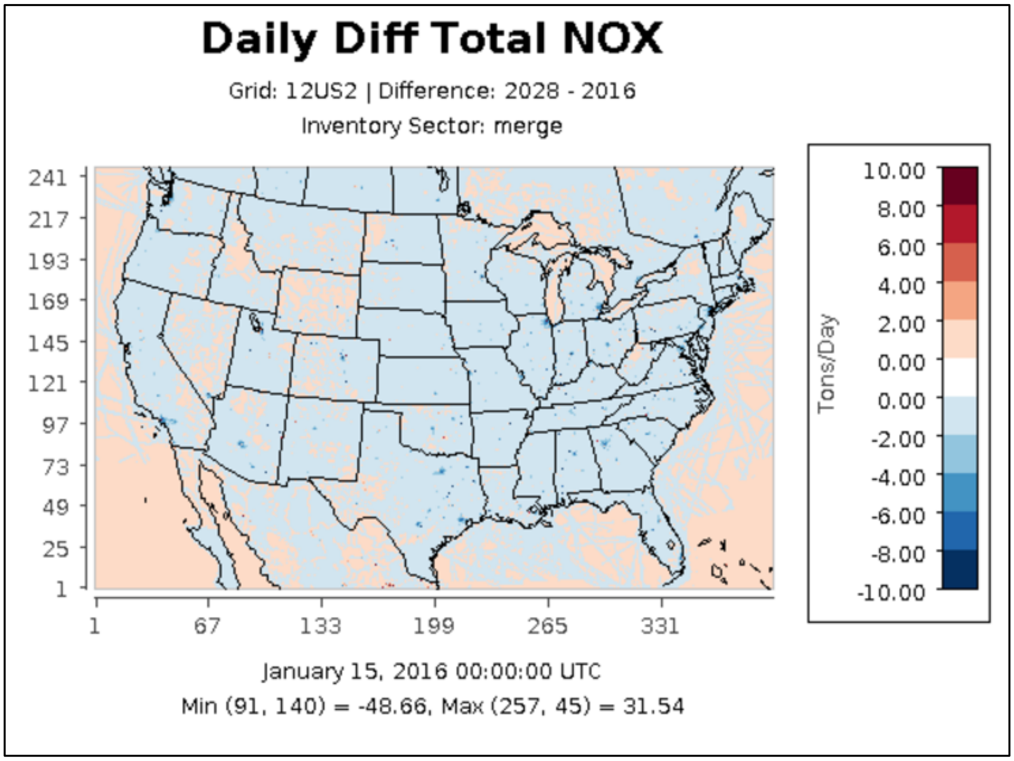


Figure 4-10. Difference (2028-2016) in daily total gridded NOx emissions for an example weekday (tons/day)

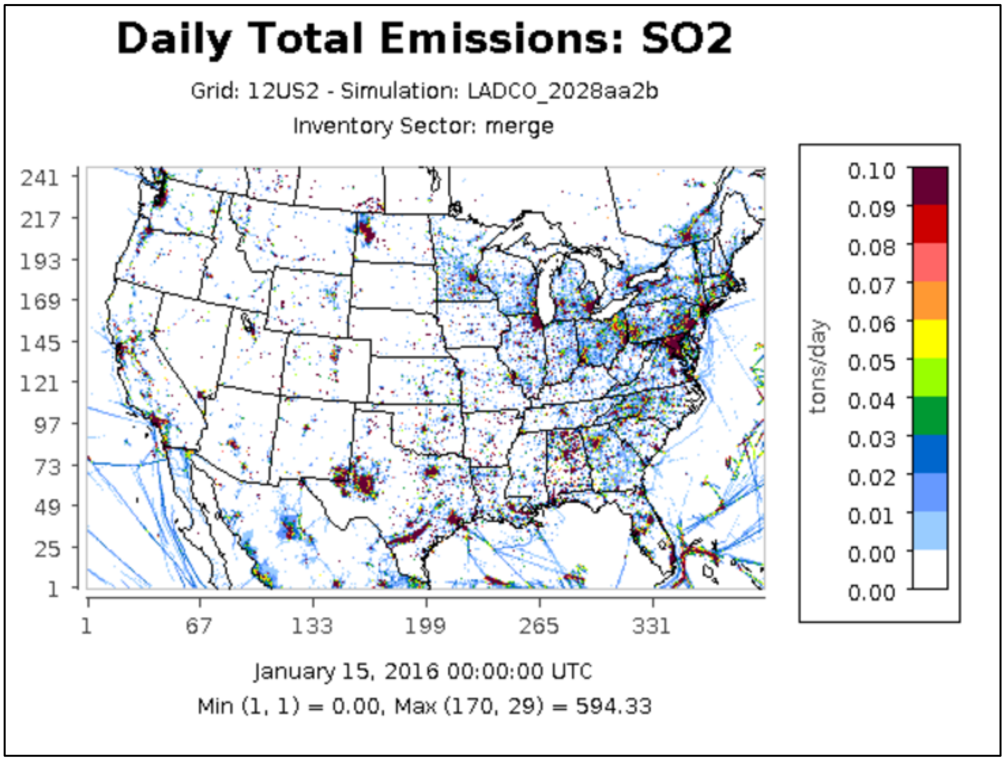


Figure 4-11. Daily total gridded 2028$_{2016}$ SO_2 emissions for an example weekday (tons/day)

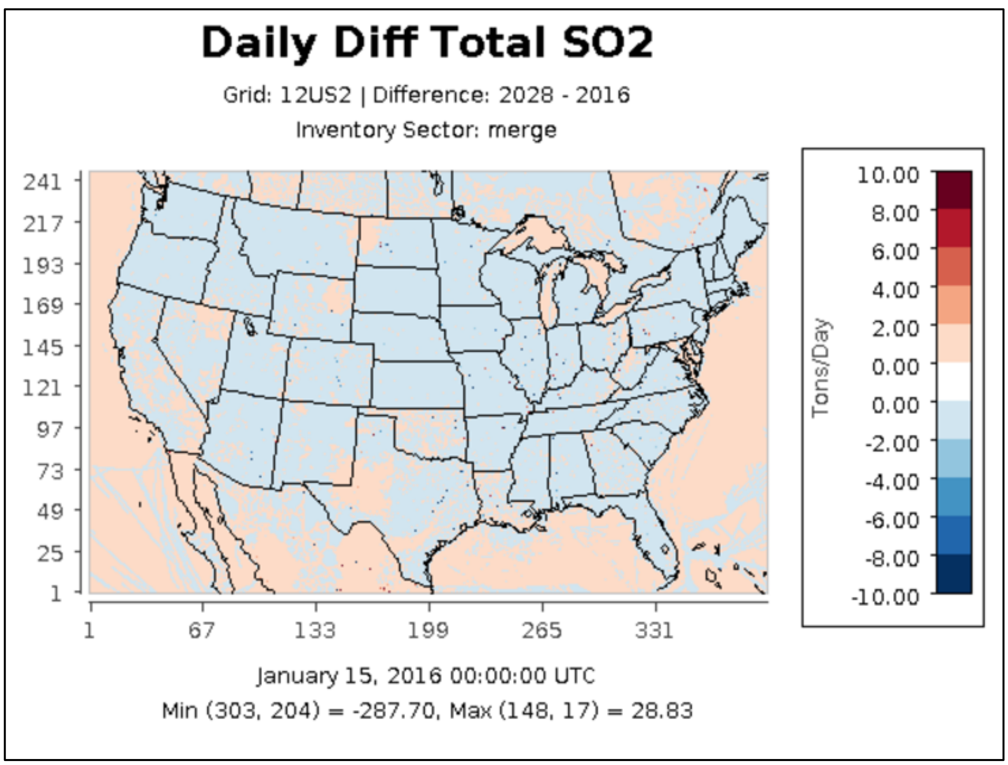


Figure 4-12. Difference (2028-2016) in daily total gridded SO_2 emissions for an example weekday (tons/day)

Table 4-9. 2028₂₀₁₆ annual emissions totals

State	Group	2028 Emissions (tons/year)				
		NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	Biogenics		38,921			422,736
	fires	1,434	1,390	7,662	716	20,607
	nonpoint	104,358	88,663	78,804	6,002	212,101
	nonroad	87	25,289	2,281	68	28,404
	onroad	2,845	41,417	1,987	402	29,271
	point	2,147	73,061	12,575	45,600	43,695
Indiana	Biogenics		21,381			279,976
	fires	720	697	3,849	359	10,356
	nonpoint	89,324	30,049	46,254	1,097	130,268
	nonroad	65	18,170	1,518	54	15,928
	onroad	2,292	36,034	1,588	321	23,806
	point	2,530	90,558	23,675	82,983	34,049
Michigan	Biogenics		14,572			593,916
	fires	605	435	3,133	256	8,699
	nonpoint	50,722	60,755	47,159	7,098	171,926
	nonroad	57	16,675	1,667	41	34,236
	onroad	2,606	31,924	1,544	295	28,268
	point	1,896	80,375	9,063	46,286	26,532
Minnesota	Biogenics		28,031			510,385
	fires	4,931	2,606	24,907	1,807	70,882
	nonpoint	212,377	36,904	81,747	4,208	130,097
	nonroad	79	23,742	2,055	60	33,624
	onroad	1,629	22,024	984	192	19,091
	point	1,358	60,955	11,597	23,052	20,492
Ohio	Biogenics		18,120			360,156
	fires	465	459	2,492	235	6,689
	nonpoint	85,161	57,923	70,496	4,361	197,290
	nonroad	77	22,287	1,940	60	27,314
	onroad	3,155	40,015	1,948	378	34,097
	point	5,420	90,341	19,709	104,849	33,329
Wisconsin	Biogenics		16,095			484,780
	fires	793	709	4,200	378	11,404
	nonpoint	60,146	30,053	53,158	2,046	82,126
	nonroad	49	13,894	1,250	36	25,025
	onroad	1,687	25,272	1,025	229	16,538
	point	2,771	59,034	5,243	24,259	22,972
Grand Total		**641,787**	**1,218,830**	**525,512**	**357,727**	**4,201,065**

Table 4-109. 2016 modeling platform annual emissions percent change (2016-2028)

State	Group	Percent Change 2016 to 2028				
		NH_3	NOX	$PM_{2.5}$	SO_2	VOC
Illinois	Biogenics		0.00%			0.00%
	Fires	0.00%	0.00%	0.00%	0.00%	0.00%
	NonPoint	8.65%	-13.41%	-1.99%	0.93%	0.08%
	Nonroad	9.53%	-48.64%	-49.47%	-27.73%	-26.30%
	Onroad	-13.78%	-64.85%	-52.88%	-43.07%	-55.36%
	Point	43.35%	-6.45%	-0.78%	-54.64%	6.29%
Indiana	Biogenics		0.00%			0.00%
	Fires	0.00%	0.00%	0.00%	0.00%	0.00%
	NonPoint	9.32%	-13.69%	-1.36%	-3.94%	0.82%
	Nonroad	15.23%	-50.61%	-52.68%	-18.34%	-21.95%
	Onroad	-16.26%	-65.25%	-53.08%	-47.88%	-56.75%
	Point	68.25%	-30.21%	-8.98%	-34.73%	2.49%
Michigan	Biogenics		0.00%			0.00%
	Fires	0.00%	0.00%	0.00%	0.00%	0.00%
	NonPoint	5.12%	-8.25%	-1.46%	-5.11%	-1.29%
	Nonroad	7.83%	-34.97%	-42.89%	-38.35%	-36.71%
	Onroad	-15.19%	-67.38%	-49.43%	-57.51%	-55.70%
	Point	37.25%	-19.31%	-0.55%	-53.14%	2.66%
Minnesota	Biogenics		0.00%			0.00%
	Fires	0.00%	0.00%	0.00%	0.00%	0.00%
	NonPoint	6.08%	-9.99%	-2.67%	-4.45%	0.30%
	Nonroad	8.30%	-44.84%	-50.98%	-30.31%	-36.36%
	Onroad	-14.94%	-66.86%	-55.16%	-51.31%	-53.86%
	Point	12.85%	-10.00%	-3.61%	-19.83%	2.83%
Ohio	Biogenics		0.00%			0.00%
	Fires	0.00%	0.00%	0.00%	0.00%	0.00%
	NonPoint	8.09%	-10.82%	-0.91%	7.40%	2.46%
	Nonroad	13.21%	-44.87%	-47.45%	-27.56%	-28.88%
	Onroad	-15.55%	-67.46%	-50.43%	-55.60%	-55.49%
	Point	64.29%	-14.53%	-22.49%	-27.03%	3.11%
Wisconsin	Biogenics		0.00%			0.00%
	Fires	0.00%	0.00%	0.00%	0.00%	0.00%
	NonPoint	1.74%	-10.70%	-0.39%	-1.38%	0.41%
	Nonroad	10.22%	-41.88%	-48.58%	-33.78%	-39.77%
	Onroad	-9.38%	-68.44%	-63.97%	-44.56%	-52.53%
	Point	88.67%	46.16%	-3.38%	-27.69%	0.83%
Average		**6.89%**	**-32.87%**	**-6.35%**	**-36.73%**	**-5.77%**

4.2.3 Typical Year Emissions Platform

Emissions estimates used in modeling can provide a faithful match to real-world base year activity, called an “actual” inventory. Actual inventories are used for model validation to confirm that the model can reproduce the initial pollutant concentrations. In LADCO’s point source actual inventories, which are based on hourly CEM data, we modeled extended point source facility shutdowns in the base year for some large facilities. These shutdowns may have occurred for maintenance or due to malfunctions at the facility.

We also build “typical” inventories to be used as the basis for a future year projection. For some point source facilities in Minnesota that did not operate in 2016, we included zero emissions in the actual emissions scenarios. If the plants operated in subsequent contemporary years, we reviewed the historical record for those plants and found that for three sources in Minnesota the 2017 emissions were representative of typical emissions activity.

LADCO worked with staff from the state of Minnesota to include hourly data and alternate base and future year estimates for some facilities that were not operating in 2016 because of maintenance or other operational issues. For these facilities, we used 2017 emissions numbers in the 2016 typical year modeling inventory and projected 2028 emissions from these numbers. We did this because the alternative approach of using actual (zero) 2016 emissions and a 2028 projected inventory in which the plants were operating at expected levels would simulate increases in future year emissions that were not representative of the base period. These unrepresentative increases would incorrectly impact the relative reduction factors used to project future haze conditions in the region.

LADCO used actual 2016 emissions inventories for a model performance evaluation run and typical inventories as the basis for future year projections. All the emissions summary tables in this TSD use typical emissions from the impacted facilities. Emissions for most inventory sectors were identical between the two types of emissions platforms. The facilities that had significant emissions differences between the actual and typical inventories are shown in Table 3-3.

4.3 Comparison of 2011 and 2016 Emissions Platforms

LADCO's 2016 modeling platform differs from the 2011 platform in several important ways. For EGU sources we used the ERTAC model. The ERTAC model is designed to use base year CEM data to define emissions patterns. These patterns define both base and future year regional and plant level behaviors. Our projections to 2028 used the corresponding base year CEM data for both 2011 and 2016. Since the 2011-based projections to 2028 were developed in 2017, we did not include any new EGU shutdowns or controls announced between 2017 and mid-2020 in the simulation.

The ERTAC EGU runs in 2017 that were used for our 2011-based modeling had 54 unit shutdowns between 2017 and 2028. The ERTAC 16.1 runs done in late 2020, which we used for our 2016-based modeling, included 46 additional shutdowns above the ones included in the 2011 simulation. Further, LADCO included an additional 62 unit shutdowns in our 2028_{2016} simulation based on information from our member states on new shutdowns as of September 2020. The final LADCO 2028_{2016} CAMx simulation excluded emissions from a total of 162 units because of announced shutdowns.

LADCO staff worked with the Coordinating Research Council (CRC) to build national emissions modeling inputs that became the county-specific national defaults for several onroad mobile inputs and resulted in improved emissions in the 2016 modeling platform. This work included CRC project A-115, which decoded all the vehicle identification numbers (VIN) in the country to produce updated vehicle fleet age distributions. CRC, LADCO, and a group of states evaluated the methods and data used to set default age distributions and found that older vehicles were being over-counted in the national default data because they were not being removed from the vehicle count database when they left the in-use fleet of vehicles. Figure 4-13 shows the impact on vehicle counts in one state when these older vehicles are removed from the data. We were able to show that because these vehicles are the oldest and highest emitting vehicles in the fleet, a small difference in their population had a significant impact on emissions. Telemetry data for vehicle speed and a second Telemetry project for data on time of hour/weekday/month activity were also included in new national defaults in the 2016 modeling platform.

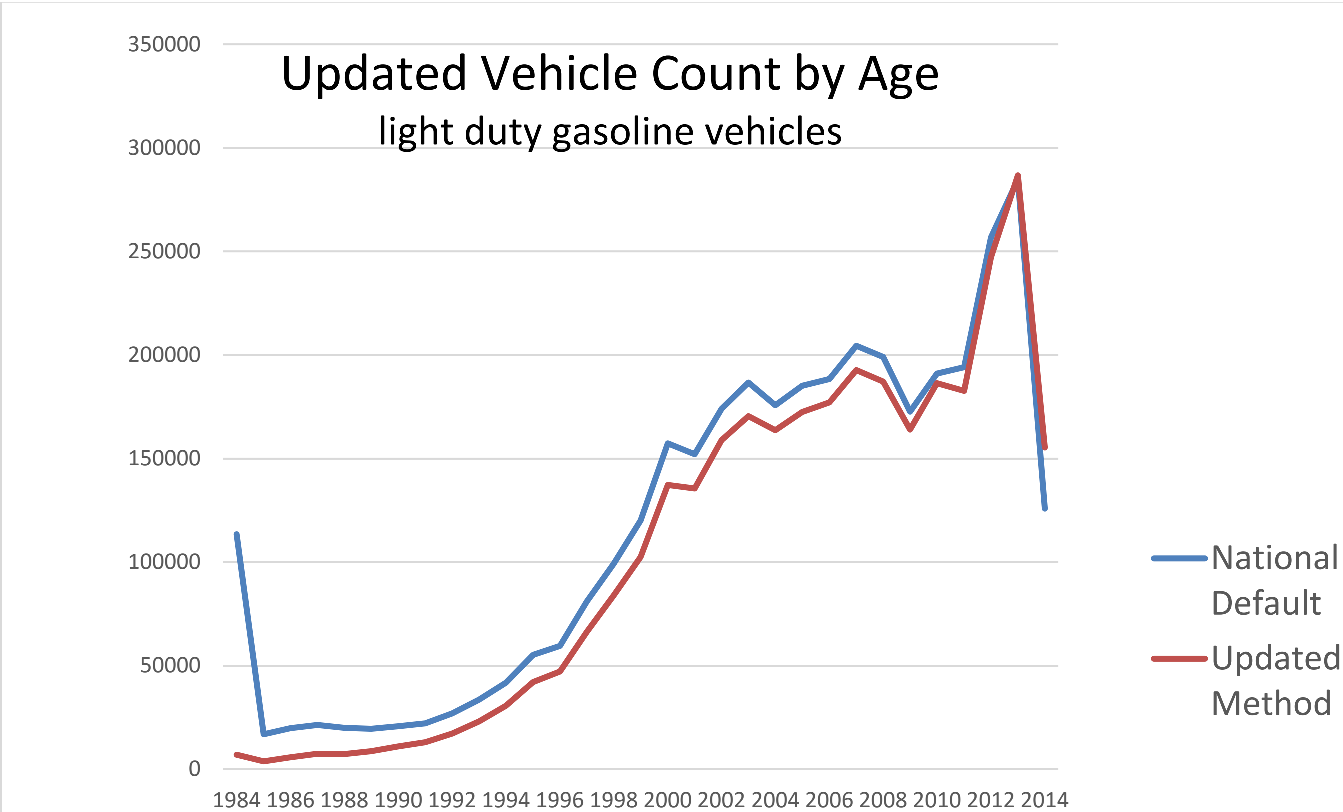


Figure 4-13 Change in vehicle age counts based on updated methodologies to decode VINs.

Several emissions sectors use day-specific temperature and activity data as the basis of their emissions estimates. As the different base years have different meteorology and activity data, the base and future year emissions are changed with the different base year conditions. These sectors include biogenics, wind-blown dust, wildfire, prescribed fire, and onroad motor vehicles.

In the 2011 emissions inventory there were limited emissions estimates from livestock and fertilizer operations. In the 2016 emissions inventory, EPA included agricultural ammonia emissions as a dedicated emissions sector. In most of the LADCO states this change resulted in an order of magnitude increase in estimated NH_3 emissions.

The marine vessels inventory also improved between the 2011 and 2016, when EPA included national 4-minute interval location data of individual ships to define speed, power, and location. This improvement led to hourly vessel-specific estimates of fuel use and emissions.

Oil and gas inventories were also improved as fracking became more prevalent and emissions increased in parts of the country where new fuel reserves were developed, including in Ohio. EPA and states built new national databases of site-specific oil and gas emissions as well as nonpoint inventories at the county level for smaller operations. For Ohio, the 2011 annual NOx emissions were 319 tons, while the 2016 emissions were 13,114 tons. These changes were partially improvements in inventory methods and partially due to increases in oil field development and operation.

5 Class I Area Q/d Analysis

This section describes the data and methods used by LADCO to aid our members in screening emissions source impacts on Class I areas for the second regional haze implementation period. The surrogate analysis of tons/year emissions (Q) divided by distance in kilometers (d) from the Class I areas, known as Q/d, is used to screen emissions source impacts at downwind receptors in lieu of air quality modeling results. LADCO created Q/d results for industrial point sources using preliminary 2016 emissions inventory data. LADCO completed the Q/d calculations in January 2019 using the best available inventories at that time

LADCO did not make any decisions about how the data that we generated would be applied by our member states in their four factor analysis process. We provided stationary sources emissions data and Q/d information at different Q/d threshold for different combinations of haze precursors to aid our member states in decision making for their four factor analyses. This section describes the data that LADCO collected and generated to support these decisions.

5.1 Inventory Sources

Starting in March 2018, LADCO produced a series of Q/d analyses for use by the LADCO member states for regional haze planning. The LADCO Regional Haze workgroup and Project Team provided guidance to LADCO on which sources to include in the Q/d analysis. These groups decided early in the second Regional Haze implementation period to focus the Q/d analysis on point sources of NOx and SO_2. LADCO followed this guidance to produce Q/d results for different inventory years.

The first Q/d versions used 2011-based emissions inventories and included 2011, 2018, and 2028 data. LADCO also computed Q/d values for point sources from different versions of inventories for Canada and Mexico. As LADCO and the LADCO member states learned of new EGU shutdown announcements that were made since the release of the 2011 inventories, the LADCO members requested that the Q/d analyses be redone with newer data.

In January 2019, state and federal participants in the LADCO Regional Haze Technical Workgroup agreed to use the latest available 2016 inventory for a new Q/d analysis by LADCO. The National Emissions Inventory Collaborative 2016 alpha inventory represented the best estimate of 2016 point emissions at the time[18]. Table 5-1 shows the point source components of the 2016 alpha inventory that LADCO used for the Q/d analysis.

Table 5-1. Point source inventory components used for the 2016 alpha Q/d analysis

Sector	Filename	Description
Electricity Generating Unit (EGU) point	ptegu_2016NEIv2_composite.csv	2016 emissions from the National Emissions Inventory (NEI) integrated with CEM (continuous emissions monitoring) hourly data.
Non-EGU industrial point	ptnonipm_2016alpha_POINT_ 03apr2018_nf_v3.csv	2016 emissions of non-EGU industrial point sources.
Point oil and gas	2028el_marama_pt_oilgas_2011neiv2_ point_20140913_02dec2016_v1.csv	2028 emissions for oil and gas sources. In April of 2018 no 2016 oil and gas inventory was available. We chose to use MARAMA's 2011-based projected 2028 oil and gas inventory that included many new oil and gas fields and sites.
Non-US point	canada_mexico.ff10.csv	2013 and 2025 point inventories from Environment and Climate Change Canada were interpolated to year 2016. 2008 inventories for Mexico were projected to the years 2014 and 2018, and then those emissions were interpolated to the year 2016.

5.2 Q/d Analysis Spreadsheets

LADCO developed a utility in R (QD_2028_V2.1.R) to extract the inventory data, calculate Q/d for each facility, and format the data for Microsoft Excel. Because a four factor analysis requires a list of sources at the process (Source Classification Code) level, LADCO developed the Q/d utility to generate a list of all facilities that contribute to 80% of the cumulative Q/d values for each Class 1 area. From those top 80% facilities, the utility further filters out those processes with emissions less than 1 ton/year.

LADCO originally used a cumulative Q/d threshold of 80% to select sources to be consistent with U.S. EPA's 2016 proposed regional haze rule guidance (U.S. EPA, 2016d). Although U.S. EPA ultimately did not

[18]https://www.epa.gov/air-emissions-modeling/2016v71-alpha-platform

recommend any specific threshold in their 2019 regional haze guidance (U.S. EPA, 2019a), the LADCO Regional Haze Workgroup explored the impacts of using different thresholds for selecting sources. LADCO used an 80% threshold for our final Q/d analyses. The workgroup felt that this threshold produced a sufficient list of sources for the LADCO member states to consider for further analysis, including for the four- factor analysis.

Table 5-2 presents Q/d threshold groups for sources in the LADCO region. This table shows the cumulative Q/d and emissions contributions from point sources in the LADCO region for different Q/d values. For example, an analysis that uses a Q/d of 4 would include 95 facilities across the LADCO region that are associated with 75.4% of the regional total Q/d, and emit 79.6% and 60.2% of the regional total point source NOx and SO_2, respectively.

Table 5-2. Q/D threshold groups for sources in the LADCO region

	Q/D threshold Group		
Description	**Q/d=1**	**Q/d=4**	**Q/d=10**
Total facilities In Group	175	95	47
Sum of Q/d	3,898	3,263	2,421
% of Q/d	90.1%	75.4%	57.1%
Sum of emissions (SO_2, NOx, $PM_{2.5}$, NH_3; tons/yr)	892,320	713,332	496,748
% of total emissions captured	86.4%	69.1%	48.1%
Sum of SO_2 emissions (tons/yr)	488,799	414,771	302,882
% of SO_2 emissions	93.9%	79.6%	58.2%
Sum of NOx emissions (tons/yr)	363,188	270,729	176,513
% of NOx emissions	80.7%	60.2%	39.2%

LADCO created an Excel spreadsheet for our member states to use in their Q/d analyses. We tagged the facility processes with four-factor analysis group codes, which are based on NAICS codes. We worked with the LADCO member states and stakeholders to generate a list of facilities that belong to seven NAICS-code categories. These categories include the sources across the LADCO region in specific NAICS code groups with Q/d values greater than 1.0. We calculated this Q/d threshold using the sum of NOX, SO_2, $PM_{2.5}$, NH_3, and VOC emissions at each facility (Q)[19] and for the Class 1 area closest to the facility (d).

[19] The Q/d support data developed by LADCO and shown here used the National Emissions Collaborative 2016v1 inventory.

Table 5-3 shows the NAICS codes and the four factor groups for sources in the LADCO region with Q/d values greater than 1. We provided this list of facilities organized by four factor analysis groups to the LADCO member states to refine based on alternative selection criteria, such as different Q/d thresholds. The sources included in the seven groups in Table 5-3 represent 94.7% of the total Q/d in the region[20].

Table 5-3. Four factor groups used for the LADCO Q/d analysis (Q/d > 1)

4-factor group ID	NAICS	NAICS name	# of Facilities	# of Units	Facility Total Q/d	% of Total Q/d
1	221112	Fossil Fuel Electric Power Generation	81	210	2690	69.0
2	212210	Iron Ore Mining	9	58	374	9.6
3	322121	Paper (except Newsprint) Mills	16	36	182	4.7
3	311221	Wet Corn Milling	5	13	45	1.2
3	311313	Beet Sugar Manufacturing	3	6	14	0.4
3	322110	Pulp Mills	2	4	9	0.2
3	322130	Paperboard Mills	3	3	7	0.2
4	327310	Cement Manufacturing	10	28	104	2.7
4	327410	Lime Manufacturing	8	13	45	1.2
5	331110	Iron and Steel Mills and Ferroalloy Manufacturing	9	33	77	2.0
6	486210	Pipeline Transportation of Natural Gas	16	40	77	2.0
6	221210	Natural Gas Distribution	2	2	4	0.1
7	324199	All Other Petroleum and Coal Products Manufacturing	6	12	47	1.2
7	324110	Petroleum Refineries	5	6	9	0.2

LADCO developed the spreadsheet QoverD_V5.7_2016_scc.xlsx (see the Electronic Docket) to investigate how different inventory years base years, future years, and source inventories impact the Q/d calculation results. We developed this spreadsheet as a tool for our member states to evaluate different Q/d calculation methods and values. In addition to sources in all states, Canada, and Mexico, the spreadsheet includes all facilities with emissions greater than 1 ton/year of any pollutant, and the distances from each facility to every class 1 area in the country.

[20] The LADCO regional haze workgroup concurred on a process to exclude very small sources or sources that had negligible Q/d values from this analysis. The Total Q/d number for the region only includes those sources with non-negligible Q/d impacts.

The spreadsheets and emissions data files used by the LADCO states for the Q/d analysis during the second regional haze implementation period are available in the electronic docket to this TSD.

6 CAMx Model Performance Evaluation Results

This section summarizes the operational evaluation of the LADCO CAMx simulations for the two modeling platforms used for the second regional haze implementation period. As described in Section 3.6, LADCO compared particulate matter (PM) surface layer concentrations from 2011 and 2016 annual base year CAMx simulations to ambient surface monitoring data to evaluate the skill of the model at reproducing the observations. The LADCO model performance evaluation (MPE) results for each of the modeling years are compared to model performance benchmarks and to MPE results from U.S. EPA modeling of similar data. Additional MPE results and discussion for the LADCO 2011 and 2016 CAMx simulations are in the Supplemental Materials Section S5.

We emphasize the nitrate and sulfate model performance during the winter (January, February, and December) and spring (March, April, and May) months as these are species and periods that experience the most anthropogenic impairment to visibility at the Class I areas in the LADCO region. Figure 6-1 shows the distribution of most impaired days in each month across all of the LADCO region Class I areas during the period 2014-2018. The winter and spring months account for over 70% of the most impaired days in the Great Lakes region. The PM species contribution plot for Voyageurs National Park in Figure 6-2 shows that nitrate and sulfate aerosol contributed 79% of the light extinction on the most impaired days during the period 2014-2018. The PM species contributions for the other LADCO region Class I areas are similar to Voyageurs[21].

[21] Source: Federal Land Manager Environmental Database; http://views.cira.colostate.edu/fed/

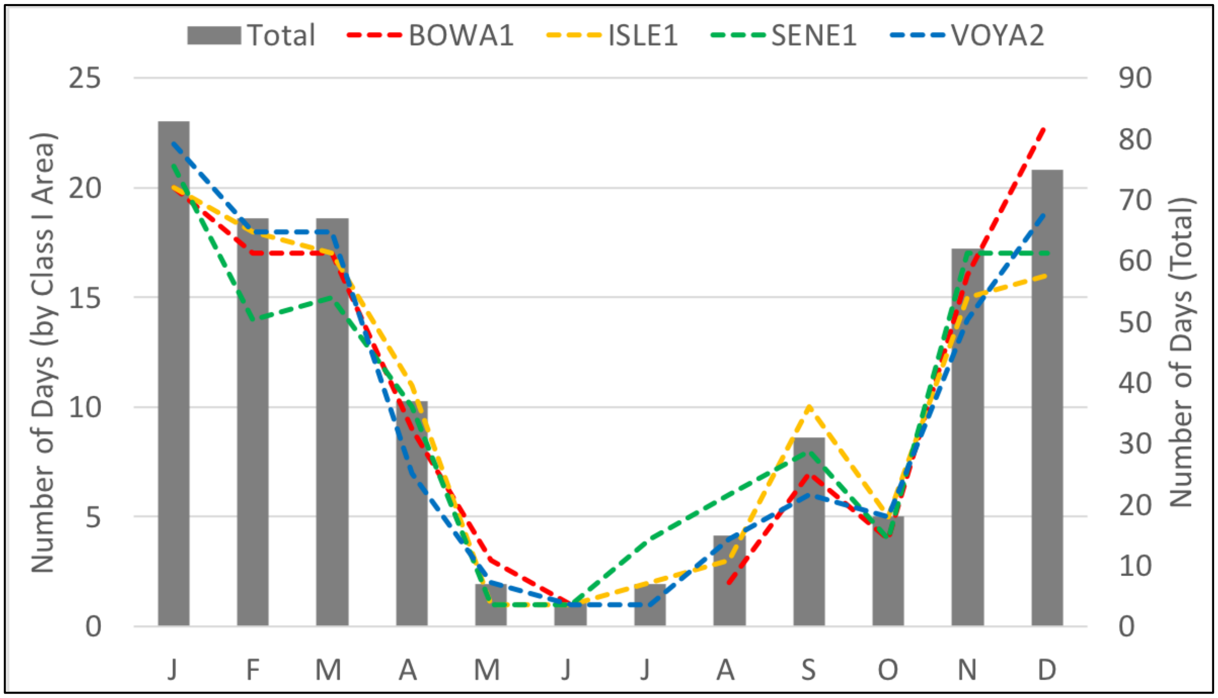


Figure 6-1. Monthly distribution of most impaired days for the LADCO region Class I areas during the period 2014-2018.

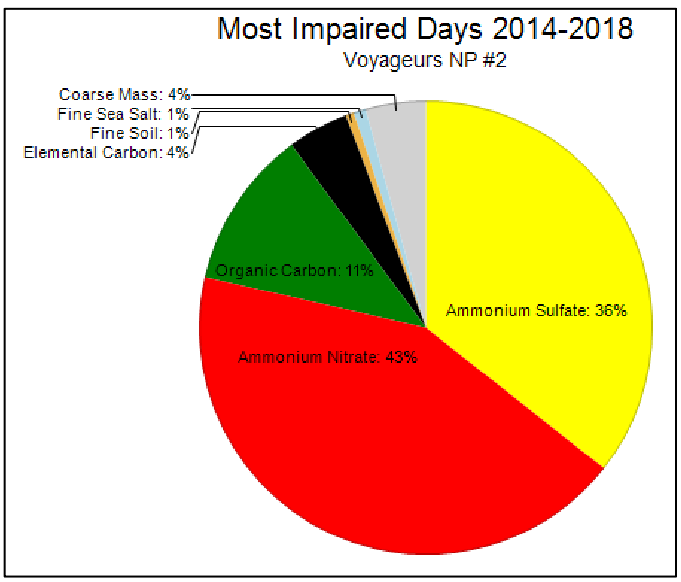


Figure 6-2. Average PM species composition at Voyageurs National Park, MN on the most impaired days during the period 2014-2018.

6.1 2011 CAMx Model Performance Evaluation Results

A summary of the CAMx MPE results for 2011 are presented in this section. The summary first presents annual and regional average MPE statistics for all CSN and IMPROVE monitoring locations in the LADCO region to provide an overview of the CAMx model's skill at simulating $PM_{2.5}$. Supplemental Materials Section S5 includes seasonal and regional MPE metrics to identify how well the model can estimate PM concentrations during different times of the year. Section S5 includes model performance information for different $PM_{2.5}$ components (total $PM_{2.5}$, sulfate, nitrate, and total carbonaceous aerosols[22]) to quantify how well the model can simulate the key light scattering species that most contribute to visibility impairment.

6.1.1 Annual PM Model Performance

Table 6-1 presents annual and regional average model performance statistics for the CSN and IMPROVE monitors in the LADCO region. Relative to the performance goals (which are more stringent) and criteria (which are less stringent) in Table 3-7, the LADCO 2011 CAMx simulation had acceptable performance for annual average total $PM_{2.5}$, sulfate, and nitrate for both the CSN and IMPROVE networks. The model performance statistics for all three of these species were near or within the more restrictive performance goals for NMB, NME, and correlation. While Emery et al. (2017) did not provide performance benchmarks for total carbonaceous (TC = organic aerosol + elemental carbon) $PM_{2.5}$, the goals and criteria for EC and OC are close to each other and can be used to evaluate the modeled TC concentrations. The 2011 CAMx estimates of TC at the IMPROVE locations in the LADCO region were within the performance benchmarks. The notable LADCO 2011 CAMx simulation performance issue on an annual and regional basis is with TC at the CSN monitors. The CAMx simulation overestimates of the observed TC concentrations (NMB = +68.5%) are outside of the performance criteria (40-50%) for carbonaceous aerosols.

[22] Ammonium ion (NH_4^+) evaluation is not reported here because the ammonium ion species reported by the monitoring networks is not a true measurement and thus is not readily comparable to the CAMx modeled species. Soil and sea salt are not included in this evaluation because they are a small component of the measured visibility at the LADCO class I areas on the most impaired days;

Annual average statistics for all of the 2011 simulation $PM_{2.5}$ species at the IMPROVE monitors in the LADCO region are within the NMB performance goals and the NME performance criteria. The LADCO 2011 CAMx simulation performance meets the performance criteria for nitrate at the IMPROVE monitors for both NMB and NME.

Table 6-1. LADCO 2011 CAMx annual average PM modeling performance summary

Species	Obs ($\mu g/m^3$)	CAMx ($\mu g/m^3$)	NMB (%)	NME (%)	r
CSN $PM_{2.5}$	10.89	11.63	9.95	35.83	0.76
IMPROVE $PM_{2.5}$	6.63	6.89	7.41	40.52	0.75
CSN SO_4	2.20	1.86	-12.96	36.29	0.76
IMPROVE SO_4	1.83	1.53	-7.58	38.20	0.76
CSN NO_3	1.83	1.83	2.47	51.01	0.73
IMPROVE NO_3	0.93	1.13	25.93	70.66	0.72
CSN TC	2.92	4.63	68.46	80.93	0.70
IMPROVE TC	2.38	2.69	19.20	53.21	0.68
Key:	Met MPE Goal		Met MPE Criteria		

6.1.2 Seasonal PM Model Performance

Supplemental Materials Section S5.1.5 includes 2011 seasonal CAMx model performance statistics tables for the CSN and IMPROVE monitors in each LADCO state. The seasonal and site average statistics in these tables include observed and modeled concentrations, NMB, NME, and correlation

The skill of the LADCO 2011 CAMx simulation at simulating observed $PM_{2.5}$ species at CSN and IMPROVE monitors in the region was mixed. The LADCO CAMx 2011 modeling results are comparable to the U.S. EPA 2011 modeling platform used for preliminary regional haze modeling (U.S. EPA, 2017a), as expected since the two modeling platforms were nearly identical. Intercomparing the LADCO and U.S. EPA 2011 CAMx simulations is complicated by the use of different regions to calculate performance statistics. The six-state LADCO region used here for calculating performance statistics overlaps with but is not completely inclusive of the states in the Ohio Valley and Upper Midwest regions used by U.S. EPA.

While the LADCO 2011 CAMx simulation of total $PM_{2.5}$ had an overprediction bias through most of the year, it achieved the MPE benchmarks for the spring and winter months at most of the CSN and IMPROVE monitors in the LADCO region. The LADCO 2011 CAMx simulation had regional average spring and winter NMBs for total $PM_{2.5}$ at the IMPROVE monitors of +8.6% and +29%, respectively.

Figure 6-3 summarizes the winter and spring 2011 CAMx model performance at the IMPROVE monitors in the LADCO region. These plots compare the observed (left stacked bar) and CAMx simulated (right stacked bar) $PM_{2.5}$ species averaged across all IMPROVE monitors in the LADCO region for each season. The spring season CAMx overprediction bias across the region is driven by excess nitrate and organic aerosol in the model. The $PM_{2.5}$ species "Other" in this plot represents fine crustal and seasalt particles, and it is also overpredicted by CAMx. The winter season CAMx overprediction bias is driven primarily by excess organic aerosol in the model, and to a lesser extent excess Other PM.

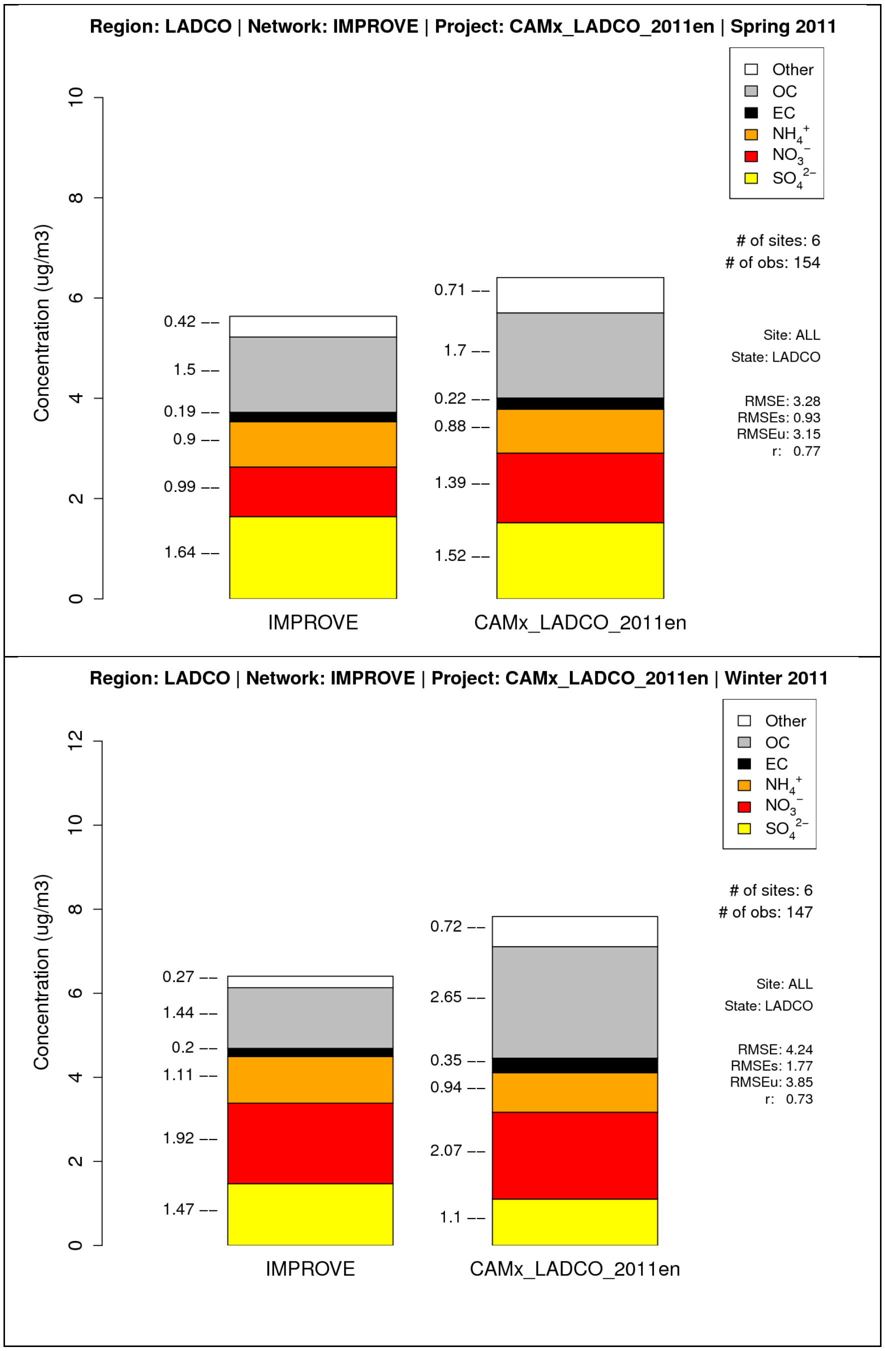


Figure 6-3. Stacked bar plot of spring (top) and winter (bottom) season $PM_{2.5}$ species averaged across all IMPROVE monitors in the LADCO region.

6.1.3 Comparison of LADCO and U.S. EPA 2011 PM Model Performance

The U.S. EPA 2011 CAMx simulation had regional average NMBs (average of the Ohio Valley and Upper Midwest regions) at the IMPROVE monitors in the spring and winter of +13.7%, and +19%, respectively.

The significant wintertime overprediction bias for total $PM_{2.5}$ at the Minnesota IMPROVE sites (NMB > +52%) noted in Supplemental Materials Section S5.1.1 is also present in the U.S. EPA results (Figure 26 in U.S. EPA, 2017a).

Both the LADCO and U.S. EPA CAMx 2011 simulations of spring season sulfate show the stark spatial gradient from overprediction to underprediction (i.e., positive to negative NMBs) along the southern part of the LADCO region. Both simulations also underpredicted wintertime sulfate throughout most of the LADCO region, and produced lower biases (i.e., good simulations) for the northern Class I area IMPROVE monitors.

The U.S. EPA CAMx 2011 simulation overpredicted nitrate in the spring and underpredicted nitrate in the winter, similar to the LADCO simulation. The two simulations both generally captured the monthly variability in observed nitrate concentrations at both the IMPROVE and CSN monitors with concentrations peaking in the winter months (e.g., Figure S 5-11). As with the LADCO CAMx simulation, the U.S. EPA simulation also had a large wintertime nitrate overprediction bias at the northern Class I area IMPROVE monitors (NMB > +40%).

The U.S. EPA (2017a) reported MPE results for elemental and organic carbon aerosols. While LADCO reports total carbonaceous aerosols here, the winter and spring season overpredictions are evident in the results from both simulations.

6.2 2016 CAMx Model Performance Evaluation Results

A summary of the CAMx MPE results for 2016 are presented in this section. The summary presents annual average MPE statistics for all CSN and IMPROVE monitoring locations in the LADCO region to provide an overview of the CAMx model's skill in simulating $PM_{2.5}$. Supplemental Materials Section S5 includes seasonal and regional MPE metrics that are used to identify how well the model can estimate PM concentrations during different times of the year. As with the 2011 simulation, Section S5 also includes model performance information for different $PM_{2.5}$ components (total $PM_{2.5}$, sulfate, nitrate, and total carbonaceous aerosols) to quantify how well the model can simulate the key light scattering species that most contribute to visibility impairment.

6.2.1 Annual PM Model Performance

Table 6-2 presents annual and regional average model performance statistics for the CSN and IMPROVE monitors in the LADCO region. Relative to the performance goals and criteria in Table 3-7, CAMx shows marginally acceptable performance for average total $PM_{2.5}$, sulfate, and nitrate. CAMx meets the more restrictive NMB performance goal only for nitrate at the IMPROVE sites. CAMx achieved the NMB model performance criteria for total $PM_{2.5}$ and sulfate at both networks, and CSN nitrate. The CAMx 2016 simulation had a severe overprediction bias for the carbonaceous aerosols.

Table 6-2. LADCO 2016 CAMx PM modeling performance summary

Species	Obs ($\mu g/m^3$)	CAMx ($\mu g/m^3$)	NMB (%)	NME (%)	r
CSN $PM_{2.5}$	8.19	10.37	30.47	44.68	0.71
IMPROVE $PM_{2.5}$	4.75	5.63	22.82	42.61	0.66
CSN SO_4	1.13	1.42	33.68	48.60	0.70
IMPROVE SO_4	0.99	1.07	16.50	39.53	0.71
CSN NO_3	1.26	1.42	40.19	78.38	0.52
IMPROVE NO_3	0.72	0.64	11.89	75.46	0.50
CSN TC	2.18	4.46	116.93	121.80	0.66
IMPROVE TC	1.89	2.72	56.44	69.95	0.64
Key:	Met MPE Goal		Met MPE Criteria		

6.2.2 Seasonal PM Model Performance

Supplemental Materials Section S5.2.6 includes seasonal CAMx model performance tables for the CSN and IMPROVE monitors in each LADCO state. The seasonal and site average statistics in these tables include observed and modeled concentrations, NMB, NME, and correlation

The LADCO 2016 CAMx simulation performance in simulating observed $PM_{2.5}$ species at CSN and IMPROVE monitors in the region was mixed. As with the 2011 CAMx modeling platform, the LADCO 2016 CAMx simulation exhibited better skill with the inorganic aerosol species than with the carbonaceous aerosols. The CAMx 2016 simulation had particularly poor performance in estimating organic aerosols.

Figure 6-4 summarizes the winter and spring CAMx model performance at the IMPROVE monitors in the LADCO region. These plots compare the observed (left stacked bar) and CAMx simulated (right stacked bar) $PM_{2.5}$ species averaged across all IMPROVE monitors in the LADCO region for each season. The spring season CAMx overprediction bias across the region is driven by excess organic aerosol and $PM_{2.5}$ "Other", which includes fine crustal and seasalt particles. On a seasonal, regionwide basis the LADCO 2016 CAMx simulation compares well to the springtime IMPROVE observations for sulfate, nitrate, ammonium, and elemental carbon. The winter season CAMx overprediction bias at the LADCO IMPROVE sites is also driven primarily by excess organic aerosol in the model, and to a lesser extent excess $PM_{2.5}$ Other. The total $PM_{2.5}$ overprediction is attenuated by underpredictions of wintertime nitrate and ammonium.

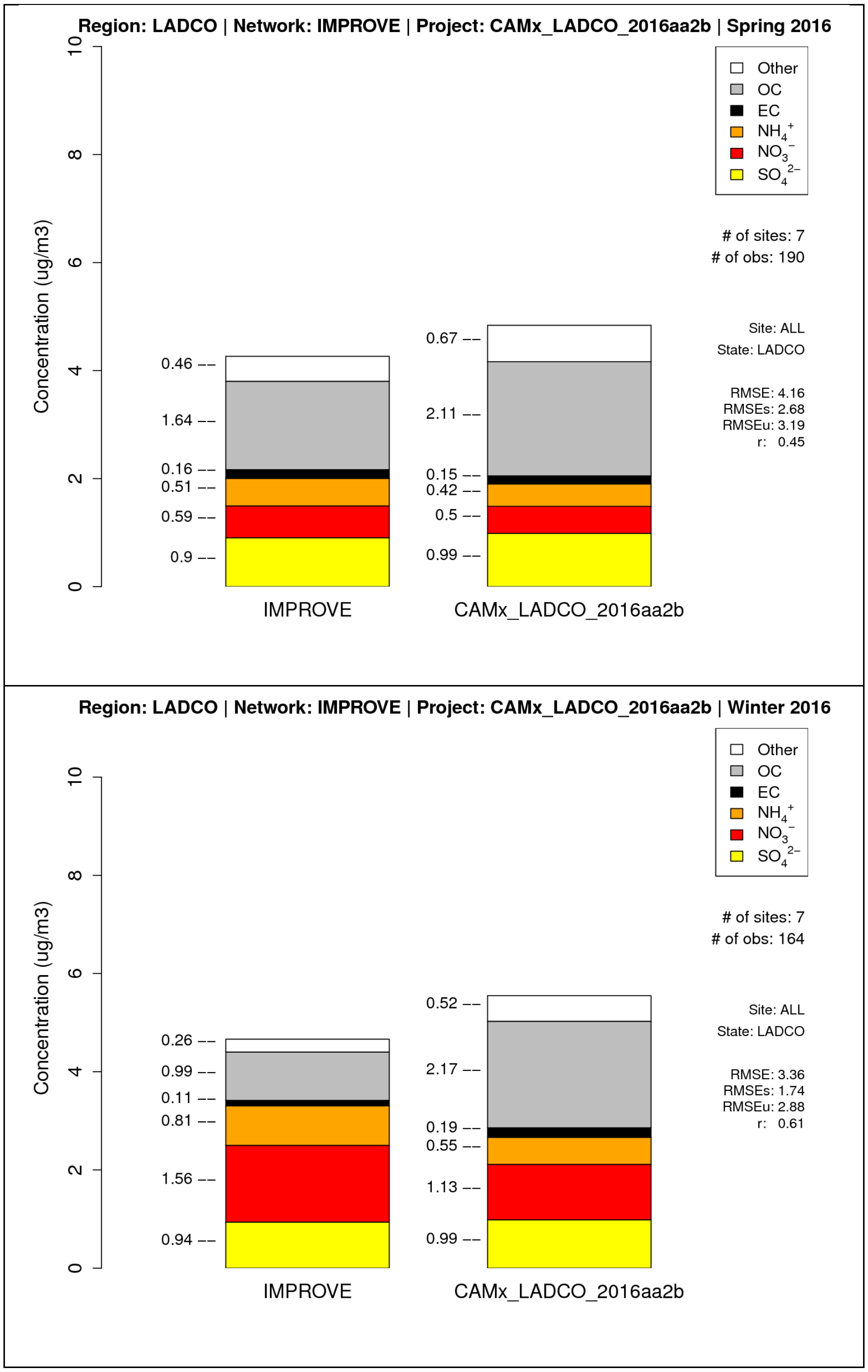


Figure 6-4. Stacked bar plot of 2016 spring (top) and winter (bottom) season $PM_{2.5}$ species averaged across all IMPROVE monitors in the LADCO region.

6.2.3 Comparison of LADCO and U.S. EPA 2016 PM Model Performance

The LADCO CAMx 2016 modeling results are comparable to the U.S. EPA 2016 modeling platform used for their preliminary regional haze modeling (U.S. EPA, 2019b), as expected since the two modeling platforms were nearly identical. As with the 2011 modeling platform, intercomparing the LADCO and U.S. EPA 2016 CAMx simulations is complicated by the use of different regions to calculate performance statistics.

While the LADCO 2016 CAMx simulation of total $PM_{2.5}$ had an overprediction bias through most of the year, it achieved the model performance benchmarks for the spring and winter months at most of the CSN and IMPROVE monitors in the LADCO region. The LADCO 2016 CAMx simulation had regional average spring and winter NMBs for total $PM_{2.5}$ at the IMPROVE monitors of +15.5% and +29.2%, respectively. The U.S. EPA 2016 CAMx simulation of total $PM_{2.5}$ had regional average NMBs (average of the Ohio Valley and Upper Midwest regions) at the IMPROVE monitors in the spring and winter of +16.3% and +31%, respectively. The LADCO 2016 CAMx simulation had regional average spring and winter NMBs for total $PM_{2.5}$ at the CSN monitors of +23.3% and +34%, respectively. In comparison, the U.S. EPA 2016 CAMx simulation had regional average NMBs at the CSN monitors in the spring and winter of +12% and +17%, respectively.

Both the LADCO and U.S. EPA CAMx 2016 simulations overpredicted sulfate throughout the year in most of the LADCO region. Both simulations better predicted (i.e., lower NMBs) sulfate in the winter months than in the spring. The LADCO 2016 CAMx simulation had regional average spring and winter NMBs for sulfate at the IMPROVE monitors of +7.2% and +9.4%, respectively. The U.S. EPA 2016 CAMx simulation had regional average NMBs at the IMPROVE monitors in the spring and winter of +11% and +7.2%, respectively.

The U.S. EPA 2016 CAMx simulation overpredicted nitrate in the spring and underpredicted nitrate in the winter, similar to the LADCO 2016 simulation. The two simulations both generally captured the monthly variability in observed nitrate concentrations at both the IMPROVE and CSN monitors with concentrations peaking in the winter months. As with the LADCO CAMx simulation, the U.S. EPA 2016 simulation also produced a large underprediction bias at the northern Class I area IMPROVE monitors in the winter (NMB > +40%).

The U.S. EPA (2019b) reported MPE results for elemental and organic carbon aerosols. While LADCO reports total carbonaceous aerosols here, the severe winter and spring season overpredictions are evident in the results from both simulations.

6.3 Model Performance Discussion

In the preceding sections and in Supplemental Materials Section S5 we present MPE results for the PM species components of regional haze estimated by the LADCO 2011 and 2016 CAMx simulations. To narrow the scope of the evaluation for this TSD, we focused on the CAMx performance in simulating spring and winter season nitrate and sulfate. We chose to focus our evaluation on these periods and species because they are associated with the most anthropogenically impaired conditions at the Class I areas in the LADCO region.

Table 6-3 compares the LADCO 2011 CAMx and 2016 CAMx simulation model performance for the spring and winter seasons by monitoring network and PM species. The table shows the average CAMx NMB and NME values across the CSN and IMPROVE monitor locations in the six-state LADCO region for the spring and winter seasons. This table presents a more comprehensive view of the model species than in the preceding sections because it includes the carbonaceous aerosol species and ammonium ion in addition to sulfate and nitrate. Dark green shading indicates if the simulation achieved the performance goal for the model species; light green shading indicates that the model achieved the less stringent performance criteria (Emery et al., 2017).

Looking across all of the MPE benchmarks in Table 6-3, both of the LADCO CAMx simulations achieved either the model performance goals or criteria for most of the species in the two seasons. The LADCO 2011 CAMx simulation of spring season PM species at the IMPROVE sites had the best model performance with most of the species achieving the more stringent MPE goals for both NMB and NME. While not as strong as the 2011 simulation, the spring season 2016 CAMx simulation of PM at the IMPROVE monitors achieved at least the NMB and NME criteria for most of the species. In both years, the CAMx simulations generally better estimated PM at the more rural IMPROVE sites compared to the CSN sites (i.e., lower NMB and NME at IMPROVE vs CSN).

A comparison of the CAMx model performance across the two base years shows fairly comparable results. CAMx did not simulate well the carbonaceous aerosols, and organic aerosol in particular, in either of the base years. The model overestimated these species in both the spring and winter seasons and at both of the networks shown in Table 6-3. The CAMx 2011 simulation of nitrate at the CSN monitor locations is slightly better than the 2016 simulation, but both simulation years achieved the MPE goals for winter season nitrate. Where the 2011 simulation overpredicted nitrate at the IMPROVE monitors in both seasons, the 2016 simulation underpredicted nitrate and had slightly lower absolute NMB and NME values. The 2011 and 2016 simulations of sulfate at the IMPROVE monitors were comparable. Where the 2011 simulation unpredicted sulfate on average across the IMPROVE sites, the 2016 simulation overpredicted spring and winter season sulfate. Notable deficiencies in the LADCO CAMx simulation performance are winter 2011 (NMB = -38%) and spring 2016 (NMB = +31%) sulfate at the CSN monitors, and organic aerosols in both years at the CSN monitors.

The LADCO CAMx simulations performed relatively well in estimating spring and winter season nitrate and sulfate at the IMPROVE monitors in both years. This result is significant because these two species are the biggest contributors to haze in the LADCO region Class I areas on the most impaired days. The PM model performance for both the 2011 and 2016 LADCO simulations are very similar to the models used by U.S. EPA for their recent regional haze assessments (U.S. EPA, 2017a; U.S. EPA, 2019b). We cannot infer the impacts of the CAMx biases and errors on how the model responds to emissions changes with the information that we have here. Namely, we cannot quantify the impacts of the CAMx biases on the relative response factors (RRFs) and derived future year PM design values and derived haze projections because we don't know how much each of the model processes (e.g., emissions, chemistry, deposition) contribute to the total bias and error in the model.

Table 6-3. NMB (%) and NME (%) summary statistics for LADCO 2011 and 2016 CAMx simulations[23]

Species	2011				2016			
	Spring		Winter		Spring		Winter	
Statistic	NMB	NME	NMB	NME	NMB	NME	NMB	NME
CSN								
EC	42.80	64.11	88.27	97.86	-4.86	43.05	45.92	63.25
NH_4	17.77	39.36	-16.40	39.21	120.26	130.69	31.46	63.74
NO_3	30.79	63.58	-11.49	35.06	20.08	67.29	-10.27	48.21
OA	56.91	66.65	111.73	117.23	61.15	71.74	129.51	132.40
$PM_{2.5}$	19.60	37.73	8.43	30.43	18.81	37.85	25.82	41.74
SO_4	1.49	37.18	-38.15	46.23	31.17	45.60	10.05	38.68
TC	53.84	64.50	107.62	113.43	35.08	54.74	105.17	108.63
IMPROVE								
EC	16.46	47.23	82.02	83.93	0.41	43.60	90.36	94.67
NH_4	-8.12	35.64	-6.05	40.57	-14.65	37.01	-32.62	42.88
NO_3	18.50	61.85	29.65	61.57	-8.40	59.04	-25.11	61.56
OA	12.19	44.58	88.07	89.42	41.97	69.76	126.35	126.85
$PM_{2.5}$	11.48	35.26	36.81	49.06	21.18	47.91	30.78	54.23
SO_4	-0.69	32.37	-17.72	49.80	17.08	36.72	11.78	39.36
TC	12.53	43.78	87.39	88.53	38.52	66.78	122.76	123.28
Key:	Met MPE Goal		Met MPE Criteria					

[23] Dark green shading indicates if the simulation achieved the performance goal for the model species; light green shading indicates that the model achieved the less stringent performance criteria (Emery et al., 2017).

7 Future Year Haze Projections

The air quality modeling that LADCO completed to support regional haze SIPs for the second implementation period culminated in estimating 2028 regional haze conditions in U.S. Class I areas. The future year haze projections described in this section will be available to the LADCO member states to use as weight of evidence to support their demonstration of progress towards natural visibility conditions in 2064. This section presents the methods that LADCO used to forecast 2028 haze conditions, examples of the analysis products from our work, and instructions for how to access our forecasted visibility data for all of the nation's Class I areas.

7.1 Methods

LADCO followed the U.S. EPA Modeling Guidance for Demonstrating Air Quality Goals for Ozone, $PM_{2.5}$, and Regional Haze (US EPA, 2018) for estimating the 2028 future year visibility condition. Hereafter, the EPA's modeling guidance is referred to as "the SIP Modeling Guidance". The SIP Modeling Guidance describes the recommended modeling analyses to track RHR reasonable progress goals (RPGs). The RPGs reflect the states' long-term strategy for meeting the requirements of the RHR. LADCO completed two set of CAMx modeling runs for forecasting haze in 2028, one is based on 2011 base year and another one is based on 2016 base year. Using these modeling outputs and IMPROVE visibility data, LADCO estimated 2028 visibility conditions.

As required by the RHR, a state's RPGs must produce an improvement in visibility for the 20 percent most anthropogenically impaired days and ensure no degradation in visibility for the 20 percent clearest days, relative to baseline visibility conditions. The baseline for each Class I area is the average visibility (in deciviews) for the years 2000 through 2004. The visibility conditions in these years are the benchmarks for the requirements to improve or not degrade visibility on different types of days. In addition, states are required to determine the rate of improvement in visibility needed to reach natural conditions by 2064 for the 20 percent most anthropogenically impaired days.

The LADCO visibility projections followed the procedures in Section 5 of the SIP Modeling Guidance. Future year modeled visibility is forecast relative to a 5-year period centered around the base modeling year. LADCO estimated the 2028 visibility from the 2011 and 2016 base years using ambient IMPROVE data for the 2009-2012 and the 2014-2018 periods, respectively. LADCO estimated base and future year visibility with the "revised" IMPROVE equation (Pitchford, 2007). The revised IMPROVE equation "reconstructs light extinction" from modeled and measured PM species concentrations and relative humidity data. The IMPROVE equation calculates visibility impairment or beta extinction (b_{ext}) in units of inverse megameters (Mm^{-1}) as follows:

$$b_{ext} = 2.2 \times fs(RH) \times [\text{Small Sulfate}] + 4.8 \times fL(RH) \times [\text{Large Sulfate}]$$

$$+ 2.4 \times fs(RH) \times [\text{Small Nitrate}] + 5.1 \times fL(RH) \times [\text{Large Nitrate}]$$

$$+ 2.8 \times \{\text{Small Organic Mass}] + 6.1 \times [\text{Large Organic Mass}]$$

The total sulfate, nitrate, and organic mass concentrations are each split into two fractions, representing small and large size distributions of those components. Site-specific Rayleigh scattering is calculated based on the elevation and annual average temperature of each IMPROVE monitoring site.

LADCO used the U.S. EPA Software for Model Attainment Test- Community Edition (SMAT-CE) Version 1.6 (SMAT-CE)[24] tool to calculate 2028 deciview (dv) values on the 20% most anthropogenically impaired and 20% clearest days at each of the IMPROVE monitors in Class I Areas. We used SMAT-CE to estimate the 2028 future year visibility on the 20% most anthropogenically impaired days and 20% clearest days at each Class I area using the observed IMPROVE data (2009-2013 and 2014-2018) and the relative percent change in modeled PM species between 2016 and 2028; and between 2011 and 2028. The SMAT-CE tool outputs individual year and 5-year average base year and future year dv values on the 20% most impaired days and 20% clearest days. Additional SMAT-CE output variables include the results of intermediate calculations, such as PM species light extinction values (both base and future year) and species-specific RRFs (on the 20% most impaired and clearest days).

The process for calculating future year visibility conditions with SMAT-CE is described in the following six steps (see the SIP Modeling Guidance for a more detailed description and examples). LADCO applied this process to data from each Class I area (i.e., each IMPROVE monitoring site).

[24] https://www.epa.gov/scram/photochemical-modeling-tools

1. Estimate anthropogenic impairment (in Mm^{-1}) on each day using observed speciated $PM_{2.5}$ and PM_{10} data for each of the 5 years comprising the base period and rank the days based on impairment. This ranking is used to determine the 20 percent most anthropogenically impaired days. For each Class I area, also rank observed visibility (in dv) on each day using the same speciated data. This ranking will determine the 20 % clearest days.
2. Calculate the mean dv for the 20 percent most anthropogenically impaired days and 20 percent clearest days for each of the 5 years comprising the base period and the 5-year mean dv for the most impaired and clearest days.
3. Use the CAMx model to simulate air quality with base (2011 and 2016) and future year (2028) emissions. We applied SMAT-CE to the model results to develop site-specific relative response factors (RRFs) for each component of PM identified in the “revised” IMPROVE equation. The RRFs are an average percent change in species concentrations based on the measured 20% most impaired and 20% clearest days from 2011 or 2016.
4. Multiply the species-specific RRFs by the measured daily species concentration data during the 2009-2013 and 2014-2018 base periods for each day in the measured 20% most impaired day set and each day in the 20% clearest day set. This results in daily future year 2028 PM species concentration data.
5. Using the results in Step 4 and the IMPROVE algorithm, calculate the future daily extinction coefficients for the previously identified 20% most impaired days and 20% clearest days in each of the five base years.
6. Calculate daily dv values (from total daily extinction) and then compute the future year (2028) average mean dv values for the 20% most impaired days and 20% clearest days for each year. Average the five years together to get the final future mean dv values for the 20% most impaired days and 20% clearest days.

Table 7-1 details the settings used by LADCO for the SMAT-CE runs to estimate the 2028 future year dv value.

Table 7-1. SMAT-CE software configuration settings for 2028 visibility calculations

SMAT Option	Settings/file used for the 2011-based 2028 visibility calculation	Settings/file used for the 2016-based 2028 visibility calculation
IMPROVE algorithm	Use new version	Use new version
Grid cells at monitor or Class I area centroid?	Use grid cells at monitor	Use grid cells at monitor
IMPROVE data file	ClassIareas_NEWIMPROVEALG_2000to2018_2020_may5_IMPAIRMENT.csv[25]	ClassIareas_NEWIMPROVEALG_2000to2018_2020_may5_IMPAIRMENT.csv
Start monitor year	2009	2014
End monitor year	2013	2018
Temporal adjustment at monitor	3x3	3x3
Minimum years required for a valid monitor	1	1
Baseline model file	mats.PM.12US2.bulk.LADCO_2011en.csv	mats.PM.12US2.bulk.2016_ladco_v1b.cb6r4.csv
Forecast model file	mats.PM.12US2.bulk.LADCO_2028HAZE.csv	mats.PM.12US2.bulk.2028_ladco_v1b.cb6r4.csv

7.2 LADCO 2028 Haze Projections

The base and future year dv values on the 20% clearest and most impaired days at Class I areas within LADCO states for the 2011 and 2016 base model periods and 2028 future year are shown in Table 7-2 and Table 7-3, respectively. The last column of each table shows the predicted dv change at each Class I area on the 20% most impaired days. The visibility conditions at the Class I areas in the LADCO region

[25] The IMPROVE ambient data file has the 20% most impaired days identified as "group 90" days and 20% clearest days identified as "group 10" days. The definition of the most impaired days uses the EPA recommended methodology from Technical Guidance on Tracking Visibility Progress for the Second Implementation Period of the Regional Haze Program. Technical Guidance on Tracking Visibility Progress for the Second Implementation Period of the Regional Haze Program | Visibility and Regional Haze | US EPA. The IMPROVE data file used for this analysis included patched and/or substituted data.

were predicted to improve on average by about 2 dv by 2028 as compared to the 2011 base year, and to have about a 0.8 dv improvement relative to the 2016 base year.

Table 7-2. Base and future year deciview values on the 20% clearest and 20% most impaired days at Class I area within LADCO region for the base model period (2009-2013) and future year (2028)

	20% Clearest Days (dv)			20% Most Impaired Days (dv)		
IMPROVE Site ID	Base Period	Future Year	Change (2028-2011)	Base Period	Future Year	Change (2028 -2011)
BOWA1	4.83	4.79	-0.04	16.42	14.43	-1.99
ISLE1	5.40	5.29	-0.11	17.63	15.48	-2.15
SENE1	5.50	5.35	-0.15	19.92	17.34	-2.58
VOYA2	5.68	5.60	-0.08	17.12	15.08	-2.04

Table 7-3. Base and future year deciview values on the 20% clearest and 20% most impaired days at Class I area within LADCO region for the base model period (2014-2018) and future year (2028)

	20% Clearest Days (dv)			20% Most Impaired Days (dv)		
IMPROVE Site ID	Base Period	Future Year	Change (2028 -2016)	Base Period	Future Year	Change (2028 -2016)
BOWA1	4.48	4.30	-0.07	13.96	13.17	-0.79
ISLE1	5.30	5.23	-0.07	15.54	14.83	-0.71
SENE1	5.27	5.17	-0.10	17.57	16.67	-0.90
VOYA2	5.31	5.25	-0.06	14.18	13.36	-0.82

Figure 7-1 shows the visibility glidepath at the Boundary Waters Canoe Area (BOWA) in Minnesota for the 20% most impaired days based on the 2011- and 2016-based 2028 CAMx simulations. The glidepath represents a linear rate of progress and shows the amount of visibility improvement needed in each implementation period to achieve natural visibility conditions in the Class I area by 2064. The figure compares the glidepath with the observed visibility conditions (yellow dots) for 2000-2018[26], baseline visibility condition (observed condition in 2000-2004 period)[27], base year visibility condition (green dot at 2011 or 2016), as well as the predicted 2028 visibility condition (red dot at 2028), and the 2064 target

[26] Dataset was obtained from EPA in June 2020; Filename: ClassIareas_NEWIMPROVEALG_2000to2018_2020_may5_IMPAIRMENT.csv

[27]Guidance on Regional Haze State Implementation Plans for the Second Implementation Period (8/2019) https://www.epa.gov/visibility/guidance-regional-haze-state-implementation-plans-second-implementation-period; Natural and Baseline Visibility Condition Values from https://www.epa.gov/sites/production/files/2020-06/documents/memo_data_for_regional_haze_technical_addendum.pdf

of natural conditions[27] for a particular Class I area. In addition, a dashed blue line drawn between the visibility condition in baseline period (2000-2004) and natural condition in 2064 shows a uniform rate of progress (URP) and/or called "glidepath" line between these two points. The glidepath represents a linear or uniform rate of progress and is the amount of visibility improvement needed in each implementation period to achieve natural visibility conditions in the Class I area by 2064.

The RHR allows states to optionally propose adjustments at the end point of the glidepath (URP) to exclude uncontrollable haze contributions, such as contributions from international anthropogenic emissions and certain prescribed fires. The proposed adjustments for each Class I area must be developed using scientifically valid data and methods. U.S. EPA demonstrated in their preliminary (U.S. EPA, 2017a) and updated (U.S. EPA, 2019b) regional haze modeling efforts how the glidepath endpoints could be adjusted. LADCO used the same approaches demonstrated by U.S. EPA to adjust the glidepath endpoints for our 2011 and 2016-based visibility projections.

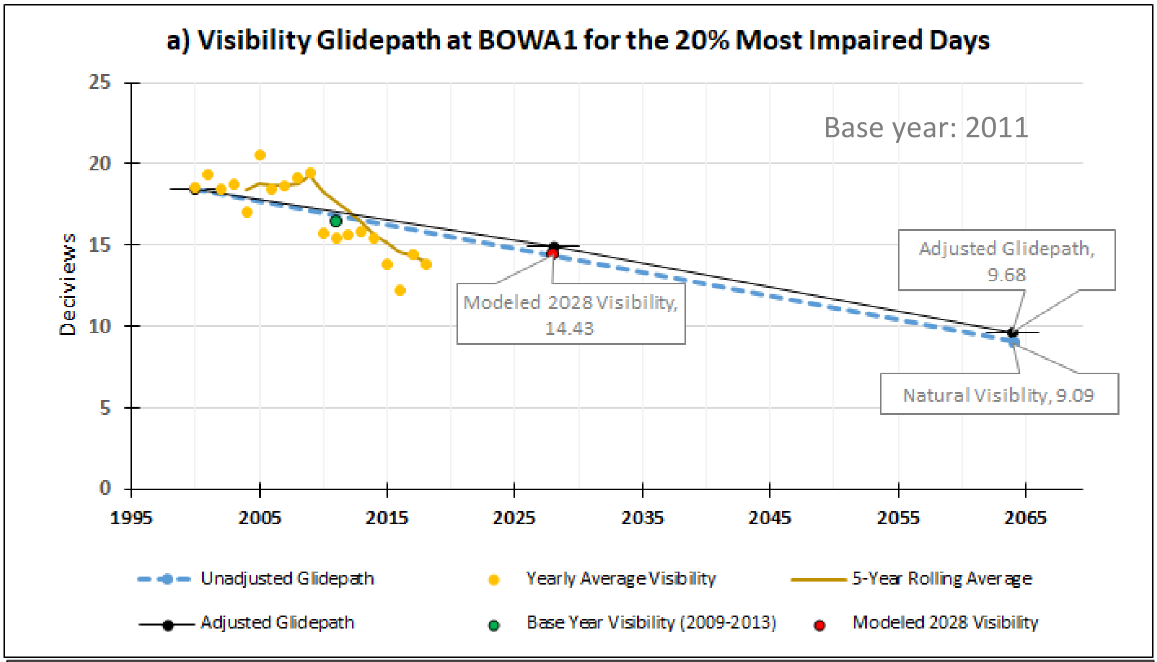
The figures below also show the adjusted glidepath. The adjusted glidepath for the 2011-based 2028 visibility prediction accounts for contributions from Mexico and Canada anthropogenic emissions. In addition to the Canadian and Mexico sources inside the modeling domain, the adjustment to the glidepath for the 2016-based 2028 visibility predictions also considered international anthropogenic sources outside of the modeling domain, including non-U.S. Class 3 commercial marine emissions (U.S. EPA, 2019b). The glidepath adjustments for the 2011-based modeling are smaller than the 2016-based modeling because they are calculated using fewer haze precursor sources.

Figure 7-1 through Figure 7-4 show the 2011-based and 2016-based LADCO 2028 visibility predictions relative to the URP glidepath for the Boundary Waters Canoe Area (BOWA), Isle Royale National Park (ISLE), Seney National Wildlife Refuge (SENE), and Voyageurs National Park (VOYA) Class I areas, respectively.

LADCO's CAMx visibility forecasts for Class I areas outside of the LADCO region are available in an electronic docket to this TSD in the following spreadsheets:

LADCO 2011-based 2028 Class I Area Visibility Forecasts (6.6 Mb XLSX file)

LADCO 2016-based 2028 Class I Area Visibility Forecasts (6.4 Mb XLSX file)



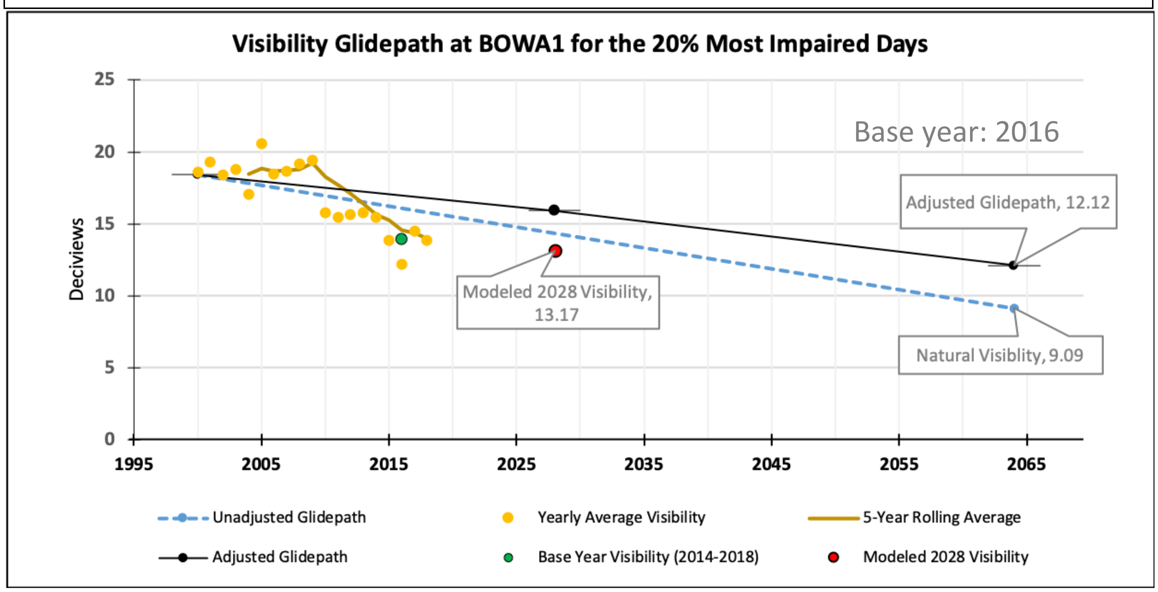


Figure 7-1. Visibility glidepath at BOWA1 IMPROVE site for the 20% most impaired days based on the (a) 2011 based 2028 prediction and (b) the 2016 based 2028 prediction[28].

[28] Note that the adjusted glidepath for the 2011 based prediction is accounted only the contribution from Mexico & Canada anthropogenic emissions, while the adjusted glidepath for 2016 based prediction was accounted for contributions from Mexico & Canada anthropogenic, Non-US C3 commercial marine, international boundary condition and wildland prescribed fire emissions.

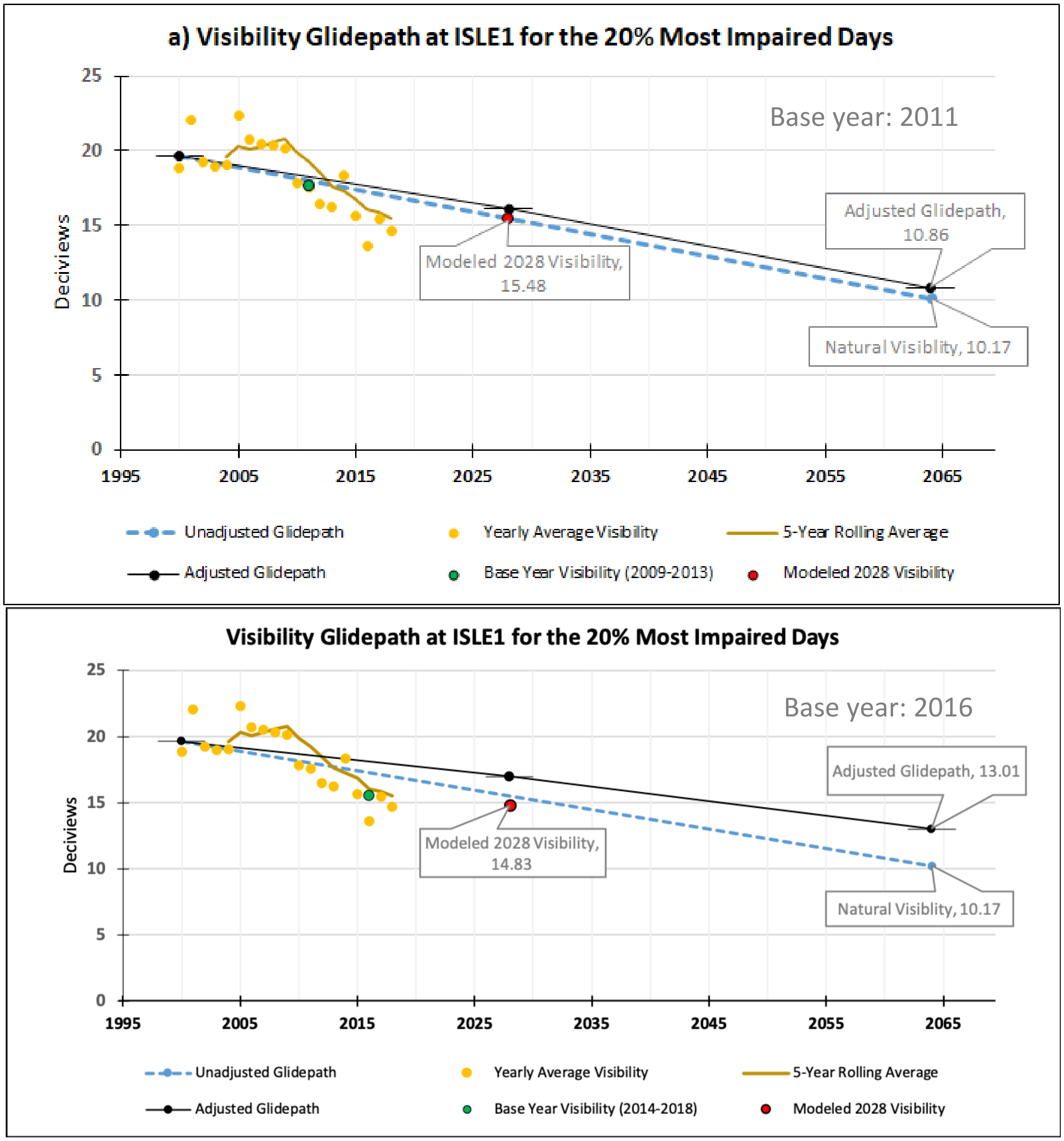


Figure 7-2. Visibility glidepath at ISLE1 IMPROVE site for the 20% most impaired days based on the (a) 2011 based 2028 prediction and (b) the 2016 based 2028 prediction.

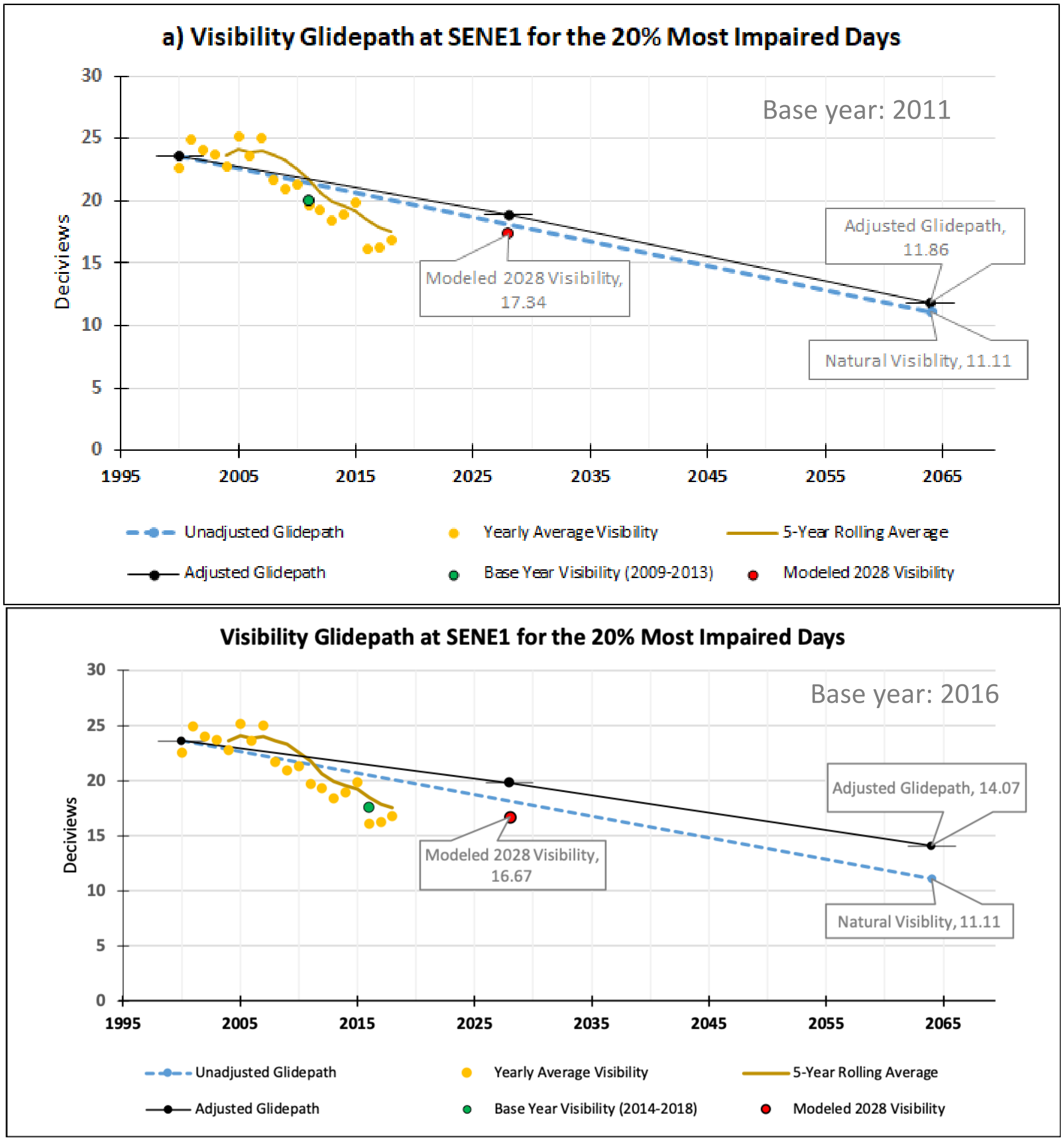


Figure 7-3. Visibility glidepath at SENE1 IMPROVE site for the 20% most impaired days based on the (a) 2011 based 2028 prediction and (b) the 2016 based 2028 prediction.

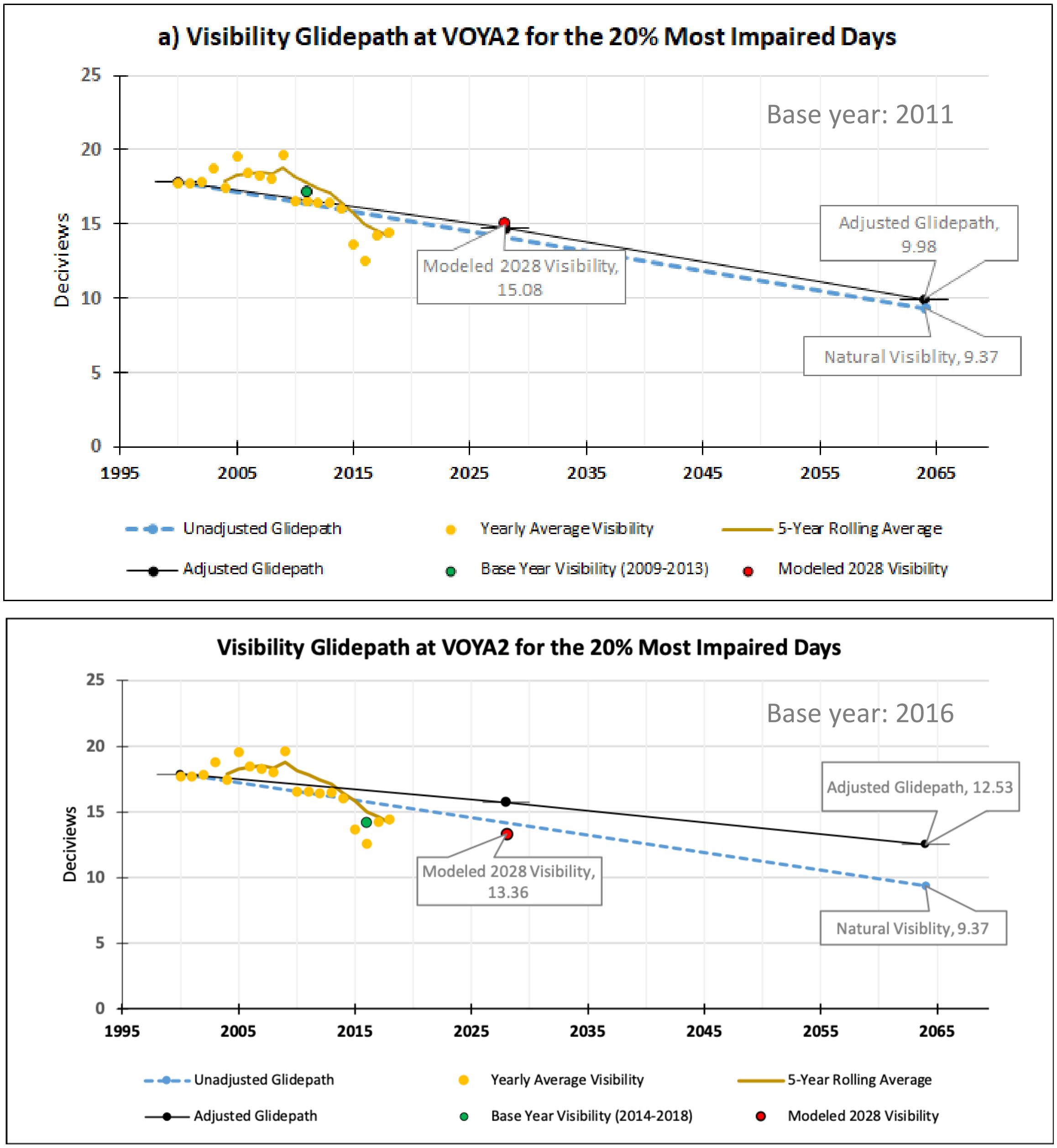


Figure 7-4. Visibility glidepath at VOYA2 IMPROVE site for the 20% most impaired days based on the (a) 2011 based 2028 prediction and (b) the 2016 based 2028 prediction.

The information in these figures is tabulated in Table 7-4 and Table 7-6. The glidepath plots show that the yearly average dv values at the IMPROVE monitors in the LADCO region are decreasing from year to year. One notable trend in these plots is the reduction in the base year visibility (green dot) in the 2016 base year relative to 2011. The 2016 base year visibility conditions are all well below the glidepath. Predicted 2028 visibility conditions based on the 2016 modeling platform shows that the visibility in the

Class I areas in Minnesota and Michigan is about 1.4 dv below the unadjusted glidepath line (i.e., URP). Accounting for the adjustment due to the international contribution, LADCO estimated 2028 visibility on the 20% most impaired days to be about 2.6 dv below the URP line. Table 7-5 and Table 7-7 show the baseline and predicted visibility on the 20% clearest days for the 2011 and 2016-based LADCO modeling.

Table 7-4. Comparison of observed and projected visibility on the 20% most impaired days at Class I areas within LADCO region (2011 base year)

IMPROVE Site ID	Visibility on 20% Most Impaired Days for the 2011 base year (dv)					Impact of Glidepath Adjustment (2028) (B-A)
	Observed Baseline (2000-2004)	Observed Base Years (2009-2013)	Projected Year (2028) (A)	Unadjusted Glidepath Value (2028) (B)	Natural Conditions (2064)	
BOWA1	18.43	16.42	14.43	14.69	9.09	-0.26
VOYA2	17.88	17.12	15.08	14.48	9.37	0.60
ISLE1	19.63	17.63	15.48	15.85	10.17	-0.37
SENE1	23.58	19.92	17.34	18.59	11.11	-1.25

Table 7-5. Comparison of observed and projected visibility on the 20% clearest days at Class I areas within LADCO region (2011 base year)

IMPROVE Site ID	Visibility on 20% Clearest Days for the 2011 base year (dv)			
	Observed Baseline (2000-2004)	Observed Base Years (2009-2013)	Projected Year (2028)	Natural Conditions (2064)
BOWA1	6.50	4.83	4.79	3.48
VOYA2	7.15	5.68	5.60	4.27
ISLE1	6.77	5.40	5.29	3.72
SENE1	7.14	5.50	5.35	3.74

Table 7-6. Comparison of observed and projected visibility on the 20% most impaired days at Class I areas within LADCO region (2016 base year)

IMPROVE Site ID	Visibility on 20% Most Impaired Days for the 2016 base year (dv)					Impact of Glidepath Adjustment (2028) (B-A)
	Observed Baseline (2000-2004)	Observed Base Years (2014-2018)	Projected Year (2028) (A)	Unadjusted Glidepath Value (2028) (B)	Natural Conditions (2064)	
BOWA1	18.43	13.96	13.17	14.69	9.09	-1.52
VOYA2	17.88	14.18	13.36	14.48	9.37	-1.12
ISLE1	19.63	15.54	14.83	15.85	10.17	-1.02
SENE1	23.58	17.57	16.67	18.59	11.11	-1.92

Table 7-7. Comparison of observed and projected visibility on the 20% clearest days at Class I areas within LADCO region (2016 base year)

IMPROVE Site ID	Visibility on 20% Clearest Days for the 2016 base year (dv)			
	Observed Baseline (2000-2004)	Observed Base Years (2014-2018)	Projected Year (2028)	Natural Conditions (2064)
BOWA1	6.50	4.48	4.41	3.48
VOYA2	7.15	5.31	5.25	4.27
ISLE1	6.77	5.30	5.23	3.72
SENE1	7.14	5.27	5.17	3.74

8 PSAT Source Apportionment Results

LADCO conducted source apportionment modeling with CAMx to quantify source-receptor relationships for PM and haze in 2028. The PSAT results show the extent to which emission from different source regions impair visibility in downwind Class I areas. In particular, the techniques used by LADCO to process the PSAT results provide information on the sources that contribute to haze on both the most impaired and clearest days at Class I areas.

In Section 3.5, we discussed the Particulate Matter Source Apportionment Technique (PSAT) configurations for the LADCO 2011-based and 2016-based CAMx simulation. The configuration descriptions included the PSAT emission source or sector tags for quantifying the contributions of upwind states, regions, and inventory sectors at downwind Class I areas. For the 2011-based 2028 PSAT run, LADCO tagged the 2028 emissions by individual LADCO states and neighboring regions (Table 8-1).

CAMx PSAT uses multiple tracer families to track the fate of both primary and secondary PM species, including sulfate (PSO4), particulate nitrate (PNO3), ammonium (PNH4), primary elemental carbon (PEC), primary organic aerosol (POA), secondary organic aerosol (SOA), and primary fine and coarse particles. In addition, PSAT can track contributions from the initial and boundary conditions to the model.

For the 2011-based simulation, LADCO used all of the PSAT tracer families to quantify the haze contributions at Class I areas. Based on those results, we refined the PSAT configuration for the 2016-based simulation to exclude the SOA tracer because it is both computationally expensive to simulate and anthropogenic sources are small contributors to SOA in the LADCO-region Class I areas.

Table 8-1. Source Tag Descriptions for CAMx PSAT runs for 2028_{2011} and 2028_{2016} simulations

Tag #	2028_{2011} Tag Description	2028_{2016} Tag Description
1	Biogenic	Other
2	IL	IL
3	WI	WI
4	IN	IN
5	OH	OH
6	MI	MI
7	MN	MN
8	IA	IA
9	MO	MO
10	AR	TX
11	LA	LA, OK, KS, NE, AR
12	TX	ME, NH, VT, MA, RI, CT, NY, NJ, PA, DE, MD, DC
13	OK	WV, KY, VA, NC, SC, TN, GA, AL, MI, FL
14	KS	NM, AZ, CO, UT, WY, MT, ID, WA, OR, CA, NV, ND, SD
15	NE	Canada/Mexico
16	ND	Commercial Marine (C1/C2/C3)
17	SD	Fires
18	WV	Rockport EGU (IN)
19	KY	Gibson EGU (IN)
20	ME, NH, VT, MA, RI, CT, NY, NJ, PA, DE, MD, DC	All other IN EGUs
21	VA, NC, SC, TN, GA, AL, MI, FL	IN Cement Manufacturing
22	NM, AZ, CO, UT, WY, MT, ID, WA, OR, CA, NV	IN Iron and Steel
23	Canada/Mexico	IN Plastics and Resin
24	Fire	IN Aluminum Production
25	Offshore	All other IN point sources
26	Tribes	IC
27	IC	BC
28	BC	

8.1 PSAT Post-processing for Source Contribution Estimates

LADCO post-processed the CAMx PSAT tagged species model outputs to create SMAT-CE input files. This process involved operations on both the 2028 "bulk outputs" and the source sector specific (or "tagged") source apportionment outputs. The "bulk outputs" are the total PM species concentrations (e.g. sulfate, nitrate, etc.) that are identical to the total species concentrations from the non-source apportionment model run for 2028. However, the source apportionment tracking of PM species uses slightly different variables names for the tagged outputs. The SMAT-CE input variable names and matching CAMx species names for the 2028 bulk and 2028 tagged outputs are tabulated in Table 8-2.

Table 8-2. SMAT input variables and their matching species names for CAMx "bulk" and "PSAT" source output files

SMAT-CE species	SMAT-CE species name	"Combine file" output species	CAMx species in "bulk output"	CAMx species in "tag output"
SO4	Sulfate	PM25_SO4	PSO4	PS4
NO3	Nitrate	PM25_NO3	PNO3	PN3
NH4[29]	Ammonium	PM25_NH4	PNH4	PN4
EC	Elemental carbon	PM25_EC	PEC	PEC
OC[30]	Organic carbon	PM25_OM	POA+SOA1+SOA2+SOPA+SOA3+SOA4+SOPB	POA+PO1+PO2+PPPA+O3+PO4+PPB
CRUSTAL[31]	Crustal	PM25_CRUSTRAL	FPRM+FCRS	PFN+PFC
CM	Coarse PM	PMC_TOT	CCRS+CPRM	PCS+PCC
PM25[32]	Total $PM_{2.5}$	PM25_TOT	PSO4+PNO3+PNH4+PEC+NA+PCL+FPRM+FCRS+SOA1+SOA2+SOPA+SOA3+SOA4+SOPB+POA	PS4+PN3+PN4+POA+PEC+PO1+PO2+PO3+PO4+PPA+PPB+PFN+ PFC

[29] Modeled ammonium concentrations are not used in the post-processing of the 2028 visibility values because the IMPROVE network does not measure ammonium. The IMPROVE equation assumes that sulfate and nitrate is fully neutralized by ammonia.
[30] LADCO's 2028_{2016} CAMx PSAT simulation did not include the organic carbon tracers
[31] LADCO's 2028_{2011} CAMx PSAT simulation was run without writing individual crustal fine particles, thus, the crustal amount was estimated by the sum of fine crustal particles (FCRS) and other fine particles (FPRM).
[32] Total PM2.5 concentration data is needed as a SMAT input variable, however, it is not used in the visibility calculations for regional haze. Visibility calculations only use the species specific model outputs.

The model attainment test software SMAT-CE processes daily total and speciated PM concentrations from the base and future year model (bulk and PSAT) runs from a 3 grid cell x 3 grid cell matrix surrounding each IMPROVE monitor location in the CAMx modeling domain. LADCO used the following steps to prepare the SMAT-CE input files and to run the software to calculate future year visibility at the Class I areas:

1. Combine hourly CAMx "bulk output" into hourly total and speciated PM concentrations (File A) using the species shown in Table 8-2.
2. Generate hourly pseudo total and speciated PM concentration outputs (File X') for each source tag by subtracting the tagged source apportionment output (File X) from File A.
3. Generate daily average total (File $\bar{A}$) and speciated PM (File $\overline{X}'$) concentration files from File A and File X', respectively
4. Extract the results in File $\bar{A}$ and File $\overline{X}'$ from 3x3 grid cells surrounding each IMPROVE monitor location in the modeling domain. LADCO then converted the extracted netCDF data to comma-delimited (CSV) files in the SMAT-CE input file format; the CSV outputs for File $\overline{A2}$ and File $\overline{X2'}$ were then ready for SMAT-CE.
5. Run SMAT-CE version 1.6 using the File $\overline{A2}$ and File $\overline{X2'}$ with observed IMPROVE data as inputs and with the settings in Table 7-1. In this SMAT-CE run, LADCO used the advanced option "Create forecast IMPROVE visibility file" to output the future year (2028) daily species extinction values at each IMPROVE monitor for each of the 20% best and the 20% most impaired days. With this configuration, SMAT-CE generated a "Forecast IMPROVE Daily Data.csv" file, which we used in the next step for calculating the visibility contributions for each PSAT tag.
6. We then used R to prepare the raw SMAT-CE for easy import to a spreadsheet for plotting and tabulation of the results.

LADCO created a comprehensive spreadsheet for each 2028 simulation that included dynamic plotting features with information on natural conditions, baseline visibility, base year and projected year visibility conditions at the Class I areas. We combined this information with the glidepath results described in the previous section.

LADCO's CAMx PSAT visibility forecasts are available in an electronic docket to this TSD in the following spreadsheets:

LADCO 2011-based 2028 Class I Area Visibility Forecasts (6.6 Mb XLSX file)

LADCO 2016-based 2028 Class I Area Visibility Forecasts (2.2 Mb XLSX file)

8.2 2011 Platform PSAT Results

This section presents the results from the LADCO CAMx 2011-based 2028 PSAT configuration that are included in the spreadsheets described in the previous section.

8.2.1 Source Region Tracer Results

The LADCO CAMx 2028_{2011} PSAT modeling estimated the state, biogenic, initial and boundary condition (ICBC), and international (Canada and Mexico) anthropogenic emissions source contributions to visibility in the U.S. Class I areas (Table 8-3 and Figure 8-1). CAMx estimated the average light extinction in 2028 across all of the LADCO region Class I areas to be about 50 Mm^{-1}. CAMx estimated that about 24% of the extinction is due to Rayleigh scattering, 20% from ICBC (mostly from boundary condition), 7-14% from the residing state, about 6% from biogenic emissions, and about 3% from the international anthropogenic emissions, mostly from Canada. The remainder of the extinction comes from other states. Figure 8-1 illustrates the results in Table 8-3 as a stacked bar plot. An aggregation of the PSAT source region tags to regional planning organization (RPO) area for the LADCO's Class I areas is shown in Figure 8-2. Natural sources such as Rayleigh, sea salt, biogenic and fire emissions are projected to contribute 28-36 % of the light extinction coefficients in the LADCO's Class I areas, while the LADCO and CenSARA RPOs are projected to contribute 23-24% and 8-13% of the extinction, respectively.

Table 8-3. 2028_{2011} tracer contributions to b_{ext} on the most impaired days at the LADCO Class I areas

Source region tags	Source contributions to 2028 visibility at IMPROVE Sites (Mm^{-1})					Percent source contributions to 2028 visibility at IMPROVE Sites (%)			
IMPROVE Sites	ISLE1	SENE1	BOWA1	VOYA2		ISLE1	SENE1	BOWA1	VOYA2
Total Bext	50.5	60.7	45.3	47.7					
Rayleigh	12.0	12.0	11.0	12.0		24%	20%	24%	25%
Sea salt (SS)	0.2	0.2	0.1	0.2		0%	0%	0%	1%
Biogenic	3.2	3.7	2.9	3.0		6%	6%	7%	6%
ICBC	10.0	11.1	8.9	8.9		20%	18%	20%	19%
Fire	1.5	1.1	1.6	2.5		3%	2%	3%	5%
Int'l anthropogenic	2.0	2.4	1.5	1.6		4%	4%	3%	3%
Tribal	0.0	0.0	0.0	0.0		0%	0%	0%	0%
Offshore	0.1	0.1	0.0	0.0		0%	0%	0%	0%
West	0.6	0.8	0.8	0.7		1%	1%	2%	1%
Northeast	0.4	1.2	0.2	0.2		1%	2%	0%	0%
Southeast	0.2	0.5	0.1	0.1		0%	1%	0%	0%
IL	2.3	3.4	0.8	1.0		5%	6%	2%	2%
WI	3.5	4.5	2.2	1.7		7%	7%	5%	4%
IN	1.2	2.9	0.5	0.6		2%	5%	1%	1%
OH	0.6	1.5	0.4	0.5		1%	3%	1%	1%
MN	2.4	1.7	6.2	6.5		5%	3%	14%	14%
MI	3.3	6.5	0.8	0.7		7%	11%	2%	2%
IA	1.3	1.3	1.8	1.7		3%	2%	4%	4%
MO	1.4	1.3	0.8	0.9		3%	2%	2%	2%
AR	0.3	0.4	0.2	0.3		1%	1%	1%	1%
LA	0.1	0.1	0.1	0.0		0%	0%	0%	0%
TX	1.3	0.5	1.2	1.0		3%	1%	3%	2%
OK	0.4	0.2	0.6	0.6		1%	0%	1%	1%
KS	0.3	0.4	0.5	0.5		1%	1%	1%	1%
NE	0.9	0.8	0.9	1.0		2%	1%	2%	2%
ND	0.7	0.7	0.8	0.9		1%	1%	2%	2%
SD	0.2	0.2	0.3	0.3		0%	0%	1%	1%
WV	0.1	0.3	0.1	0.1		0%	1%	0%	0%
KY	0.3	0.8	0.1	0.2		1%	1%	0%	0%
Aggregated by RPO									
Natural	4.7	4.9	4.5	5.5		9%	8%	10%	11%
LADCO	13.2	20.6	10.9	11.1		26%	34%	24%	23%
WRAP	1.5	0.8	1.9	1.9		2%	2%	5%	5%
CenSARA	6.0	5.0	6.0	6.0		12%	8%	13%	13%
VISTAS	0.6	1.7	0.3	0.4		1%	3%	1%	1%

Note: Natural (Sea Salt, Fire, Biogenic); LADCO (MN, MI, WI, IL, IN, OH); WRAP (ND, SD, West); CenSARA (IA, MO, AR, LA, TX, OK, KS, Northeast); VISTAS (WY, KY, Southeast)

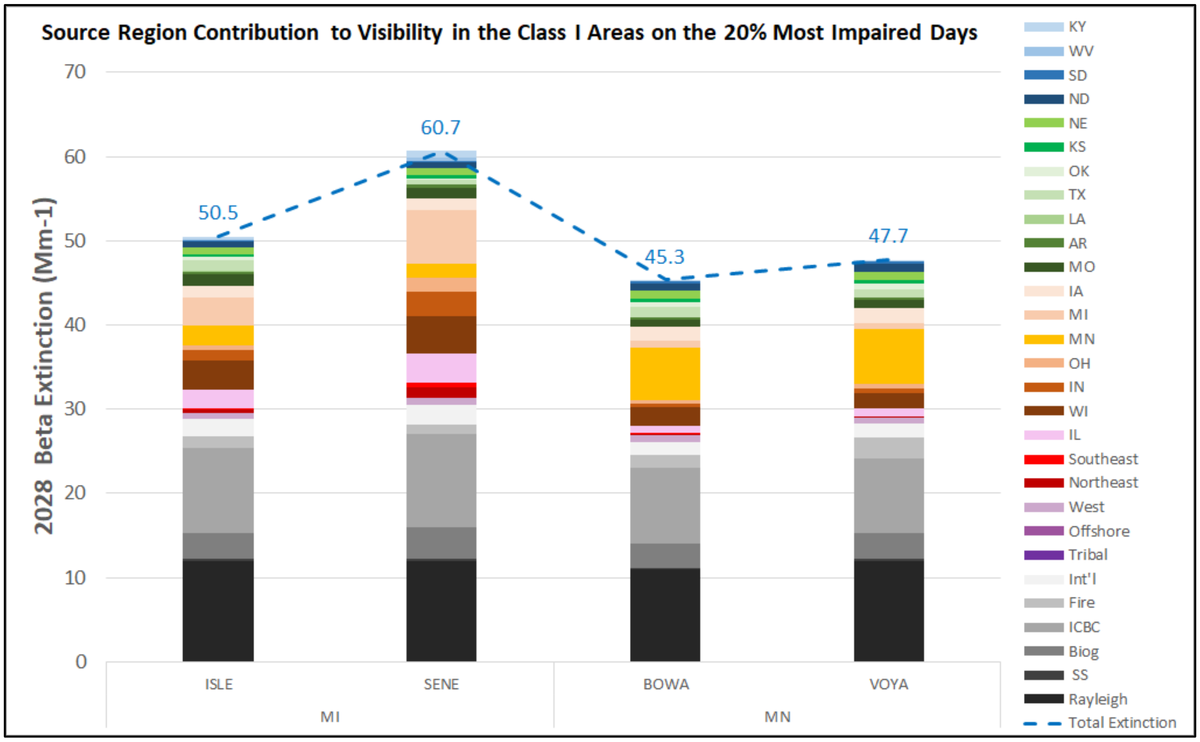


Figure 8-1. State and regional 2028_{2011} tracer contributions to b_{ext} on the 20% most impaired days at the LADCO region class I areas

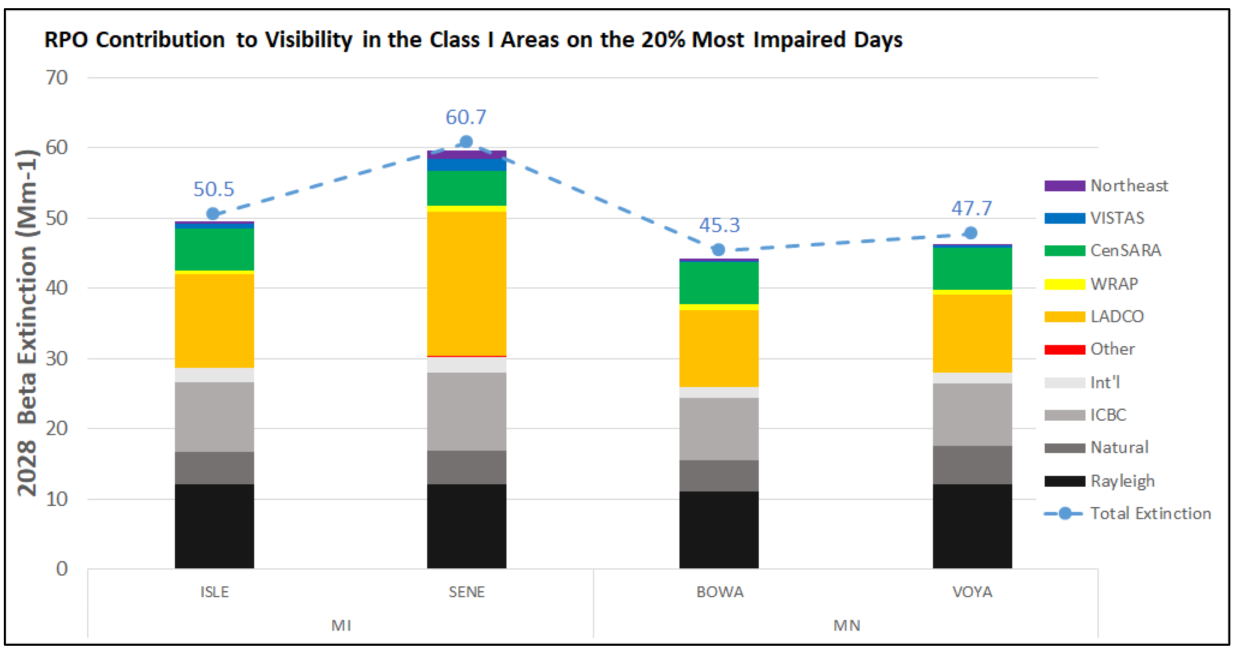


Figure 8-2. RPO 2028_{2011} tracer contributions to b_{ext} on the 20% most impaired days at the LADCO region class I areas

8.2.2 Speciated PM Tracer Results

In addition to quantifying the total contribution from each tracer at receptor areas in the model, the PSAT results can be used to quantify how much each PM species contributes to visibility conditions at the receptors. Figure 8-3 through Figure 8-14 are examples of PSAT tracer footprint plots. These plots show the maximum gridded concentrations of particulate nitrate and sulfate tracers on the 20% most impaired days at different Class I areas in the LADCO. The purpose of the footprint plot is to give a qualitative picture of the spatial signature of sources that contribute to haze impairment at Class I areas. In other words, these plots shows the maximum area of impact of each source region on sulfate and nitrate concentrations during the 20% most impaired days at the different Class I areas. Although PM concentrations do not linearly correspond with visibility impairment, they are a good qualitative surrogate for examining the linkages between emissions sources and downwind visibility impairment.

Figure 8-5 and Figure 8-6 show the maximum nitrate and sulfate tracer forecast (2028_{2011}) concentrations from sources in Minnesota during the 20% most impaired days at the Boundary Waters Canoe Area (BOWA). LADCO estimated that on the 20% most impaired days at BOWA[33], about 2-4 ug/m^3 nitrate and about 1-2 ug/m^3 sulfate concentrations originated from emissions sources in Minnesota. Figure 8-7 and Figure 8-8 show that the LADCO CAMx simulation estimated that a similar amount of nitrate and sulfate originate from the model boundary conditions.

The U.S. EPA's updated 2028 regional haze modeling study (U.S. EPA. 2019b) discussed that the impacts from both nitrate and sulfate are relatively large in the northern states. Based on the U.S. EPA's discussion on Canadian wintertime nitrate and sulfate impacts in the northern states, the modeled concentrations at the Class I areas in the LADCO region could have a minimum of 30-50% contributions from Canada anthropogenic emissions. Figure 8-3 and Figure 8-4 show that the LADCO 2028_{2011} predicted fairly small tracer impacts (<1 μg/m^3) at BOWA from Canadian sources of nitrate and sulfate.

Figure 8-5 through Figure 8-14 show home state maximum particulate nitrate and sulfate tracer concentrations on the 20% most impaired days at Voyageurs National Park, Isle Royale National Park

[33] The tracer footprint plots use the 20% most impaired days from the base year from which the modeling is projected (i.e., 2011 or 2016)

and Seney National Wildlife area, respectively. These figures show sulfate and nitrate contributions on the order of 1-1.5 $\mu g/m^3$ from emissions in the home state to each monitor.

LADCO generated footprint plots for all of the Class I areas in and around the LADCO region from our 2011-based 2028 CAMx simulation. The plots are available as an electronic docket to this TSD and can be found on the LADCO website through the following link:

[LADCO 2011-based 2028 PM tracer footprint plots]

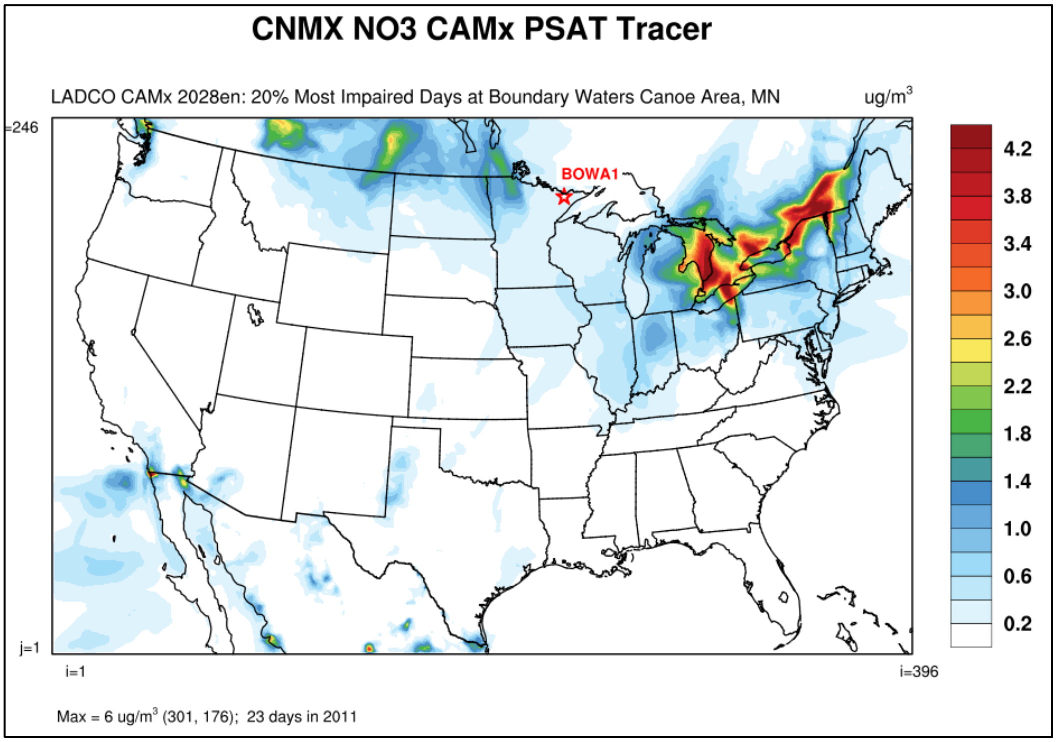


Figure 8-3. Maximum 2028_{2011} nitrate tracer concentration from Canada and Mexico sources on the 20% most impaired days at Boundary Waters, MN

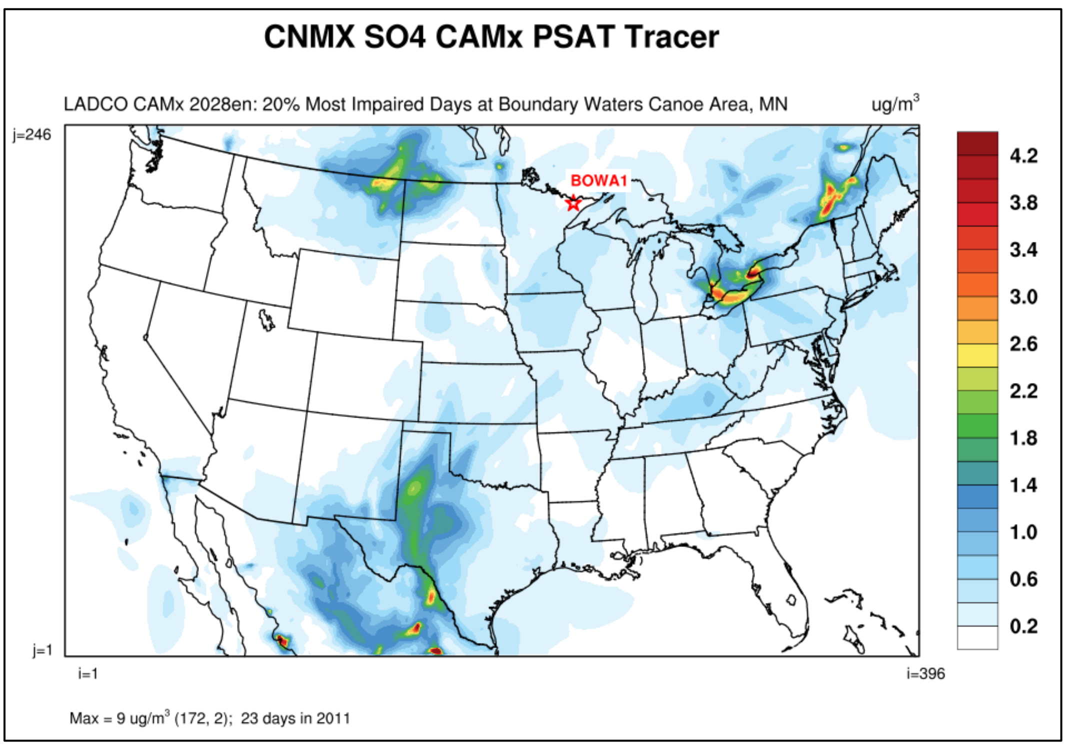


Figure 8-4. Maximum 2028_{2011} sulfate tracer concentration from Canada and Mexico sources on the 20% most impaired days at Boundary Waters, MN

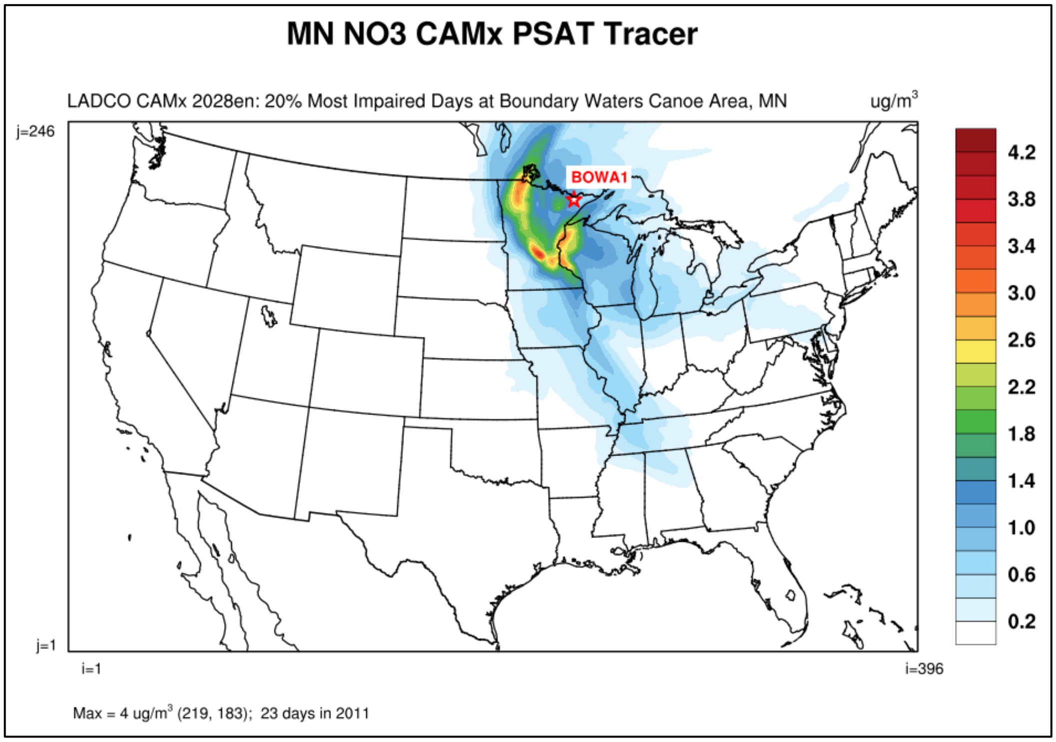


Figure 8-5. Maximum 2028$_{2011}$ nitrate tracer concentration from MN sources on the 20% most impaired days at Boundary Waters, MN

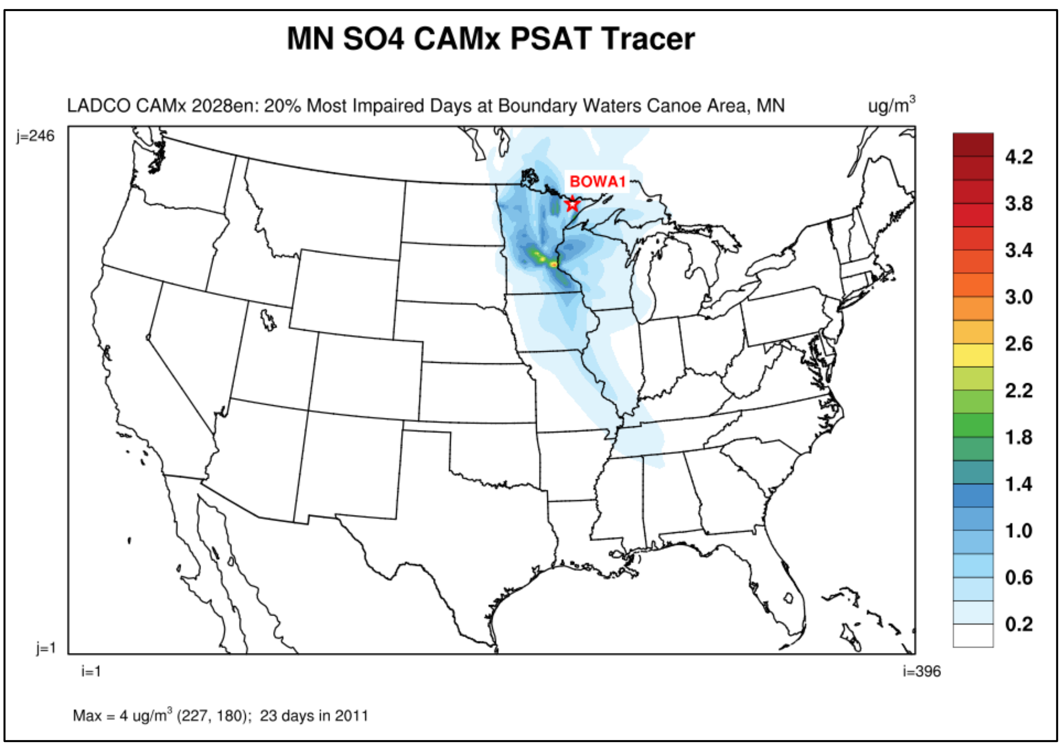


Figure 8-6. Maximum 2028$_{2011}$ sulfate tracer concentration from MN sources on the 20% most impaired days at Boundary Waters, MN

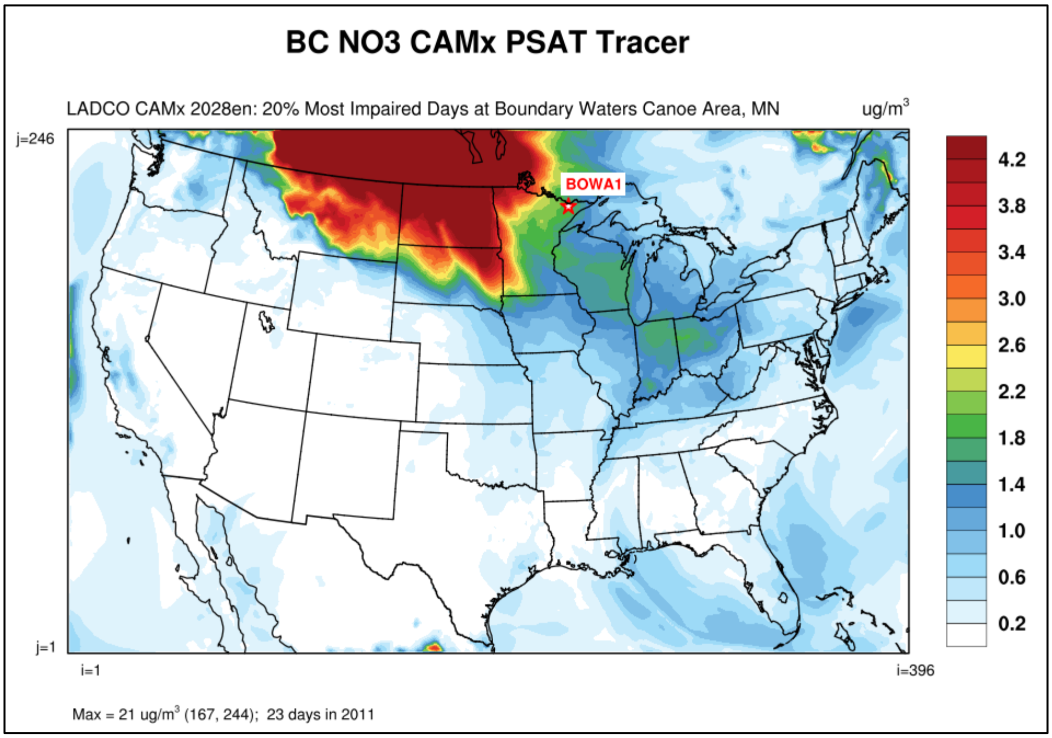


Figure 8-7. Maximum 2028$_{2011}$ nitrate tracer concentration from boundary condition on the 20% most impaired days at Boundary Waters, MN

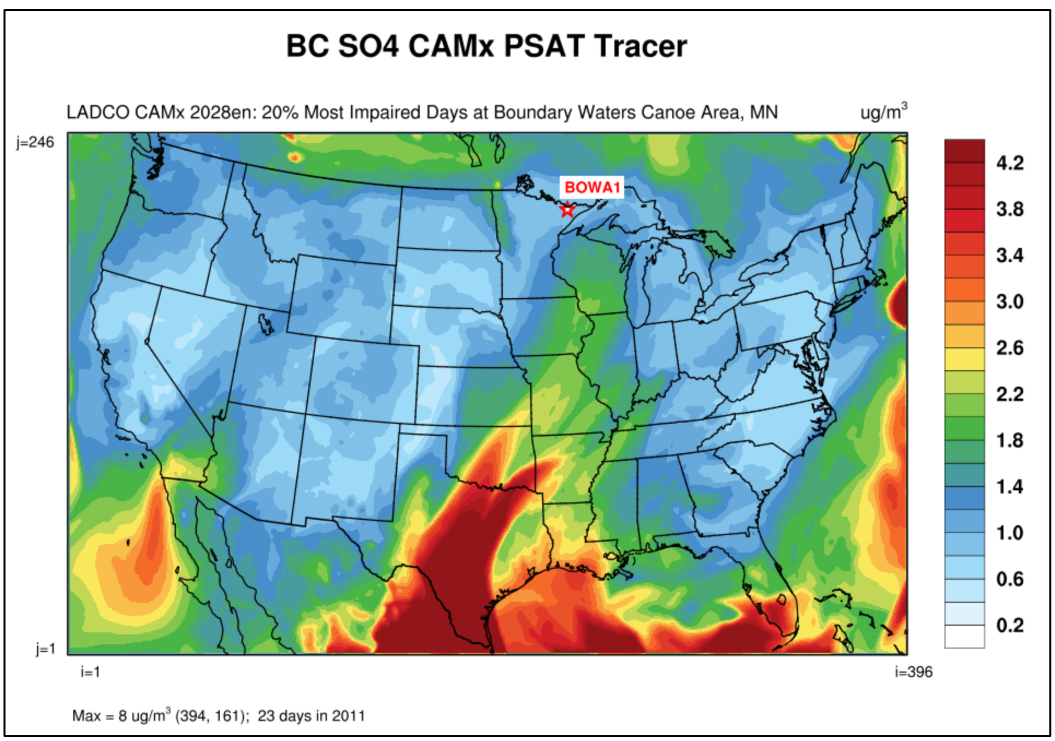


Figure 8-8. Maximum 2028$_{2011}$ sulfate tracer concentration from boundary condition on the 20% most impaired days at Boundary Waters, MN

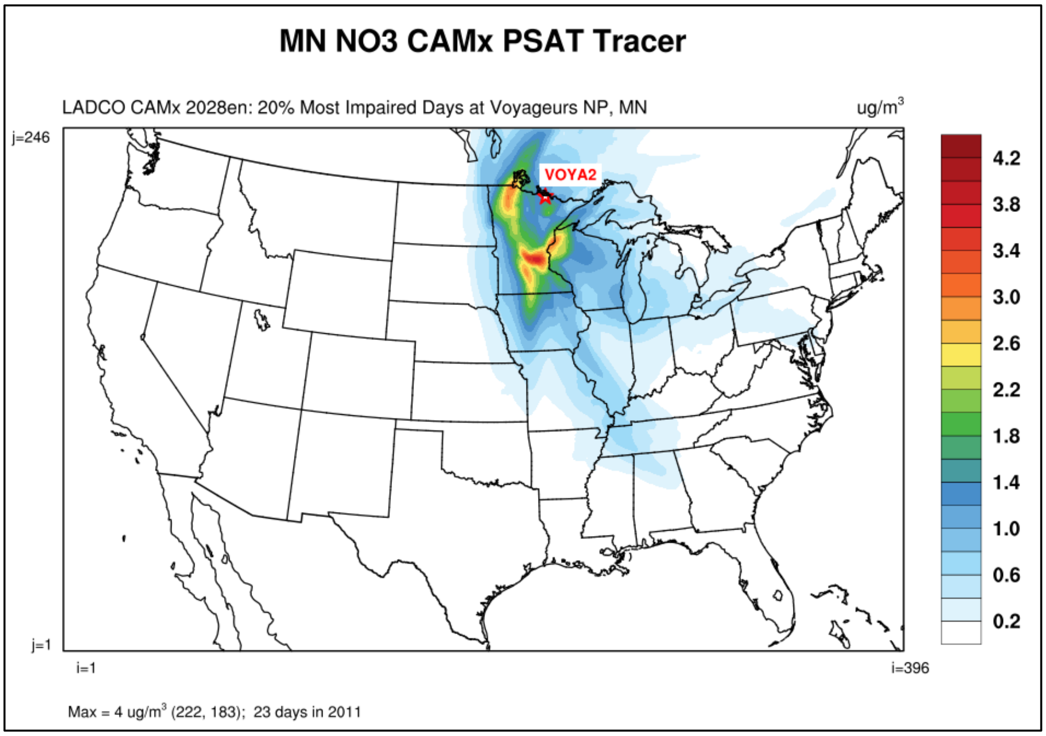


Figure 8-9. Maximum 2028_{2011} nitrate tracer concentration from MN sources on the 20% most impaired days at Voyageurs NP, MN

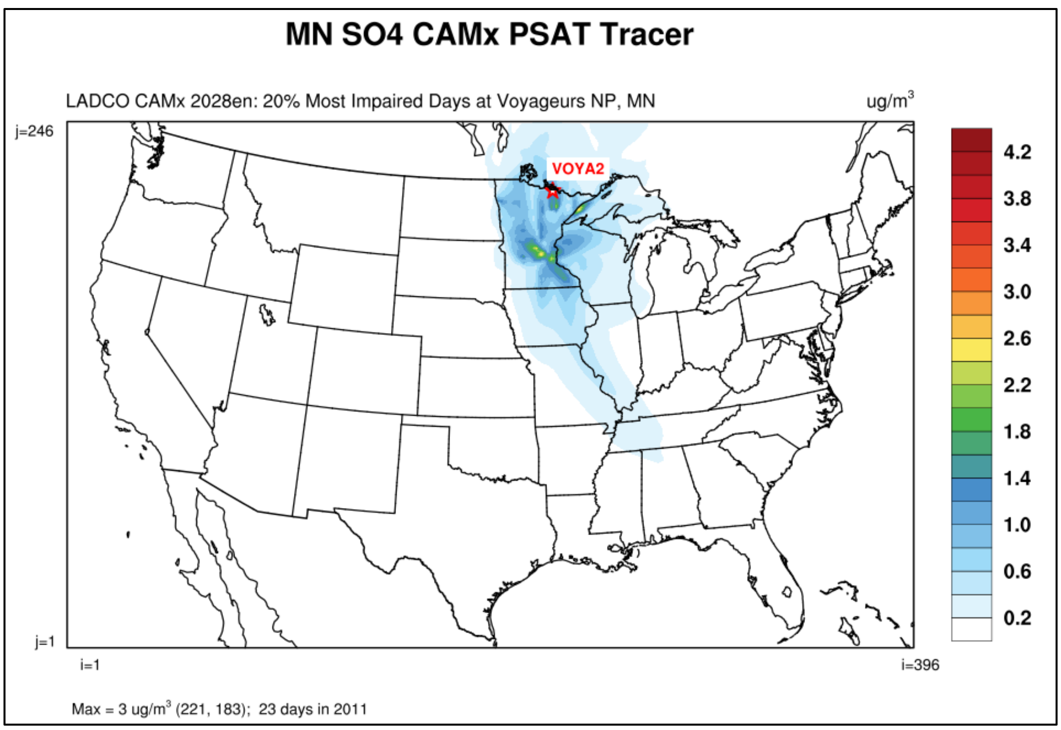


Figure 8-10. Maximum 2028_{2011} sulfate tracer concentration from MN sources on the 20% most impaired days at Voyageurs NP, MN

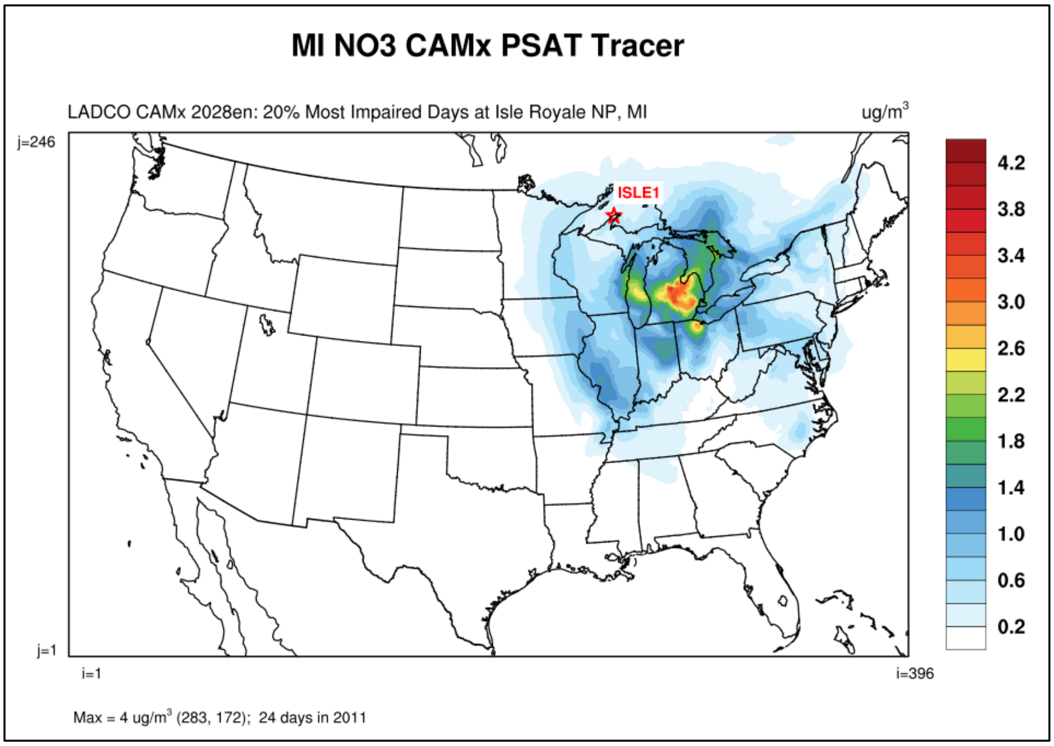


Figure 8-11. Maximum 2028_{2011} nitrate tracer concentration from MI sources on the 20% most impaired days at Isle Royale NP, MI

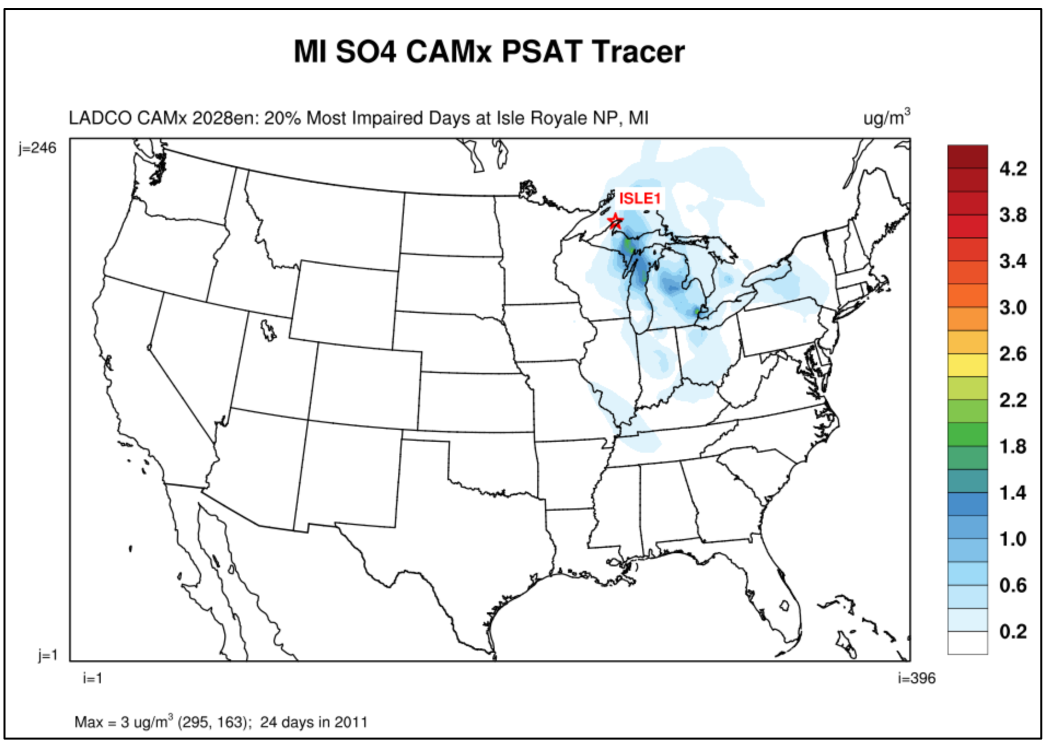


Figure 8-12. Maximum 2028_{2011} sulfate tracer concentration from MI sources on the 20% most impaired days at Isle Royale NP, MI

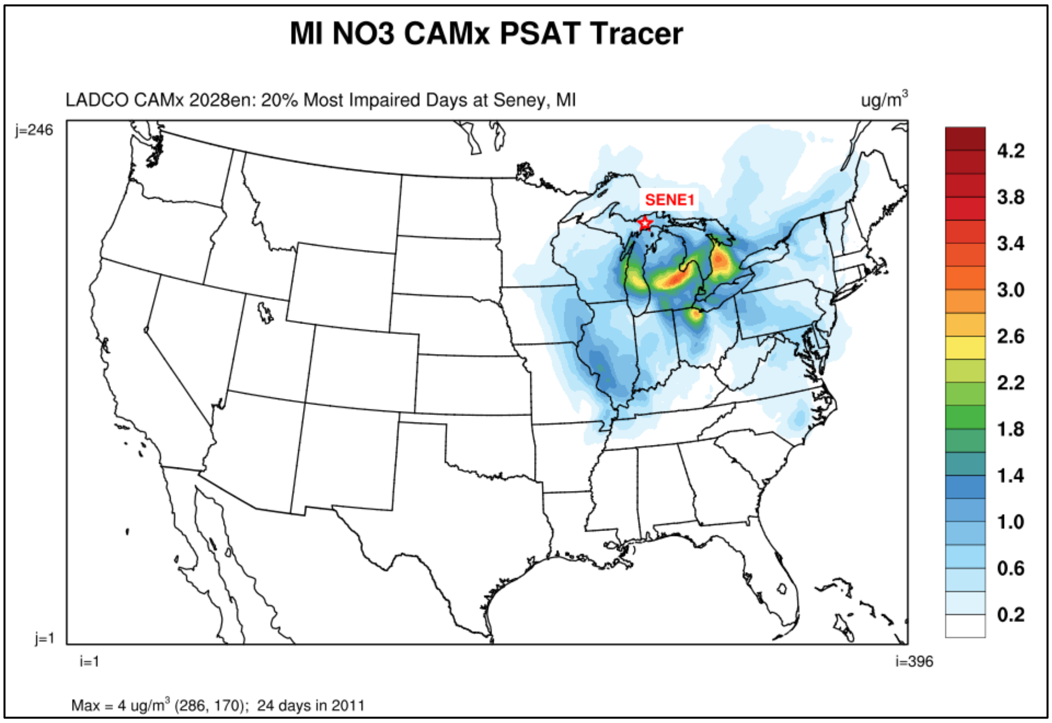


Figure 8-13. Maximum 2028_{2011} nitrate tracer concentration from MI sources on the 20% most impaired days at Seney, MI

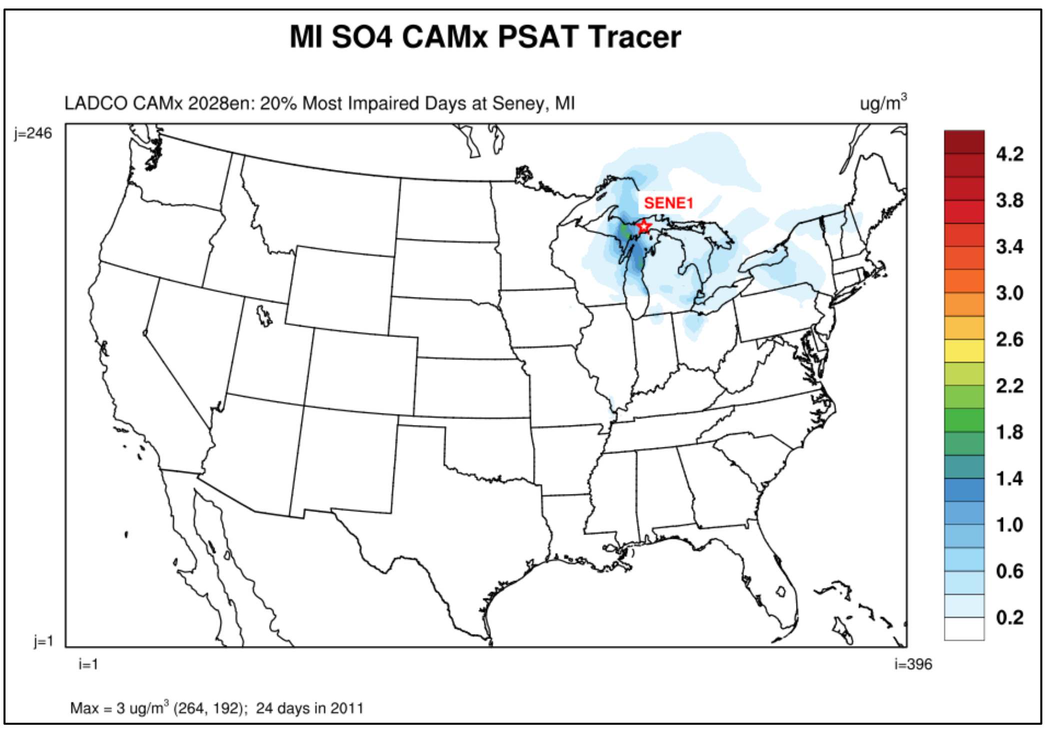


Figure 8-14. Maximum 2028_{2011} sulfate tracer concentration from MN sources on the 20% most impaired days at Seney, MI

The CAMx PSAT results can also be used to quantify the light extinction at the Class I areas by $PM_{2.5}$ composition. LADCO post-processed our CAMx 2028_{2011} modeling results to estimate individual $PM_{2.5}$ species contributions to total light extinction on the 20% most impaired days at the Class I areas. The speciated tracer result for the LADCO region Class I areas are shown in Table 8-4 and in Figure 8-15.

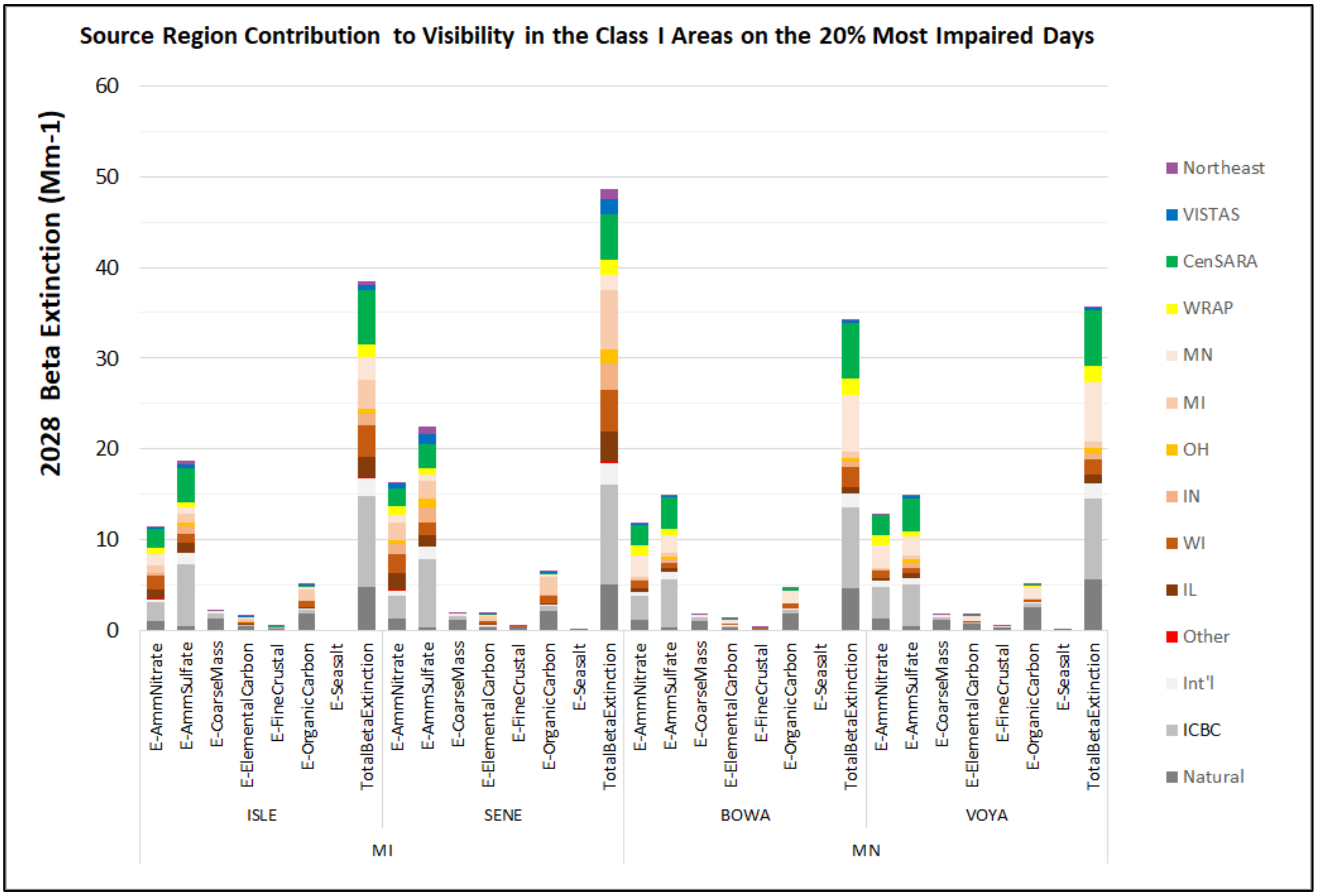


Figure 8-15. PM species tracer contributions to b_{ext} on the 20% most impaired days at the LADCO Class I areas (CAMx 2028_{2011})

Table 8-4. Speciated 2028_{2011} tracer contributions on the 20% most impaired days at the LADCO-region Class I areas

Area	Tracer	Natural	ICBC	Int'l	Other	IL	WI	IN	OH	MI	MN	WRAP	CenSARA	SE	NE	Total
ISLE	Total beta Ext	4.8	10.0	2.0	0.1	2.3	3.5	1.2	0.6	3.3	2.4	1.5	6.0	0.6	0.4	38.5
	NO_3	1.1	2.0	0.4	0.1	1.1	1.5	0.3	0.1	0.7	1.3	0.8	2.0	0.1	0.0	11.3
	SO_4	0.4	6.9	1.3	0.0	1.0	1.0	0.8	0.5	1.0	0.7	0.6	3.7	0.5	0.4	18.7
	CM	1.4	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2
	EC	0.5	0.1	0.1	0.0	0.1	0.2	0.0	0.0	0.3	0.1	0.0	0.1	0.0	0.0	1.6
	FCRS	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
	OC	1.9	0.4	0.1	0.0	0.1	0.7	0.0	0.0	1.2	0.3	0.0	0.1	0.0	0.0	5.1
	SS	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
SENE	Total beta Ext	5.1	11.1	2.4	0.1	3.4	4.5	2.9	1.5	6.5	1.7	1.7	5.0	1.7	1.2	48.7
	NO_3	1.3	2.5	0.6	0.1	1.8	2.1	1.1	0.4	2.0	0.8	0.9	1.9	0.5	0.2	16.4
	SO_4	0.4	7.5	1.3	0.0	1.3	1.3	1.7	1.0	2.0	0.6	0.7	2.8	1.0	0.9	22.5
	CM	1.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9
	EC	0.4	0.1	0.1	0.0	0.1	0.2	0.1	0.0	0.5	0.1	0.0	0.1	0.0	0.0	1.9
	FCRS	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
	OC	2.2	0.5	0.2	0.0	0.1	0.8	0.1	0.1	1.9	0.2	0.1	0.2	0.1	0.1	6.5
	SS	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
BOWA	Total beta Ext	4.6	8.9	1.5	0.0	0.8	2.2	0.5	0.4	0.8	6.2	1.8	6.0	0.3	0.2	34.3
	NO_3	1.2	2.6	0.4	0.0	0.4	0.9	0.1	0.0	0.3	2.3	1.1	2.3	0.0	0.0	11.7
	SO_4	0.4	5.3	0.8	0.0	0.3	0.7	0.4	0.3	0.4	1.9	0.6	3.5	0.2	0.2	15.0
	CM	1.1	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	1.7
	EC	0.4	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.5	0.0	0.1	0.0	0.0	1.4
	FCRS	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.4
	OC	1.9	0.4	0.1	0.0	0.0	0.5	0.0	0.0	0.1	1.3	0.1	0.2	0.0	0.0	4.6
	SS	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
VOYA	Total beta Ext	5.7	8.9	1.6	0.0	1.0	1.7	0.6	0.5	0.7	6.5	1.8	6.0	0.4	0.2	35.7
	NO_3	1.3	3.5	0.6	0.0	0.4	0.8	0.1	0.0	0.2	2.4	1.2	2.2	0.0	0.0	12.8
	SO_4	0.5	4.6	0.7	0.0	0.5	0.5	0.5	0.4	0.4	2.1	0.6	3.6	0.3	0.2	15.0
	CM	1.2	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	1.8
	EC	0.8	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.5	0.0	0.1	0.0	0.0	1.7
	FCRS	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.6
	OC	2.7	0.3	0.1	0.0	0.0	0.3	0.0	0.0	0.1	1.3	0.1	0.2	0.0	0.0	5.1
	SS	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2

8.3 2016 Platform Results

This section presents the results from the LADCO CAMx 2016-based 2028 PSAT configuration that are included in the spreadsheets described in the previous section.

8.3.1 Source Region Tracer Results

The LADCO CAMx 2028_{2016} PSAT modeling estimated the state, Indiana point source, biogenic, initial and boundary condition (ICBC), and international (Canada and Mexico) anthropogenic emissions source contributions to visibility in the U.S. Class I areas (Table 8-5 and Figure 8-16). LADCO redefined the tracers for the 2028_{2016} simulation to support analyses requested by our member states, and to eliminate tracers that had a small (<1 Mm^{-1}) estimated impact on visibility in the 2028_{2011} simulation. In particular, the 2016-based simulation excluded tracers for some of the states surrounding the LADCO region, and included tracers for specific point sources and sectors in Indiana. The 2028_{2016} simulation results include an estimated OC contribution to beta light extinction because the 2028_{2016} did not include the CAMx organic aerosol tracer. LADCO calculated the species "OC estimated" as the difference of total beta extinction from the core CAMx model and the sum of all of the PSAT tracers (including Rayleigh).

CAMx estimated the average light extinction in 2028 across all of the LADCO region Class I areas to be about 47 Mm^{-1}. CAMx estimated that about 25.5% of the extinction is due to Rayleigh scattering, 22% from ICBC (almost entirely from the model boundary conditions), 3.5-10.5% from the residing state, and about 4.6% from the international anthropogenic emissions, mostly from Canada. The average biogenic contribution of 3% does not include the contribution from organic carbon aerosols as these species were not explicitly tracked in this simulation. The relative contribution from biogenics to light extinction at the LADCO Class I areas is at least double the 2028_{2016} estimate as biogenic emissions are the primary source of organic aerosols. The majority of the remainder of the light extinction contribution comes from other states.

Figure 8-16 illustrates the results in Table 8-5 as a stacked bar plot. An aggregation of the PSAT source region tags to regional planning organization (RPO) area for the LADCO Class I areas is shown in Figure 8-17.

Table 8-5. 2028$_{2016}$ tracer contributions to b_{ext} on the most impaired days at the LADCO Class I areas

Source region tags	Source contributions to 2028 visibility at IMPROVE Sites (Mm^{-1})					Percent source contributions to 2028 visibility at IMPROVE Sites (%)			
IMPROVE Sites	ISLE1	SENE1	BOWA1	VOYA2		ISLE1	SENE1	BOWA1	VOYA2
Total Bext	48.6	57.4	40.5	41.0					
Rayleigh	12.0	12.0	11.0	12.0		24.7%	20.9%	27.2%	29.2%
Sea salt (SS)	0.3	0.2	0.2	0.3		0.5%	0.4%	0.5%	0.7%
Biogenic	1.4	1.8	1.2	1.3		2.9%	3.1%	2.9%	3.1%
ICBC	10.5	9.9	9.7	10.0		21.5%	17.2%	23.9%	24.4%
OC Estimated	4.2	5.1	3.6	3.5		8.6%	8.9%	8.9%	8.6%
Fire	0.9	0.9	0.9	0.4		1.9%	1.5%	2.1%	0.9%
Int'l anthropogenic	1.7	2.7	1.7	2.3		3.5%	4.8%	4.3%	5.7%
Offshore	0.2	0.2	0.1	0.1		0.5%	0.4%	0.1%	0.1%
West	1.6	1.9	1.9	1.8		3.4%	3.2%	4.6%	4.4%
Northeast	0.1	0.3	0.1	0.1		0.2%	0.5%	0.2%	0.2%
Southeast	0.4	1.3	0.2	0.2		0.8%	2.2%	0.6%	0.5%
CenSARA Other	2.4	1.8	1.9	1.5		4.9%	3.2%	4.6%	3.6%
IA	1.4	1.5	0.9	0.9		2.9%	2.6%	2.3%	2.1%
MO	1.4	1.7	0.8	0.6		3.0%	3.0%	2.1%	1.6%
TX	0.6	0.3	0.3	0.3		1.1%	0.6%	0.8%	0.7%
IL	2.0	3.6	0.6	0.4		4.0%	6.3%	1.6%	1.0%
WI	2.3	3.5	0.9	0.4		4.8%	6.2%	2.3%	1.0%
MI	1.7	3.4	0.1	0.2		3.5%	6.0%	0.3%	0.5%
OH	0.2	1.2	0.2	0.2		0.4%	2.0%	0.4%	0.5%
MN	2.4	1.7	3.9	4.4		5.0%	3.0%	9.6%	10.6%
IN (Total)	0.9	2.3	0.2	0.2		1.9%	4.0%	0.6%	0.5%
IN (Nonpoint)	0.3	0.7	0.1	0.1		0.6%	1.2%	0.2%	0.2%
IN (Rockport EGU)	0.0	0.1	0.0	0.0		0.1%	0.1%	0.0%	0.0%
IN (Gibson EGU)	0.0	0.1	0.0	0.0		0.1%	0.1%	0.0%	0.0%
IN (other EGU)	0.2	0.5	0.0	0.0		0.4%	0.8%	0.1%	0.1%
IN (Cement)	0.0	0.0	0.0	0.0		0.0%	0.1%	0.0%	0.0%
IN (Iron & Steel)	0.3	0.7	0.0	0.1		0.6%	1.2%	0.1%	0.1%
IN (Plastics & Resins)	0.0	0.0	0.0	0.0		0.0%	0.1%	0.0%	0.0%
IN (Aluminum)	0.0	0.0	0.0	0.0		0.0%	0.0%	0.0%	0.0%
IN (Other Point)	0.1	0.2	0.0	0.0		0.2%	0.4%	0.1%	0.0%
Other Anthro	0.0	0.0	0.0	0.0		0.0%	0.0%	0.0%	0.0%
Aggregated by RPO									
Natural	2.3	2.7	2.0	1.6		5%	5%	5%	4%
LADCO	9.6	15.7	6.0	5.8		20%	27%	15%	14%
WRAP	1.6	1.9	1.9	1.8		3%	3%	5%	4%
CenSARA	5.8	5.4	4.0	3.3		12%	9%	10%	8%
VISTAS	0.4	1.3	0.2	0.2		1%	2%	1%	0%

Note: Natural (Sea Salt, Fire, Biogenic); LADCO (MN, MI, WI, IL, IN, OH); WRAP (ND, SD, West); CenSARA (IA, MO, AR, LA, TX, OK, KS, Northeast); VISTAS (WY, KY, Southeast)

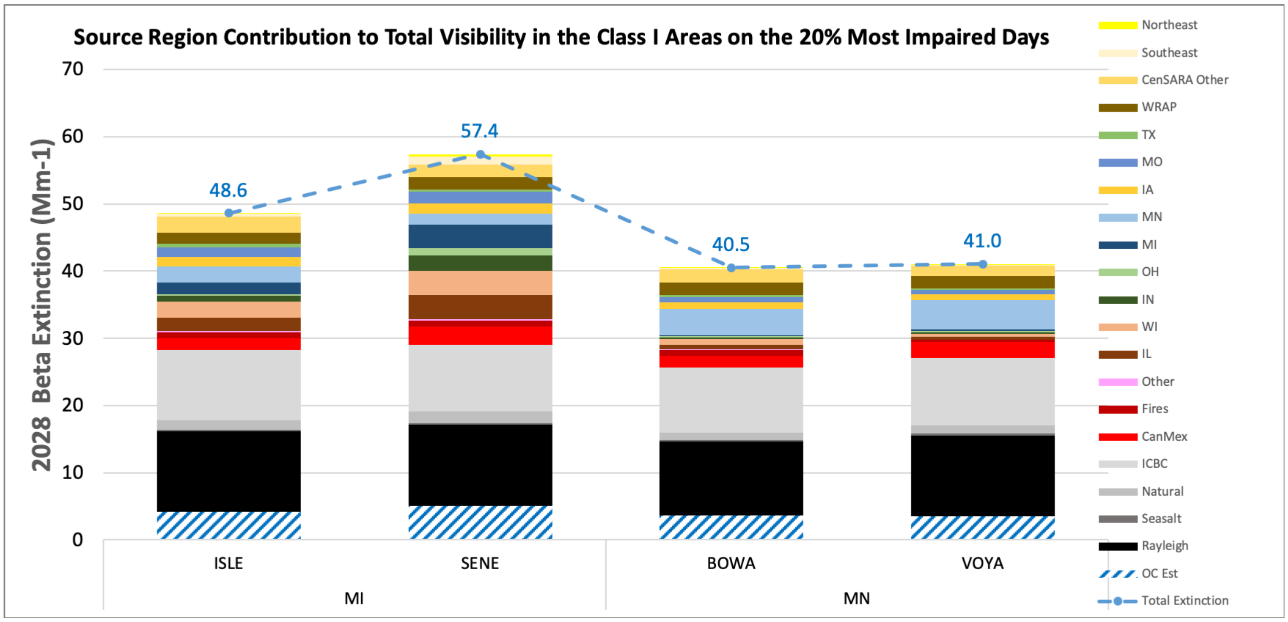


Figure 8-16. State and regional 2028_{2016} tracer contributions to b_{ext} on the 20% most impaired days at the LADCO region class I areas

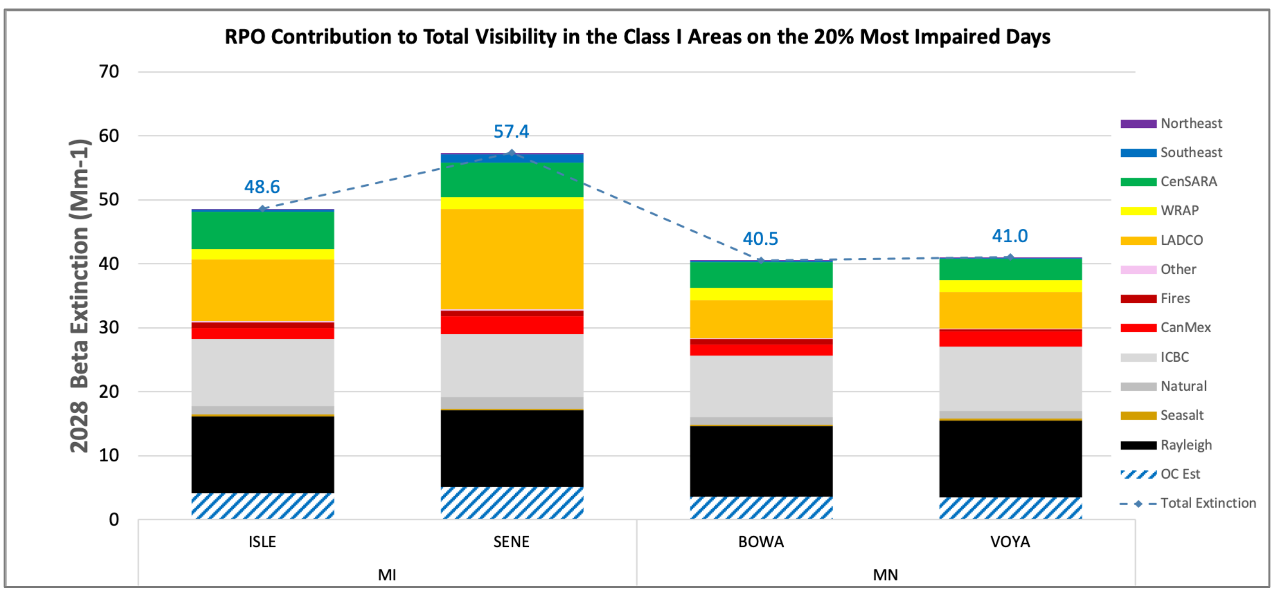


Figure 8-17. RPO 2028_{2016} tracer contributions to b_{ext} on the 20% most impaired days at the LADCO region class I areas

8.3.2 Speciated PM Tracer Results

The PSAT results can also be used to quantify how much each PM species contributes to visibility conditions at the receptors. Figure 8-18 through Figure 8-21 are examples of PSAT tracer footprint plots from LADCO CAMx 2028_{2016}. These plots show the maximum gridded concentrations of particulate nitrate and sulfate tracers on the 20% most impaired days at different Class I areas in the LADCO. These plots shows the maximum area of impact of each source region on sulfate and nitrate concentrations during the 20% most impaired days at the different Class I areas. Although PM concentrations do not linearly correspond with visibility impairment, they are a good qualitative surrogate for examining the linkages between emissions sources and downwind visibility impairment.

Figure 8-20 and Figure 8-21 show the maximum nitrate and sulfate tracer forecast (2028_{2016}) concentrations from sources in Minnesota during the 20% most impaired days at the Boundary Waters Canoe Area (BOWA). LADCO estimated that on the 20% most impaired days at BOWA[34] in 2028, about 0.5-1.5 ug/m^3 nitrate and about 0.5-1.0 ug/m^3 sulfate concentrations will be attributed from emissions sources in Minnesota. Figure 8-18 and Figure 8-19 show that the LADCO 2028_{2016} CAMx simulation estimated that a similar amount of nitrate and sulfate at BOWA originate from Canadian sources as Minnesota sources.

As with the 2011-based 2028 modeling, LADCO generated footprint plots for all of the Class I areas in and around the LADCO region from our 2016-based 2028 CAMx simulation. The plots are available as an electronic docket to this TSD and can be found on the LADCO website through the following link:

LADCO 2016-based 2028 PM tracer footprint plots

[34] The tracer footprint plots use the 20% most impaired days from the base year from which the modeling is projected (i.e., 2011 or 2016)

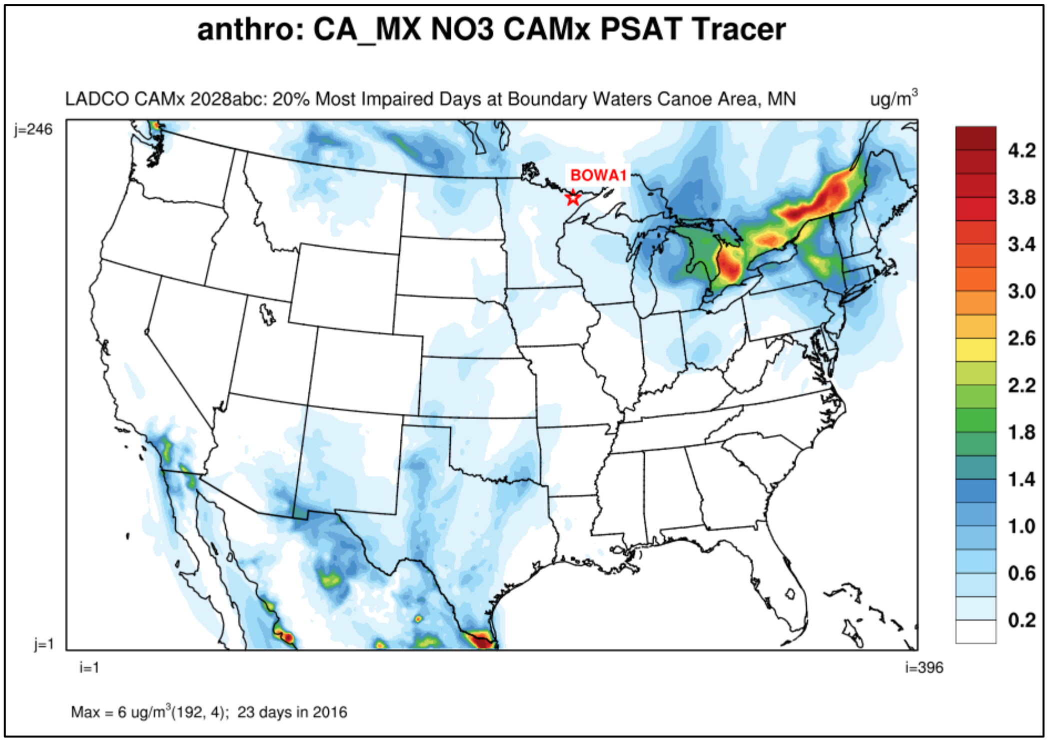


Figure 8-18. Maximum 2028_{2016} nitrate tracer concentration from Canada and Mexico sources on the 20% most impaired days at Boundary Waters, MN

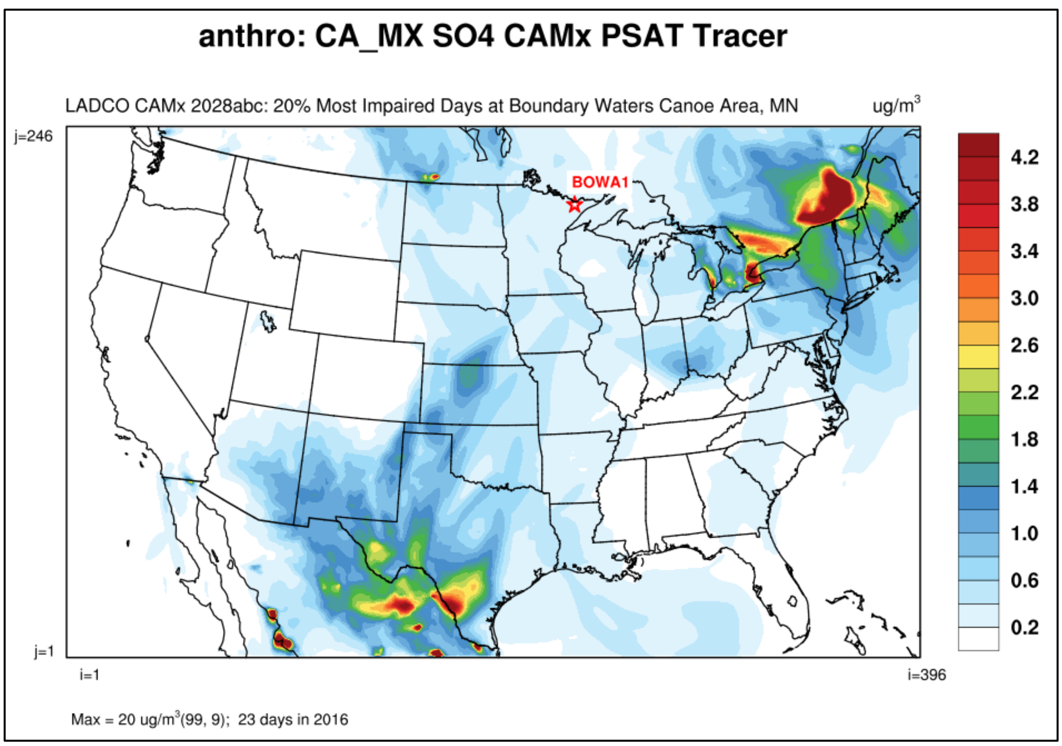


Figure 8-19. Maximum 2028_{2016} sulfate tracer concentration from Canada and Mexico sources on the 20% most impaired days at Boundary Waters, MN

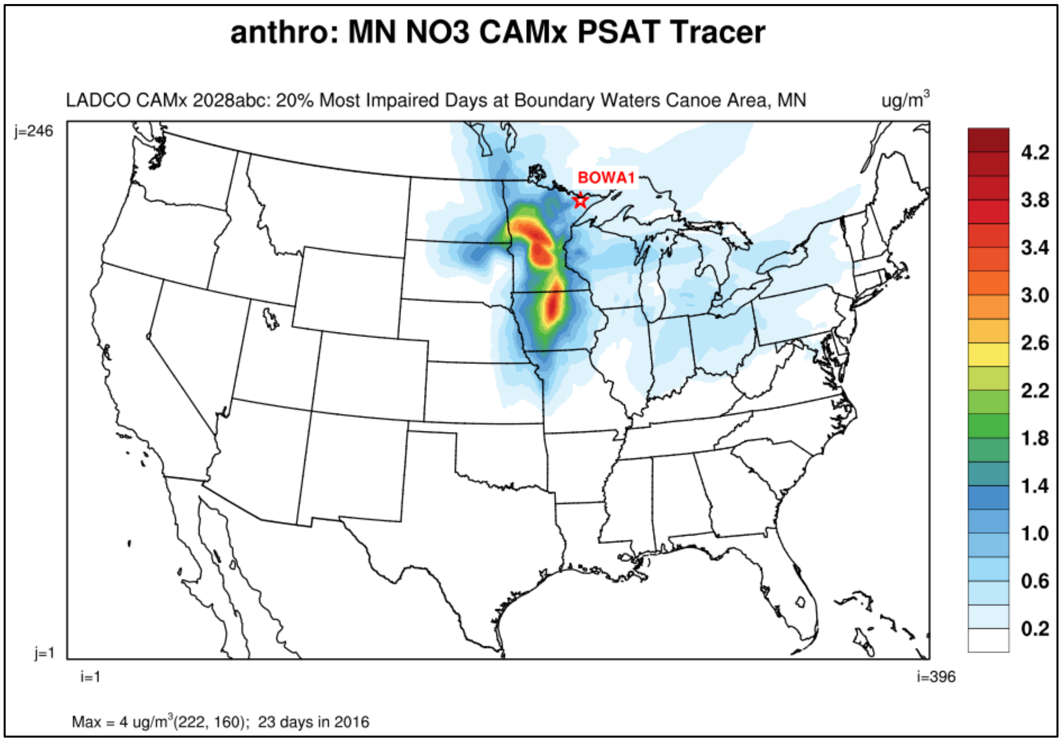


Figure 8-20. Maximum 2028_{2016} nitrate tracer concentration from MN sources on the 20% most impaired days at Boundary Waters, MN

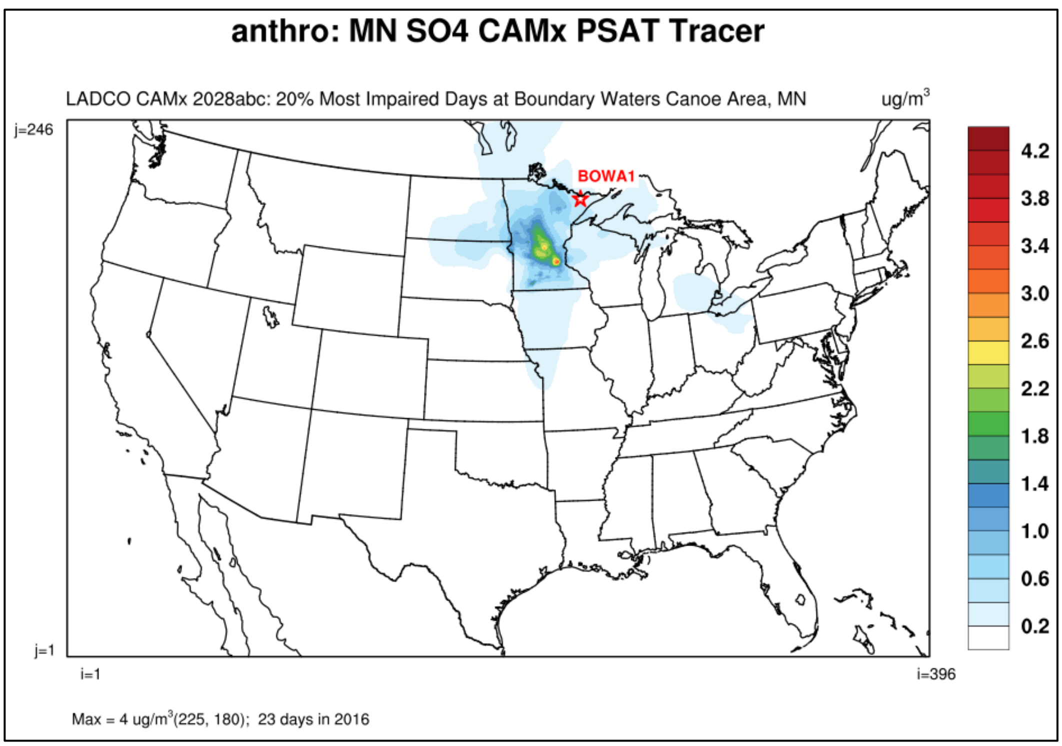


Figure 8-21. Maximum 2028_{2016} sulfate tracer concentration from MN sources on the 20% most impaired days at Boundary Waters, MN

LADCO also used the CAMx PSAT results to quantify the light extinction at Class I areas by $PM_{2.5}$ composition in 2028. LADCO post-processed our CAMx 2028_{2016} modeling results to estimate individual $PM_{2.5}$ species contributions to total light extinction on the 20% most impaired days at the Class I areas. The speciated tracer result for the LADCO region Class I areas are shown in Table 8-6 and in Figure 8-15.

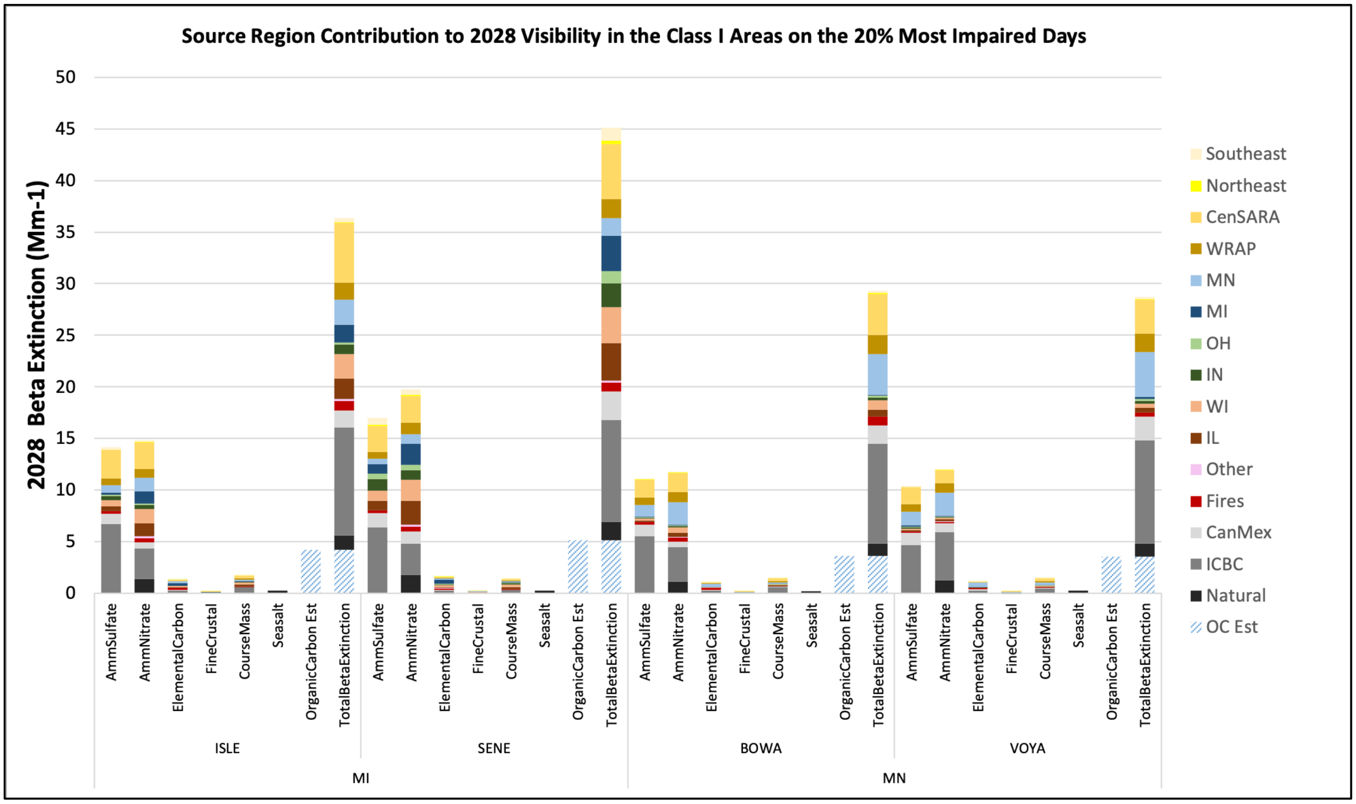


Figure 8-22. PM species tracer contributions to b_{ext} on the 20% most impaired days in 2028 at the LADCO Class I areas (CAMx 2028_{2016})

Table 8-6. Speciated 2028_{2016} tracer contributions on the 20% most impaired days at the LADCO-region Class I areas

Area	Tracer	OC_{est}	Natural	ICBC	Int'l	Fires	Other	IL	WI	IN	OH	MI	MN	WRAP	Cen	SE	NE	Total
ISLE	Total beta Ext	4.2	1.4	10.5	1.7	0.9	0.2	2.0	2.3	0.9	0.2	1.7	2.4	1.6	5.8	0.4	0.1	36.4
	NO_3	0.0	1.4	3.0	0.6	0.4	0.2	1.3	1.3	0.4	0.1	1.2	1.4	0.8	2.6	0.1	0.1	14.8
	SO_4	0.0	0.0	6.7	1.0	0.3	0.0	0.4	0.6	0.4	0.1	0.2	0.7	0.6	2.8	0.2	0.0	14.1
	CM	0.0	0.0	0.6	0.1	0.0	0.0	0.2	0.2	0.0	0.0	0.1	0.1	0.1	0.3	0.0	0.0	1.7
	EC	0.0	0.0	0.3	0.1	0.2	0.0	0.1	0.1	0.0	0.0	0.2	0.2	0.0	0.1	0.0	0.0	1.3
	FCRS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
	OC	4.2	0.0	0.0	0.0	0.0	0.0			0.0					0.0	0.0	0.0	4.2
	SS		0.3															0.3
SENE	Total beta Ext	5.1	1.8	9.9	2.7	0.9	0.2	3.6	3.5	2.3	1.2	3.4	1.7	1.9	5.4	1.3	0.3	45.1
	NO_3	0.0	1.8	3.0	1.2	0.4	0.2	2.3	2.1	1.0	0.5	2.0	1.0	1.1	2.6	0.5	0.2	19.8
	SO_4	0.0	0.0	6.3	1.4	0.2	0.0	0.9	1.0	1.1	0.5	0.9	0.5	0.7	2.5	0.7	0.1	17.0
	CM	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.2	0.1	0.1	0.1	0.0	0.1	0.2	0.0	0.0	1.4
	EC	0.0	0.0	0.2	0.1	0.2	0.0	0.1	0.2	0.1	0.0	0.4	0.1	0.0	0.1	0.0	0.0	1.6
	FCRS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
	OC	5.1	0.0	0.0	0.0	0.0	0.0			0.0					0.0	0.0	0.0	5.1
	SS		0.2															0.2
BOWA	Total beta Ext	3.6	1.2	9.7	1.7	0.9	0.1	0.6	0.9	0.2	0.2	0.1	3.9	1.9	4.0	0.2	0.1	29.3
	NO_3	0.0	1.1	3.3	0.5	0.4	0.1	0.4	0.5	0.1	0.1	0.1	2.2	1.0	1.9	0.1	0.0	11.8
	SO_4	0.0	0.0	5.5	1.1	0.3	0.0	0.1	0.2	0.1	0.1	0.0	1.1	0.7	1.7	0.1	0.0	11.2
	CM	0.0	0.0	0.6	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.2	0.1	0.3	0.0	0.0	1.5
	EC	0.0	0.0	0.3	0.1	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.1	0.0	0.0	1.1
	FCRS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.2
	OC	3.6	0.0	0.0	0.0	0.0	0.0			0.0					0.0	0.0	0.0	3.6
	SS		0.2															0.2
VOYA	Total beta Ext	3.5	1.3	10.0	2.3	0.4	0.1	0.4	0.4	0.2	0.2	0.2	4.4	1.8	3.3	0.2	0.1	28.7
	NO_3	0.0	1.2	4.7	0.9	0.1	0.0	0.2	0.2	0.1	0.1	0.1	2.2	0.9	1.3	0.1	0.0	12.0
	SO_4	0.0	0.0	4.6	1.2	0.1	0.0	0.1	0.1	0.1	0.1	0.1	1.3	0.7	1.6	0.1	0.0	10.4
	CM	0.0	0.0	0.4	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.3	0.1	0.3	0.0	0.0	1.4
	EC	0.0	0.0	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.1	0.0	0.0	1.1
	FCRS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.2
	OC	3.5	0.0	0.0	0.0	0.0	0.0			0.0					0.0	0.0	0.0	3.5
	SS		0.3															0.3

9 Conclusions and Significant Findings

LADCO presents in this TSD the results from two regional air quality modeling platforms for quantifying and evaluating future year haze conditions pursuant to tracking progress during the second planning period for the Regional Haze Rule.

Significant findings in this report include:

Trends in PM Concentrations and Regional Haze (Section 2)

- $PM_{2.5}$ design values at all monitors in the LADCO region are currently below the levels of both $PM_{2.5}$ NAAQS. In particular, the 2019 24-hour DVs are at least five $\mu g/m^3$ below the level of the NAAQS. The highest concentrations in the LADCO region are in the urban areas, and the lowest concentrations are in the far northern parts of the region, including near LADCO's Class I areas.
- Both the annual and 24-hour $PM_{2.5}$ design values for the LADCO states decreased by 33% to 51% between 2002 and 2019.
- Concentrations of all of the measured $PM_{2.5}$ species have decreased at the regional surface monitors since 2001, with the largest reductions (70%) from ammonium sulfate aerosols and the smallest reductions (7%) from organic carbon.
- From 2000 to 2018, visibility on the most impaired days at the LADCO region Class I areas improved by 18% to 26%. Visibility improvements were even greater on the clearest days, with improvements of 26% to 34%.
- Concentrations of ammonium sulfate have undergone particularly large reductions over the past two decades. As a result, ammonium nitrate and organic carbon have become relatively more important contributors to fine particulate matter and haze in the LADCO region.

Air Quality Modeling (Section 3)

- LADCO used 2011 and 2016 as modeling base years from which to project visibility conditions in 2028. LADCO selected these modeling years because they were available as modeling platforms that included projections to 2028 during the current regional haze implementation period.

Air Quality Modeling Performance Evaluation (Section 6)

- The LADCO CAMx 2011 and 2016 modeling results are comparable to the U.S. EPA 2011 and 2016 modeling platforms that the Agency used for regional haze modeling
- Both of the LADCO base year CAMx simulations achieved either the model performance goals or criteria for most of the $PM_{2.5}$ species in the winter and spring seasons
- The LADCO CAMx simulations generally better estimated $PM_{2.5}$ at the more rural IMPROVE sites compared to the CSN sites (i.e., lower NMB and NME at IMPROVE vs CSN).
- CAMx did not simulate the carbonaceous or organic aerosol well in either of the base years.
- The LADCO CAMx simulations performed relatively well in estimating spring and winter season nitrate and sulfate at the IMPROVE monitors in both 2011 and 2016.

Future Year Haze Projections (Section 7)

- The visibility conditions at the Class I areas in the LADCO region were predicted to improve on average by about 2 dv in 2028 as compared to the 2011 base year, and about 0.8 dv improvement relative to the 2016 base year.
- Predicted 2028 visibility conditions based on the 2016 modeling platform shows that the visibility in the Class I areas in Minnesota and Michigan is about 1.4 dv below the unadjusted glidepath line (i.e., URP). Accounting for the adjustment due to the international contribution, LADCO estimated 2028 visibility on the 20% most impaired days to be about 2.6 dv below the URP line.

2028 Source-Receptor Modeling Results (Section 8)

- LADCO's 2011-based 2028 projection modeling estimated that natural sources such as Rayleigh, sea salt, biogenic and fire emissions will contribute 28-33 % of the light extinction coefficients in the LADCO's Class I areas, while the LADCO and CenSARA RPOs will contribute 23-24% and 8-13% of the extinction, respectively.
- LADCO's 2016-based 2028 projection modeling estimated that natural sources such as Rayleigh, sea salt, biogenic and fire emissions will contribute 28-36 % of the light extinction coefficients in the LADCO's Class I areas, while the LADCO and CenSARA RPOs will contribute 14-27% and 8-13% of the extinction, respectively.

References

Boylan, J. W. 2004. "Calculating Statistics: Concentration Related Performance Goals", paper presented at the EPA PM Model Performance Workshop, Chapel Hill, NC. 11 February.

Boylan, J.W. and A.G. Russell. 2006. PM and Light Extinction Model Performance Metrics, Goals, and Criteria for Three-Dimensional Air Quality Models. Atmospheric Environment 40 (2006) 4946-4959.

Emery, Christopher, Zhen Liu, Armistead G. Russell, M. Talat Odman, Greg Yarwood & Naresh Kumar. 2017. Recommendations on statistics and benchmarks to assess photochemical model performance, Journal of the Air & Waste Management Association, 67:5, 582-598, DOI: 10.1080/10962247.2016.1265027

LADCO. 2018. Interstate Transport Modeling for the 2015 Ozone National Ambient Air Quality Standard. Rosemont, IL. https://www.ladco.org/wp-content/uploads/Documents/Reports/TSDs/O3/LADCO_2015O3iSIP_TSD_13Aug2018.pdf

MARAMA. 2012. Software Technical Documentation: For Software to Estimate Future Activity and Air Emissions from EGUs. Towson, MD. https://s3.amazonaws.com/marama.org/wp-content/uploads/2020/02/13092256/SystemDocumentation_EGUProjectionModel.pdf

Pitchford, M., W. Malm, B. Schichtel, N. Kumar, D. Lowenthal, J. Hand. 2007. Revised algorithm for estimating light extinction from IMPROVE particle speciation data. J. Air and Waste Mgmt. Assn., 57:11, 1326-1336. Doi: 10.3155/1047-3289.57.11.1326.

Ramboll. 2020. User's Guide: Comprehensive Air Quality Model with Extensions version 7.00. Novato, CA. http://www.camx.com/files/camxusersguide_v7-00.pdf

Simon, H., K.R. Baker, and S. Phillips. 2012. Compilation and interpretation of photochemical model performance statistics published between 2006 and 2012. Atmos. Environ. 61:124–39. doi:10.1016/j.atmosenv.2012.07.012

U.S. EPA. 2020. Technical Support Document: Preparation of Emissions Inventories for 2016v1 North American Emissions Modeling Platform. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2020-11/documents/2016v1_emismod_tsd_508.pdf

U.S. EPA. 2019a. Guidance on Regional Haze State Implementation Plans for the Second Implementation Period. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2019-08/documents/8-20-2019_-_regional_haze_guidance_final_guidance.pdf

U.S. EPA. 2019b. Technical Support Document for EPA's Updated Regional Haze Modeling. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2019-10/documents/updated_2028_regional_haze_modeling-tsd-2019_0.pdf

U.S. EPA, 2019c. Meteorological Model Performance for Annual 2016 Simulation WRF v3.8. (EPA-454/R-19-010) United States Environmental Protection Agency.

U.S. EPA, 2019d. 2016 Hemispheric Modeling Platform version 1: Implementation, Evaluation, and Attribution. Research Triangle Park, NC

U.S. EPA. 2018. Modeling Guidance for Demonstrating Air Quality Goals for Ozone, PM2.5, and Regional Haze. Research Triangle Park, NC, https://www.epa.gov/sites/production/files/2020-10/documents/o3-pm-rh-modeling_guidance-2018.pdf.

U.S. EPA. 2017a. Documentation for EPA's Preliminary 2028 Haze Modeling. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2020-10/documents/2028_regional_haze_modeling-tsd.pdf

U.S. EPA. 2017b. Technical Support Document: Additional Updates to Emissions Inventories for the Version 6.3 Emissions Modeling Platform for the Year 2023. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2017-11/documents/2011v6.3_2023en_update_emismod_tsd_oct2017.pdf

U.S. EPA. 2016a. Air Quality Modeling Technical Support Document for the 2015 Ozone NAAQS Preliminary Interstate Transport Assessment. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2017-01/documents/aq_modeling_tsd_2015_o3_naaqs_preliminary_interstate_transport_assessmen.pdf

U.S. EPA. 2016b. Technical Support Document: Preparation of Emissions Inventories for the Version 6.3, 2011 Emissions Modeling Platform. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2016-09/documents/2011v6_3_2017_emismod_tsd_aug2016_final.pdf

U.S. EPA. 2016c. EPA Base Case v5.16 for 2015 Ozone NAAQS Transport NODA Using IPM. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2017-01/documents/epa_base_case_v.5.16_for_2015_ozone_naaqs_transport_noda_incremental_documentation.pdf

U.S. EPA. 2016d. Draft guidance on progress tracking metrics, long-term strategies, reasonable progress goals and other requirements for regional haze state implementation plans for the second implementation period. https://www.epa.gov/sites/production/files/2016-07/documents/draft_regional_haze_guidance_july_2016.pdf

U.S. EPA. 2014. Meteorological Model Performance for Annual 2011 WRF v3.4 Simulation. Research Triangle Park, NC. https://www.epa.gov/sites/production/files/2020-10/documents/met_tsd_2011_final_11-26-14.pdf.

Modeling and Analysis for Demonstrating Reasonable Progress for the Regional Haze Rule 2018 - 2028 Planning Period

TSD SUPPLEMENTAL MATERIALS

Lake Michigan Air Directors Consortium

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June 17, 2021

Table of Contents

S1 Trends in Chemical Composition of Haze at LADCO Class I Area Monitors

Section 2 of the LADCO Regional Haze TSD includes plots showing the trends in the composition of light extinction (e.g., chemical composition of haze) for Minnesota's Voyageurs National Park site. This appendix includes these figures for the other three LADCO Class I Area monitors. These figures were downloaded from the Federal Land Manager Environmental Database: (http://views.cira.colostate.edu/fed/SiteBrowser/Default.aspx?appkey=SBCF_VisSum).

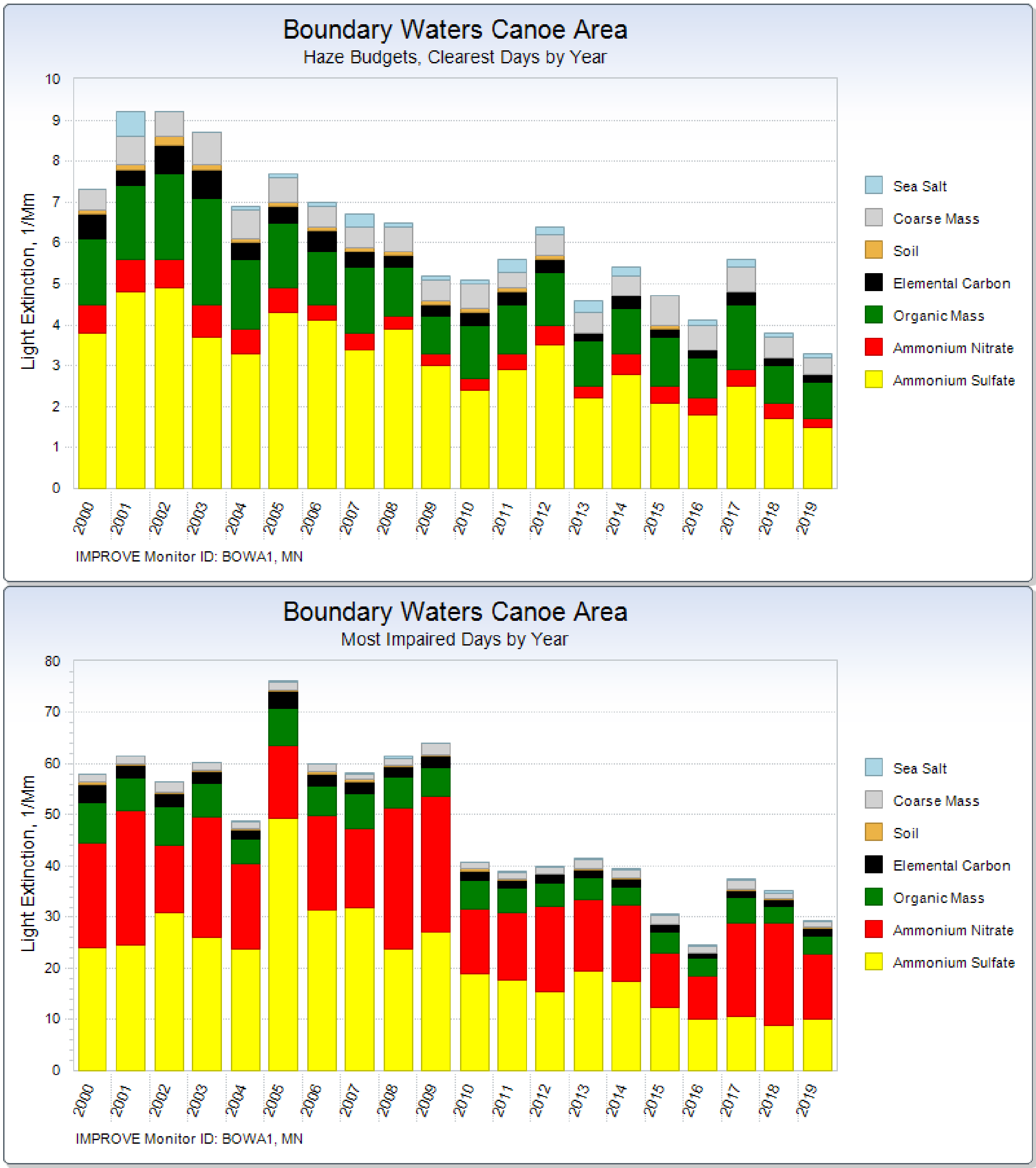


Figure S 1-1. Composition of light extinction for Minnesota's Boundary Waters Canoe Area monitor on the clearest (top) and most impaired (bottom) days.

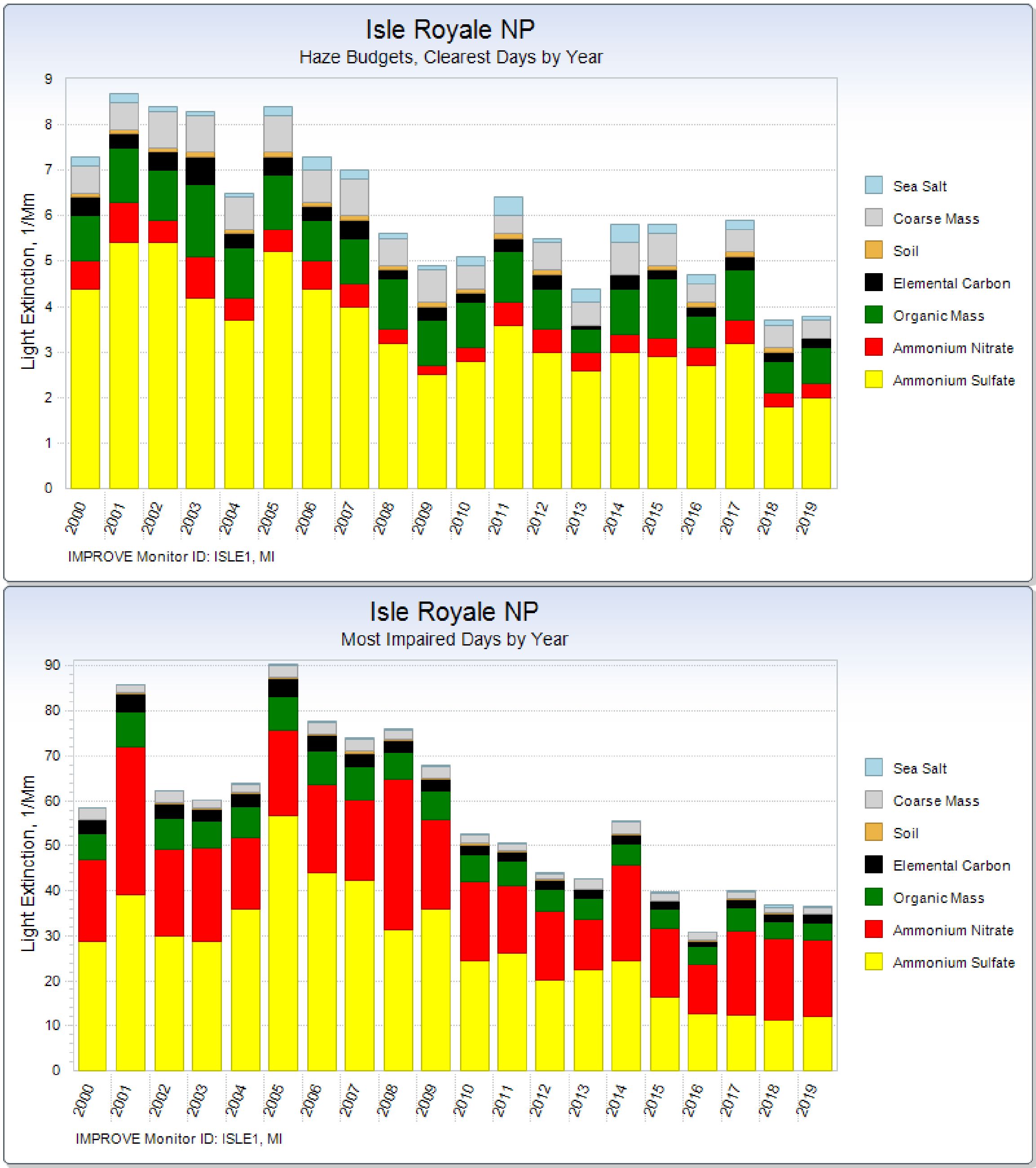


Figure S 1-2. Composition of light extinction for Michigan's Isle Royale National Park monitor on the clearest (top) and most impaired (bottom) days.

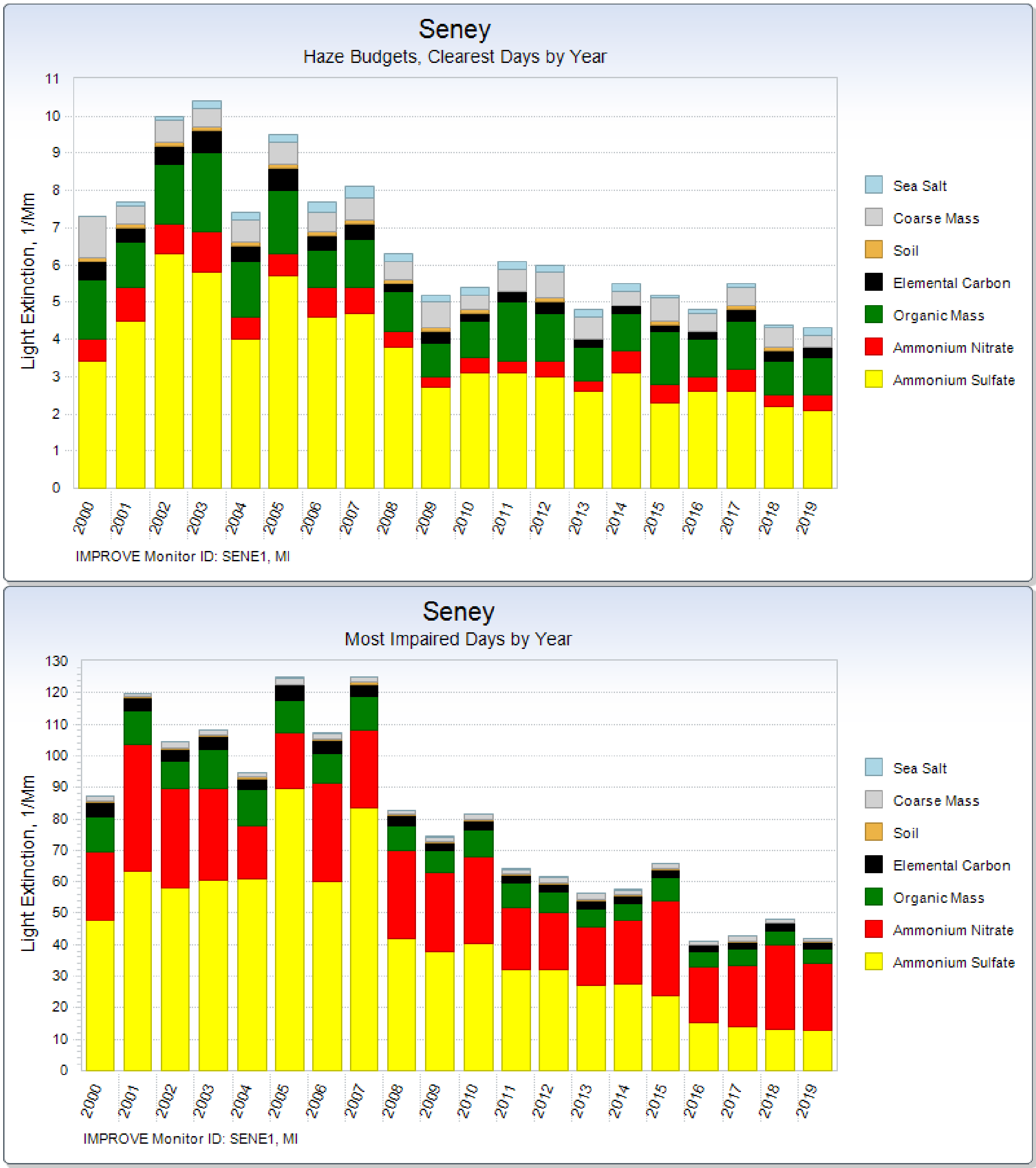


Figure S 1-3. Composition of light extinction for Michigan's Seney monitor on the clearest (top) and most impaired (bottom) days.

S2 Back Trajectory Residence Time Plots

Section 2 of the TSD includes residence time plots for the LADCO region Class I monitors based on HYSPLIT back-trajectories, weighted by distance from the monitor and determined for an end point at 200 m altitude. Figure S 2-1 through Figure S 2-8 are distance-weighted residence time figures determined for four different trajectory end heights: 100, 200, 500 and 1000 m altitude. These figures compare different types of residence times for each monitor, including unweighted, distance-weighted, and extinction-weighted residence times. In general, the residence time patterns do not vary greatly based on the weighting of the residence time or the ending altitude.

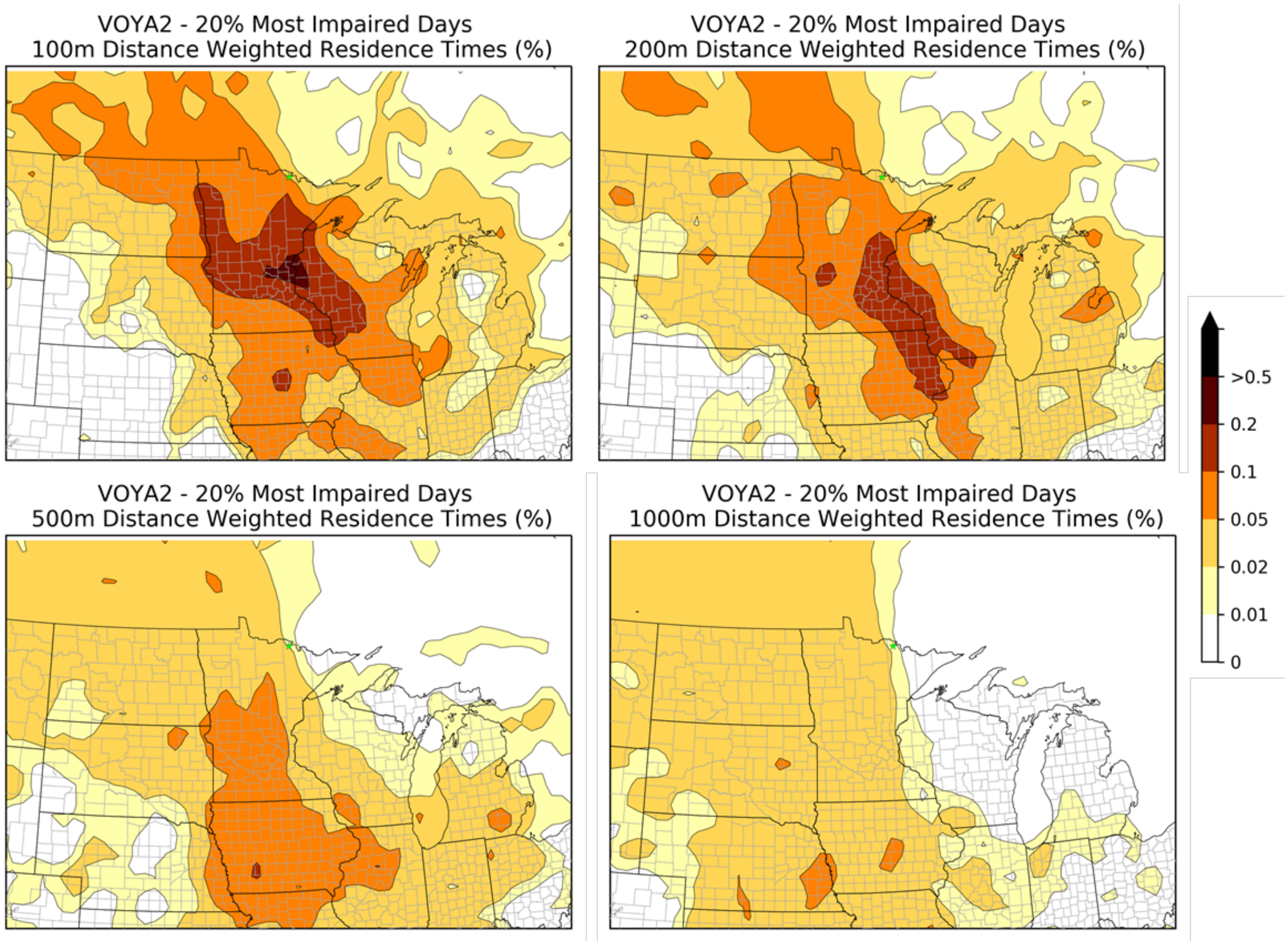


Figure S 2-1. Distance weighted residence times for air masses reaching the Voyageurs National Park monitor at a variety of heights on the 20% most impaired days for the years 2012 to 2016.

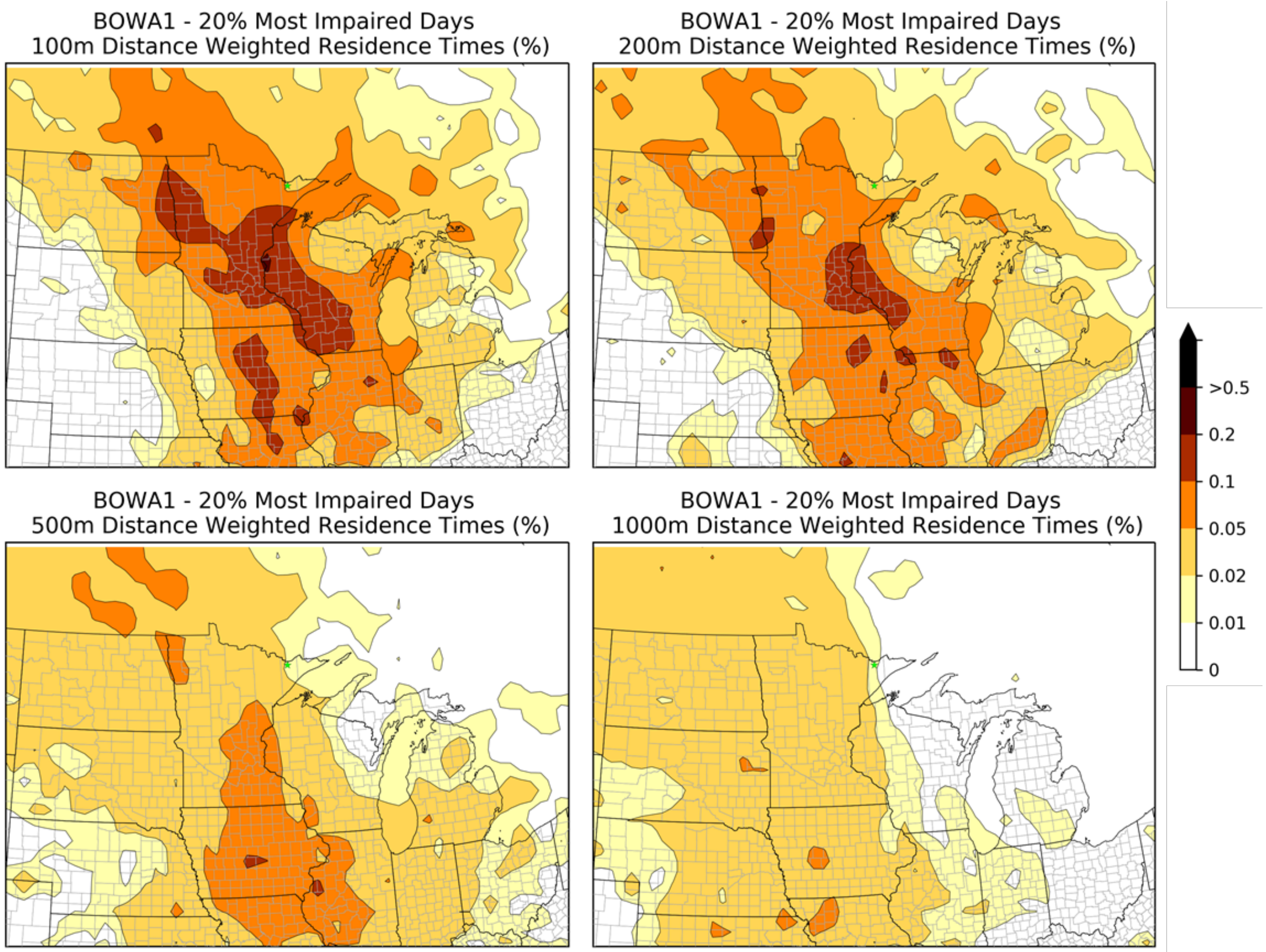


Figure S 2-2. Distance weighted residence times for air masses reaching the Boundary Waters Canoe Area monitor at a variety of heights on the 20% most impaired days for the years 2012 to 2016.

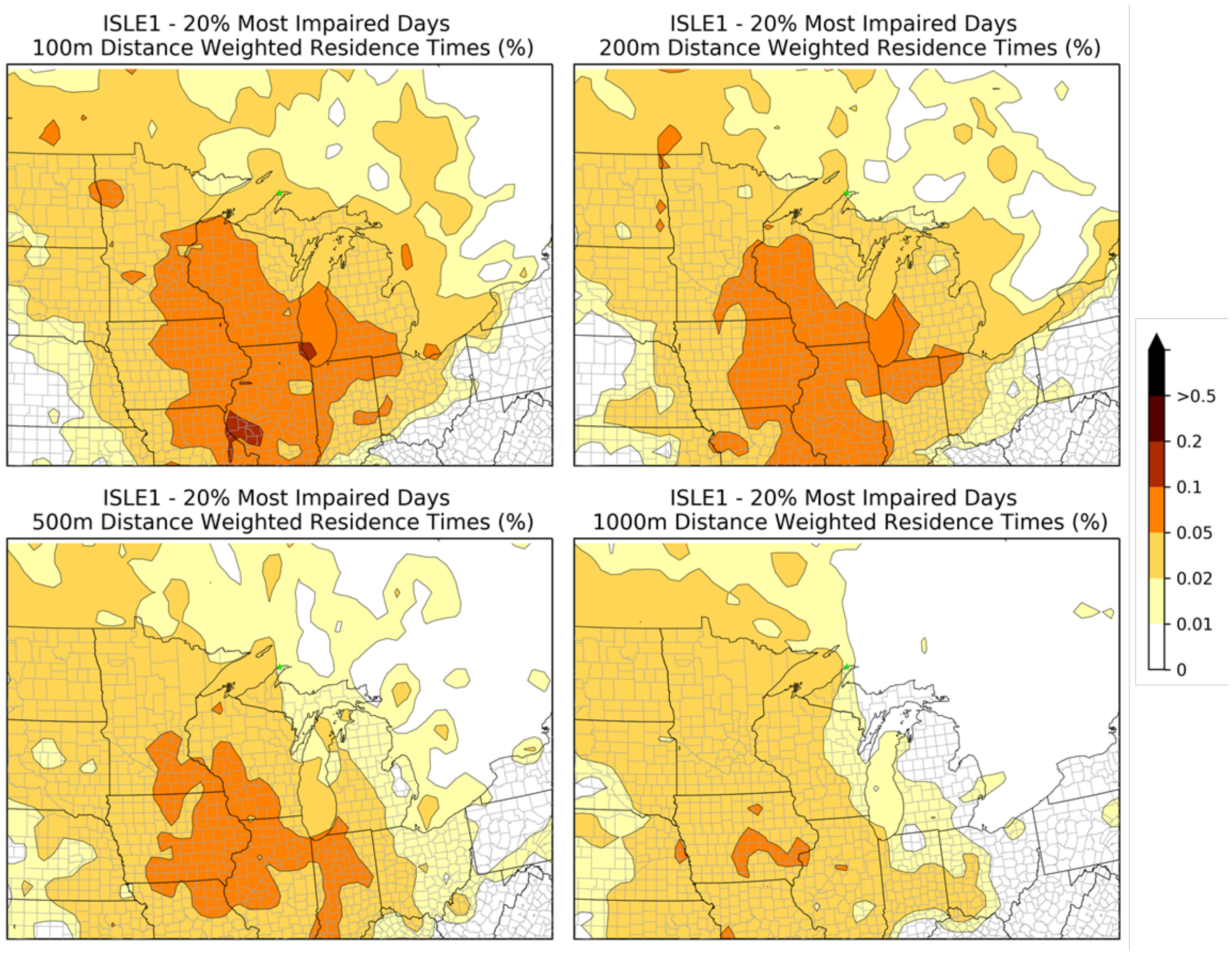


Figure S 2-3. Distance weighted residence times for air masses reaching the Isle Royale National Park monitor at a variety of heights on the 20% most impaired days for the years 2012 to 2016.

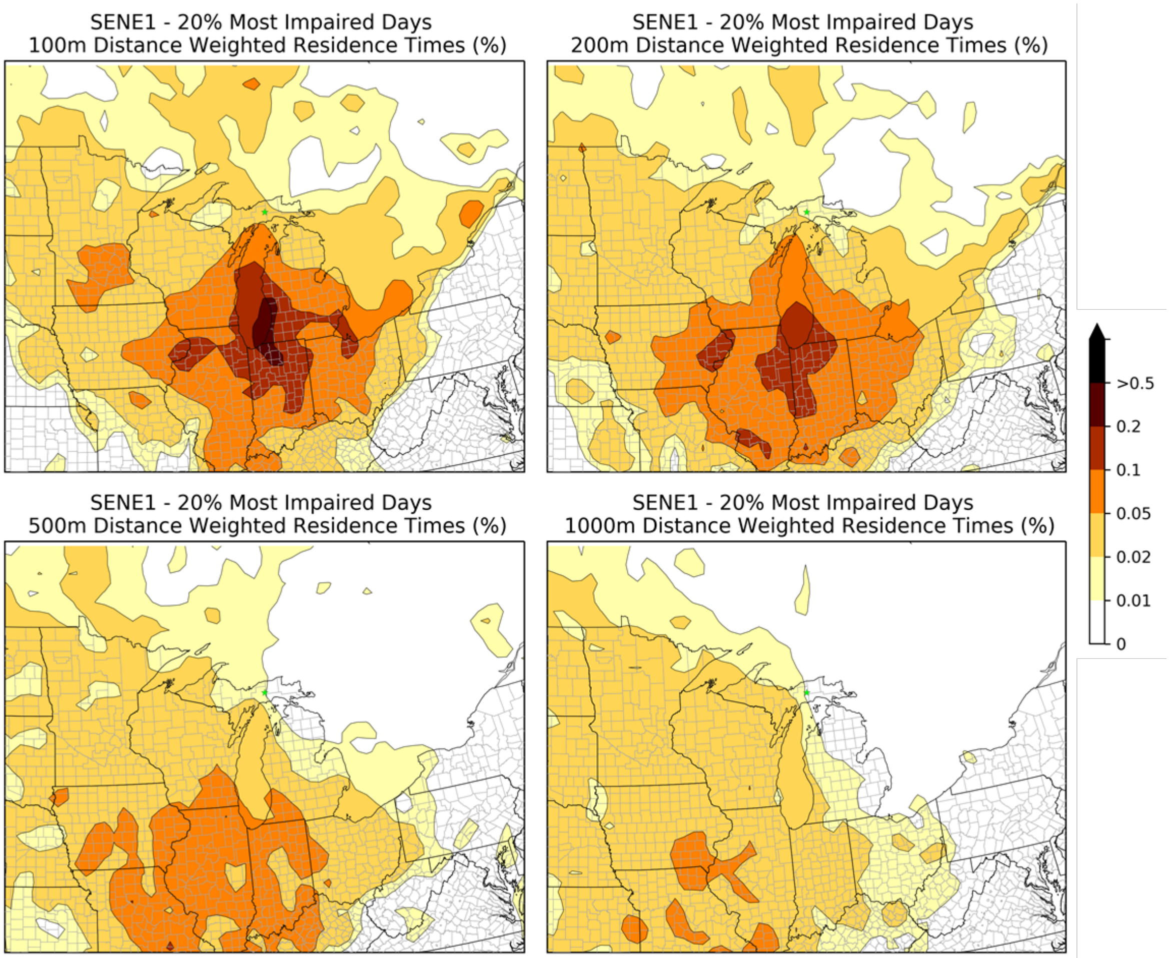


Figure S 2-4. Distance weighted residence times for air masses reaching the Seney National Wildlife Refuge monitor at a variety of heights on the 20% most impaired days for the years 2012 to 2016.

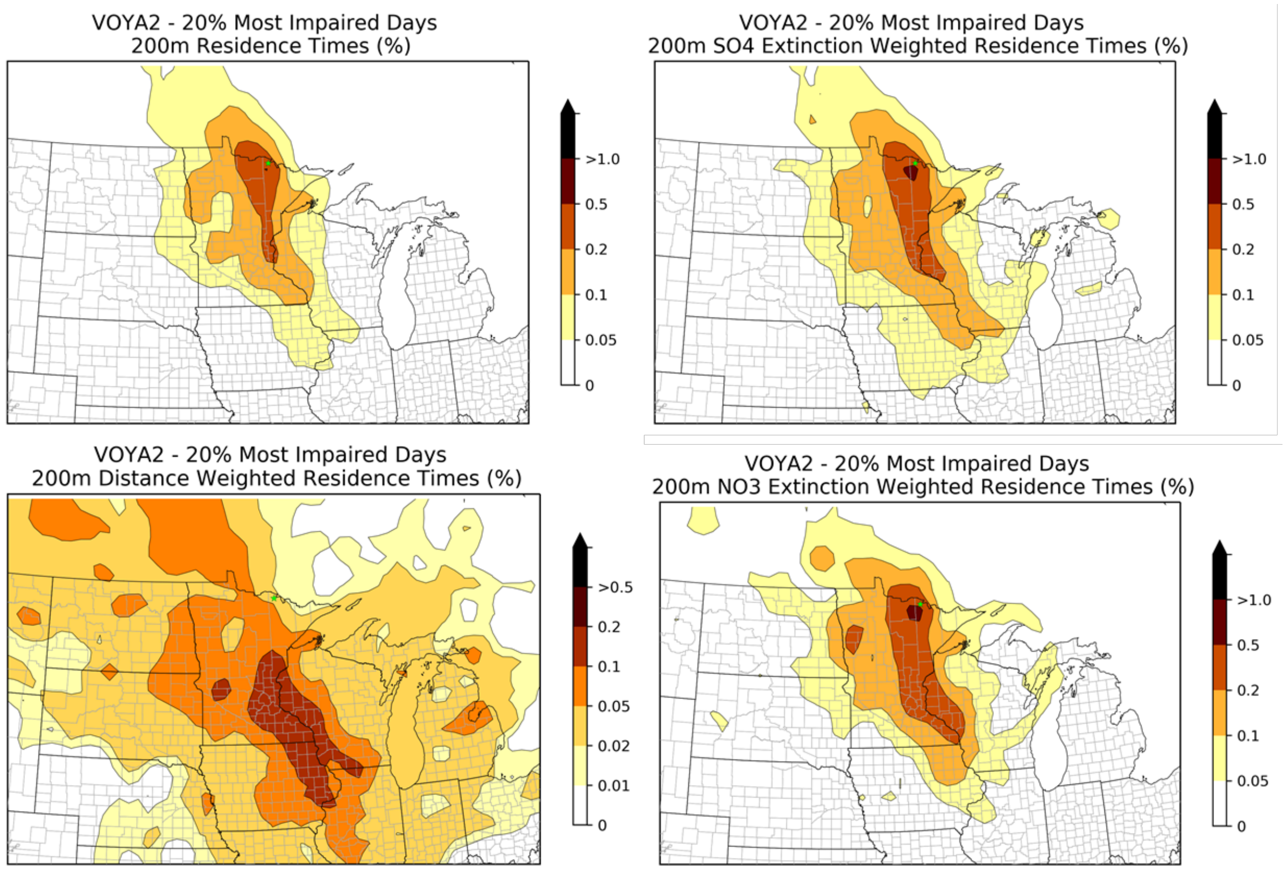


Figure S 2-5. Different measures of residence time for air masses reaching the Voyageurs National Park monitor.

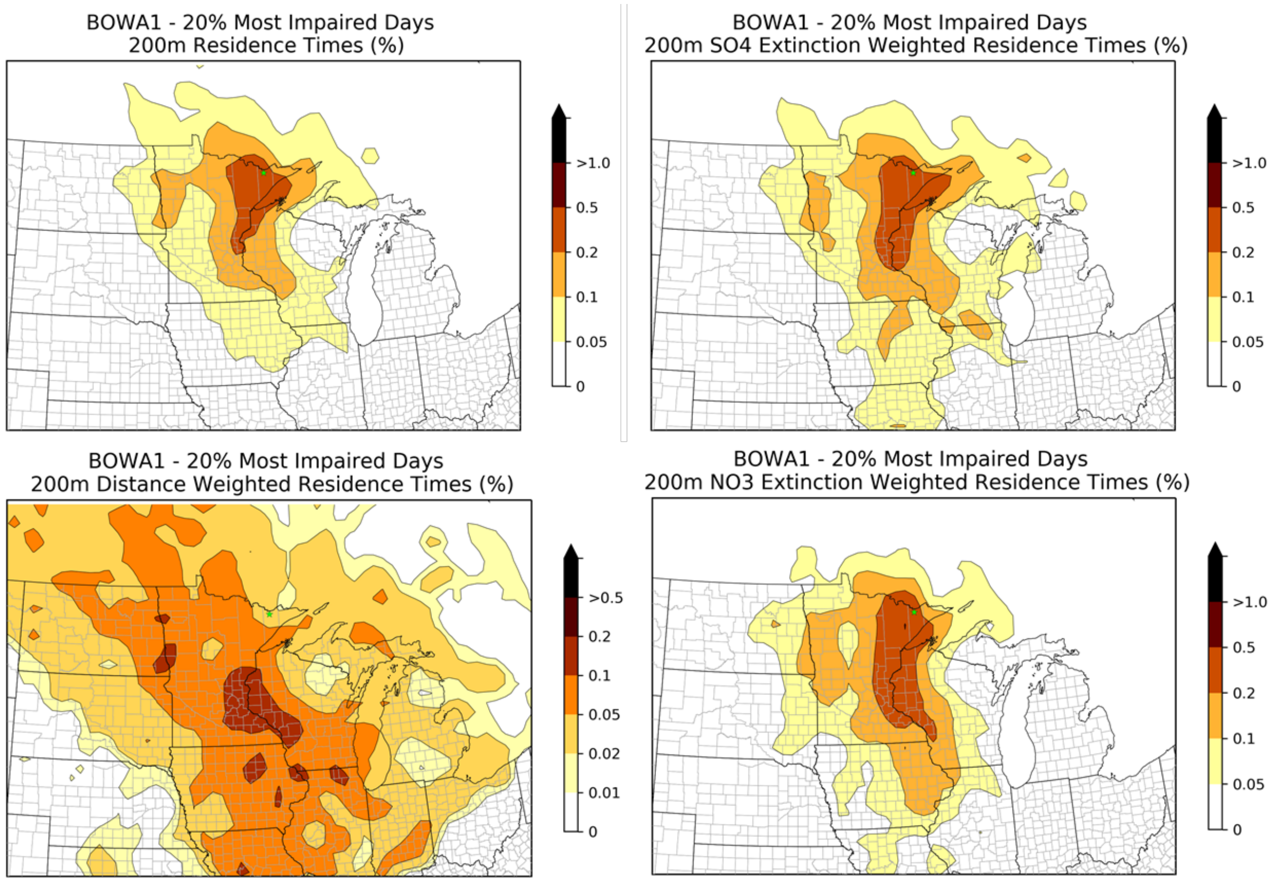


Figure S 2-6. Different measures of residence time for air masses reaching the Boundary Waters Canoe Area monitor.

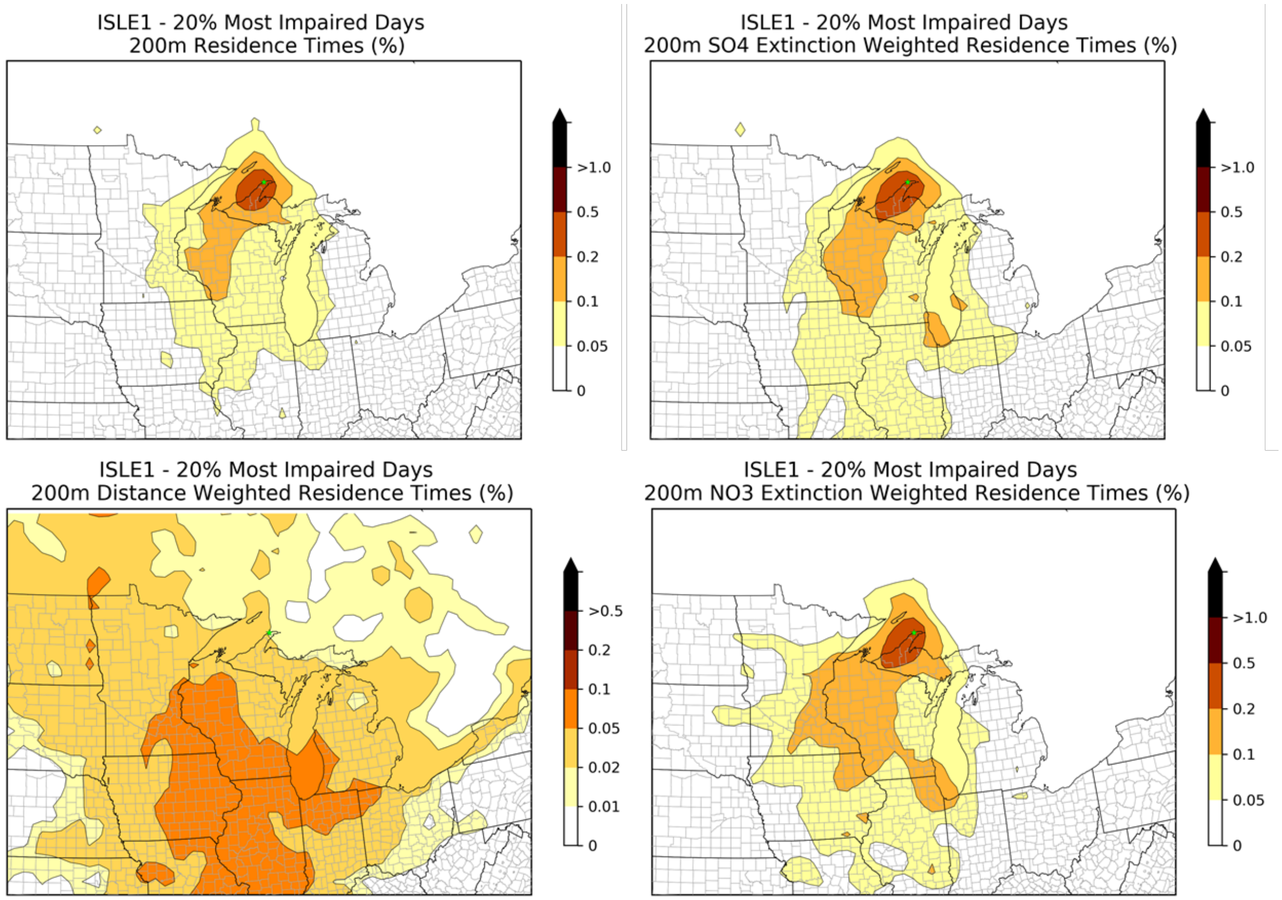


Figure S 2-7. Different measures of residence time for air masses reaching the Isle Royale National Park monitor.

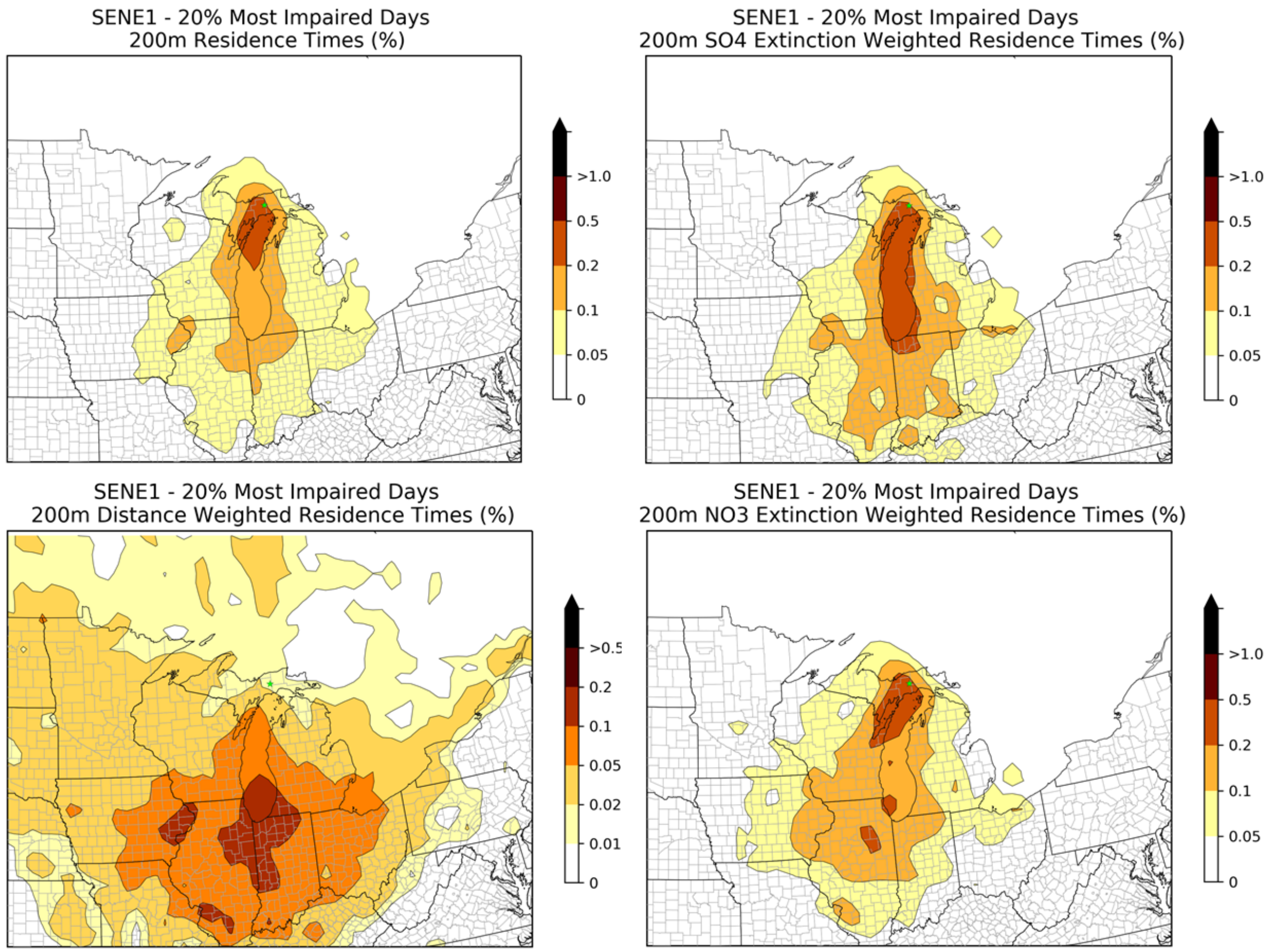


Figure S 2-8. Different measures of residence time for air masses reaching the Seney National Wildlife Area monitor.

S3 List of EGU Shutdowns Added to the 2016-based 2028 Simulation

Oris ID	BLRID	Shutdown Year	State	Facility Name
889	3	2016	IL	Baldwin
861	1	2019	IL	Coffeen
861	2	2019	IL	Coffeen
891	9	2019	IL	Havana
892	1	2019	IL	Hennepin
892	2	2019	IL	Hennepin
6016	1	2019	IL	Duck Creek
963	31	2020	IL	Dallman
963	32	2020	IL	Dallman
976	4	2020	IL	Marion
856	2	2022	IL	E D Edwards
856	3	2022	IL	E D Edwards
963	33	2023	IL	Dallman
1011	1	2018	IN	Broadway Ave
994	1	2021	IN	IPL Petersburg
994	2	2023	IN	IPL Petersburg
6213	1SG1	2023	IN	Merom
6213	2SG1	2023	IN	Merom
6705	4	2023	IN	Alcoa Allowance Mgt
6113	5	2026	IN	Gibson
1001	1	2028	IN	Cayuga
1001	2	2028	IN	Cayuga
990	GT5	2030	IN	IPM Harding
990	GT6	2030	IN	IPM Harding
990	GT4	2044	IN	IPM Harding
1843	3	2018	MI	Shiras
1825	3	2020	MI	JB Sims
1831	1	2020	MI	Eckert Station
1831	3	2020	MI	Eckert Station
1831	4	2020	MI	Eckert Station
1831	5	2020	MI	Eckert Station
1831	6	2020	MI	Eckert Station
50835	1	2025	MI	Filer City
50835	2	2025	MI	Filer City
6034	1	2030	MI	Belle River
6034	2	2030	MI	Belle River

55867	BLR-1	2018	MN	Benson Power Biomass Plant
8027	1	2023	MN	Blue Lake Generating Plant
8027	2	2023	MN	Blue Lake Generating Plant
8027	3	2023	MN	Blue Lake Generating Plant
8027	4	2023	MN	Blue Lake Generating Plant
6090	2	2023	MN	Sherburne County
1913	1	2026	MN	Inver Hills
1913	2	2026	MN	Inver Hills
1913	3	2026	MN	Inver Hills
1913	4	2026	MN	Inver Hills
1913	5	2026	MN	Inver Hills
1913	6	2026	MN	Inver Hills
6090	1	2026	MN	Sherburne County
1915	1	2028	MN	Allen S King
6090	3	2030	MN	Sherburne County
1904	5	2032	MN	Black Dog
8027	7	2034	MN	Blue Lake Generating Plant
8027	8	2034	MN	Blue Lake Generating Plant
1897	3	2048	MN	Hibbard Energy Center
1897	4	2048	MN	Hibbard Energy Center
1927	9	2049	MN	Riverside (1927)
1927	10	2049	MN	Riverside (1927)
1904	6	2058	MN	Black Dog
4050	5	2023	WI	Edgewater (4050)

S4 NAICS Codes Used to Select IN Point Sources for PSAT in the 2016 Platform

NAICS	Group	Group Name
212210	22	Iron and steel mills and ferroalloy
221112	20	Fossil fuel EGUs
221119	20	Fossil fuel EGUs
316211	23	Plastics and resin manufacturing
322221	23	Plastics and resin manufacturing
322223	23	Plastics and resin manufacturing
322225	24	Aluminum production and manufacturing
325211	23	Plastics and resin manufacturing
326111	23	Plastics and resin manufacturing
326112	23	Plastics and resin manufacturing
326113	23	Plastics and resin manufacturing
326121	23	Plastics and resin manufacturing
326122	23	Plastics and resin manufacturing
326130	23	Plastics and resin manufacturing
326160	23	Plastics and resin manufacturing
326191	23	Plastics and resin manufacturing
326199	23	Plastics and resin manufacturing
326220	23	Plastics and resin manufacturing
327310	21	Cement manufacturing, lime manufacturing
331111	22	Iron and steel mills and ferroalloy
331112	22	Iron and steel mills and ferroalloy
331210	22	Iron and steel mills and ferroalloy
331312	24	Aluminum production and manufacturing
331314	24	Aluminum production and manufacturing
331315	24	Aluminum production and manufacturing
331316	24	Aluminum production and manufacturing
331319	24	Aluminum production and manufacturing
331492	24	Aluminum production and manufacturing
331511	22	Iron and steel mills and ferroalloy
331521	24	Aluminum production and manufacturing
331524	24	Aluminum production and manufacturing
332111	22	Iron and steel mills and ferroalloy
333220	23	Plastics and resin manufacturing
422610	23	Plastics and resin manufacturing
424610	23	Plastics and resin manufacturing
424611	25	All Other Point Sources
7363111	19	Gibson (Plant ID Specific)
8017211	18	Rockport (Plant ID Specific)

99999999	25	All Other Point Sources
Blank	25	All Other Point Sources

S5 CAMx Model Performance Evaluation

This section presents a detailed operational evaluation of the LADCO CAMx simulations for the two modeling platforms used for the second regional haze implementation period. LADCO compared particulate matter (PM) surface layer concentrations from 2011 and 2016 annual base year CAMx simulations to ambient surface monitoring data to evaluate the skill of the model at reproducing the observations. The LADCO model performance evaluation (MPE) results for each of the modeling years are compared to model performance benchmarks and to MPE results from U.S. EPA modeling of similar data.

We emphasize the nitrate and sulfate model performance during the winter (January, February, and December) and spring (March, April, and May) months as these are species and periods that experience the most anthropogenic impairment to visibility at the Class I areas in the LADCO region.

S5.1 2011 CAMx Model Performance Evaluation Results

The CAMx MPE results for 2011 are presented in this section. The results are first presented as annual averages for all CSN and IMPROVE monitoring locations in the LADCO region to provide an overview of the CAMx model's skill at simulating $PM_{2.5}$. We use seasonal and regional MPE metrics to identify how well the model can estimate PM concentrations during different times of the year. We then present model performance for different $PM_{2.5}$ components (total $PM_{2.5}$, sulfate, nitrate, and total carbonaceous aerosols[1]) to quantify how well the model can simulate the key light scattering species that most contribute to visibility impairment.

The "Soccer Goal (i.e., soccer) plots in Figure S 5-1 and Figure S 5-2 show seasonal and regional average CAMx NMB and NME relative to the model performance goals by Emery et al. (2017). The lines on these plots delineate some of the performance benchmarks (i.e., 10% NMB and 35% NME) that indicate acceptable model performance relative to other PM modeling studies. The symbols on the plot present

[1] Ammonium ion (NH_4^+) evaluation is not reported here because the ammonium ion species reported by the monitoring networks is not a true measurement and thus is not readily comparable to the CAMx modeled species. Soil and sea salt are not included in this evaluation because they are a small component of the measured visibility at the LADCO class I areas on the most impaired days;

the performance statistics for different PM species (symbol shape) calculated across the CSN and IMPROVE monitors (symbol color) in the LADCO region. The soccer plot presents acceptable model performance as symbols that fall within the NMB and NME "goal lines" on the plot.

Although the LADCO CAMx simulation for the spring months in 2011 underestimated sulfate at both the CSN and IMPROVE sites, and underestimated ammonium at the IMPROVE sites, Figure S 5-1 illustrates that the seasonal average model performance for these species/sites is very good (NMB within -10%). For most of the other PM species, the CAMx simulation overestimated the concentrations on average in the springtime at both networks. The LADCO 2011 CAMx predictions of springtime nitrate averaged across the LADCO IMPROVE sites are outside of the NMB performance goal but within the performance criteria; CAMx meets the nitrate performance goal for NME. The LADCO simulation also achieved the NMB and NME performance goals for the carbonaceous aerosols (EC, OA, and TC) during the springtime at the IMPROVE monitors. The most notable performance deficiency with the LADCO 2011 CAMx simulation performance in the springtime was with the carbonaceous aerosol species at the CSN monitors. These performance statistics for these species are all outside of the more lenient performance criteria for NMB, and just within the performance criteria for NME. The LADCO simulation overestimated organic aerosol (NMB = +78%) and elemental carbon (NMB = +61%) on average in the springtime across all CSN monitors in the LADCO region.

Figure S 5-2 shows wintertime CAMx performance statistics averaged across the IMPROVE and CSN monitors in the LADCO region. On average, the LADCO 2011 CAMx simulation underpredicted the inorganic aerosols and overpredicted the carbonaceous aerosols during the winter months. Average nitrate performance is within or near the performance goals for both NMB and NME at both the IMPROVE and CSN monitors. The LADCO simulation underpredicted sulfate on average during the winter months, and exhibited worse performance at the CSN locations (NMB = -33%) than at the IMPROVE locations (NMB = -22%). The simulation overpredicted the carbonaceous aerosols in the winter at both monitoring networks, with particularly poor skill simulating organic aerosol at the CSN locations (NMB = +142%) relative to the IMPROVE locations (NMB = +77.5%). Note that the LADCO 2011 CAMx simulation did not achieve the less stringent performance criteria for any of the regional and seasonal averaged carbonaceous aerosol species in the winter.

The following sections present additional detail about the CAMx 2011 model performance for the different PM species contributing to haze impairment in the LADCO region.

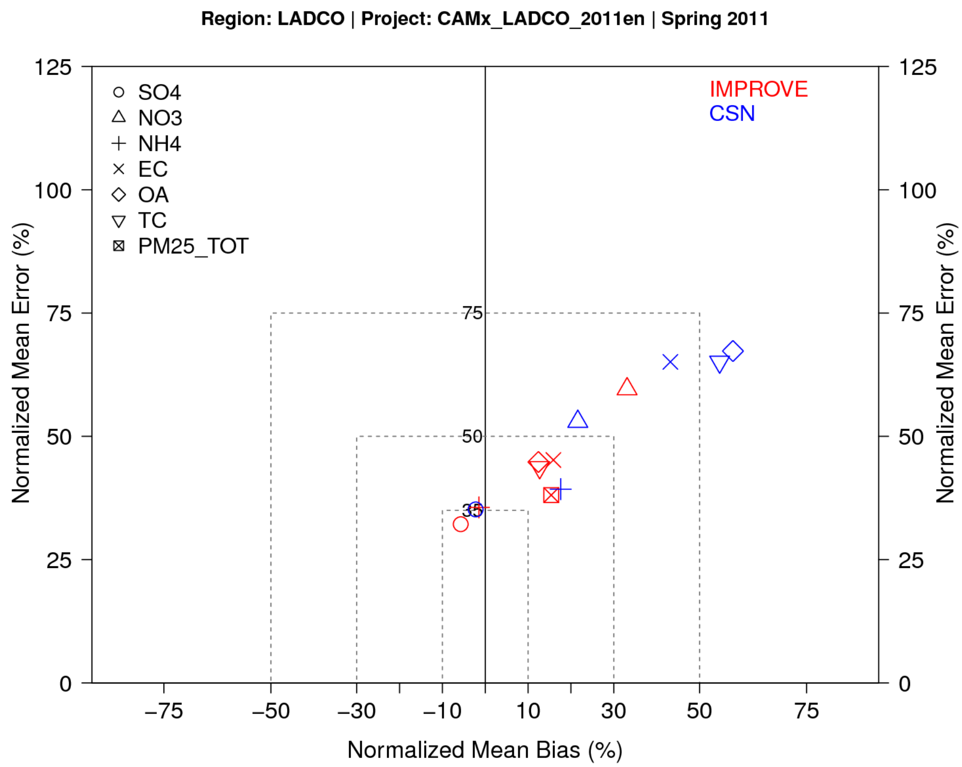


Figure S 5-1. Spring 2011 LADCO region PM2.5 performance soccer plot

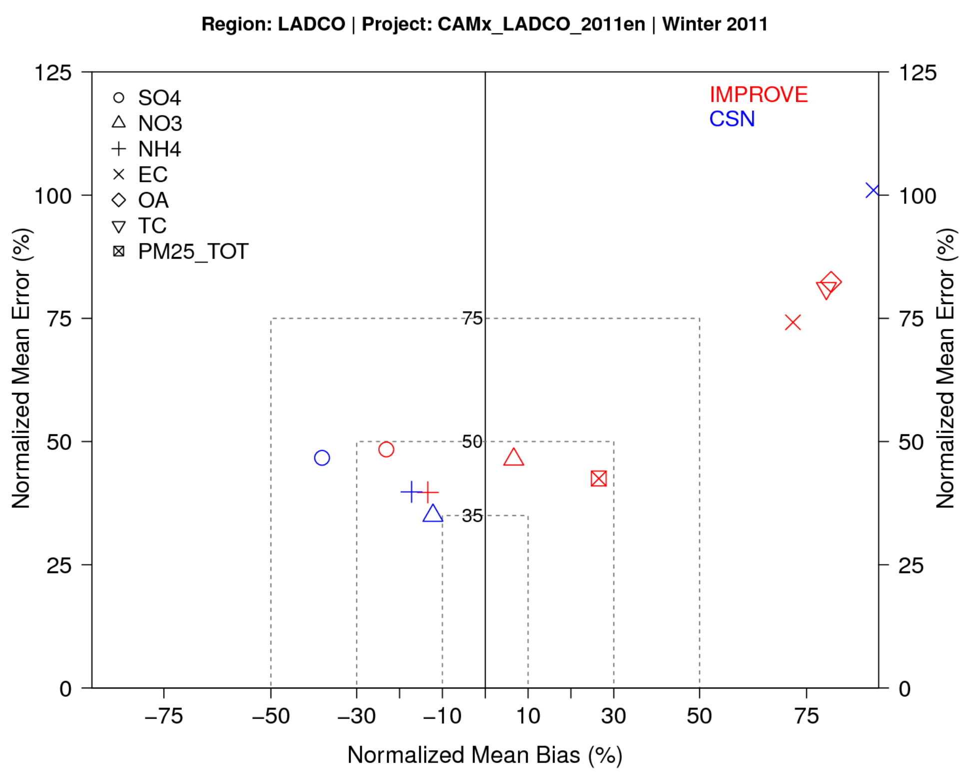


Figure S 5-2. Winter 2011 LADCO region PM2.5 performance soccer plot

S5.1.1 Total $PM_{2.5}$

This section presents the LADCO 2011 CAMx simulation performance for daily average total $PM_{2.5}$ at individual sites in the LADCO region, monthly averages across the CSN and IMPROVE networks, and seasonal averages at the monitors in the different LADCO member states. Figure S 5-3 is a "bubble" plot of seasonal average NMB at IMPROVE and CSN locations in the LADCO region. The symbols on the plot show the color coded average NMB values at each monitor. The spring season bubble plot in the figure shows that most sites fall within the +/- 35% performance criteria for $PM_{2.5}$ NMB. Monitors that fall outside of the performance benchmarks are seen in Appalachia in the southeast part of the map, coastal sites along the western shore of Lake Michigan, and in southeast Minnesota. The winter season bubble plot shows that the most significant performance problems occur at the monitors in eastern Ohio and in Minnesota.

Figure S 5-4 and Figure S 5-5 are "boxplots" of monthly average modeled and observed concentrations for the two monitoring networks. The concentration lines on this plot present the monthly mean concentrations averaged across all of the monitors in each network for each month. The red line shows the CAMx monthly average and the orange boxes show the CAMx 25th and 75th percentile concentration distributions. Similarly the black line and grey boxes show the same metrics for the observations.

The LADCO CAMx 2011 simulation overpredicted total $PM_{2.5}$ during all seasons except summer. Relative to the observations, CAMx had a higher positive bias in total $PM_{2.5}$ during the winter months at the IMPROVE sites (NMB = +24%) than at the CSN sites (NMB = +11.5%). Conversely, CAMx better simulated total $PM_{2.5}$ on average at the IMPROVE sites (+8.5%) than the CSN sites (NMB =+22.6%) during the spring months.

Table S 5-2 shows the CAMx total $PM_{2.5}$ performance statistics by season and state for monitors in the IMPROVE network. Focusing on the statistics in Michigan and Minnesota, the two LADCO member states with Class I areas subject to the RHR, shows that CAMx performance in the springtime is close to the total $PM_{2.5}$ NMB performance goal (10%) for both states (MI = -11.2%; MN = +17.3%). The wintertime NMB performance for total $PM_{2.5}$ is not as good (MI = +29%; MN = +47%), with CAMx missing the NMB performance criteria (30%) for the MN sites.

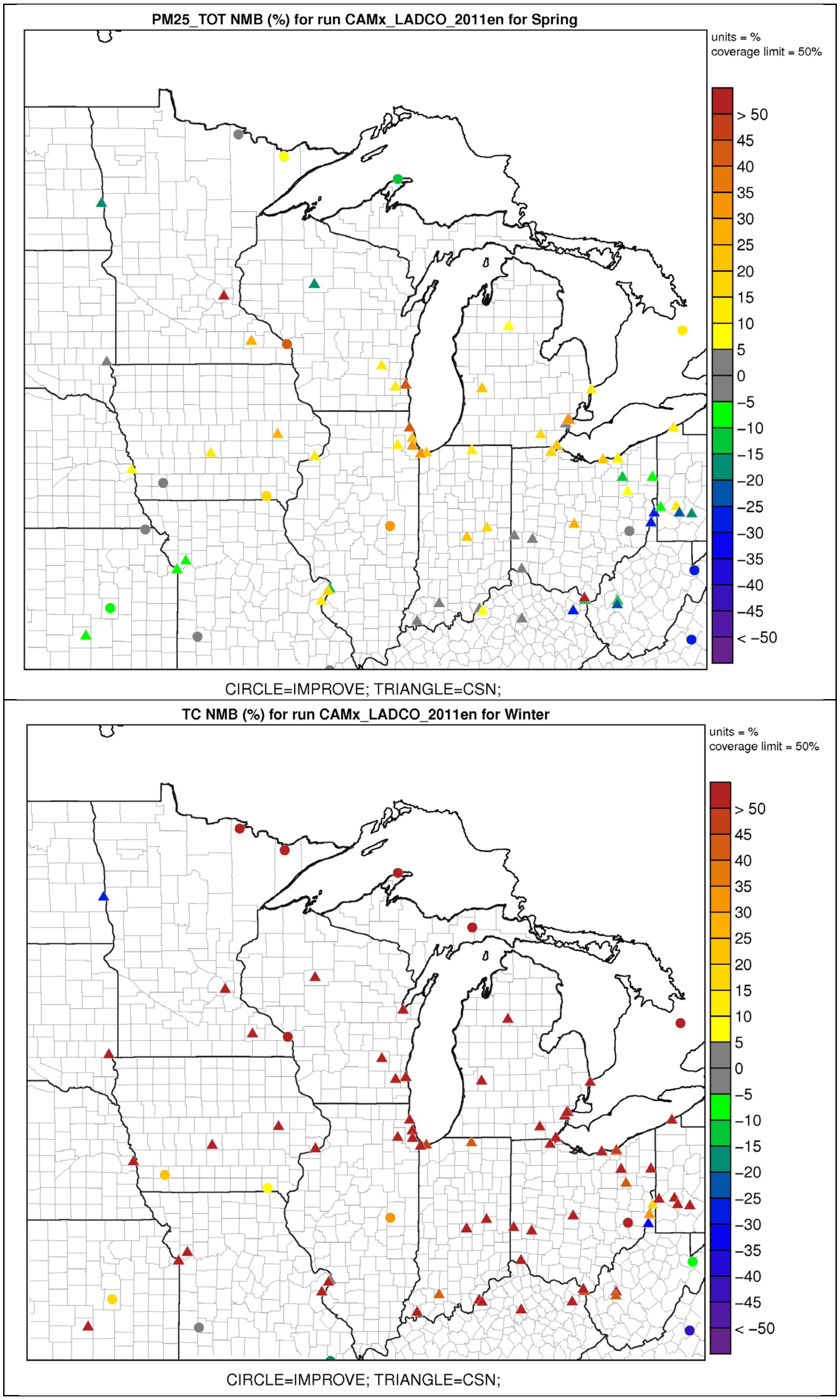


Figure S 5-3. Total $PM_{2.5}$ 2011 seasonal average NMB for the spring (top) and winter (bottom)

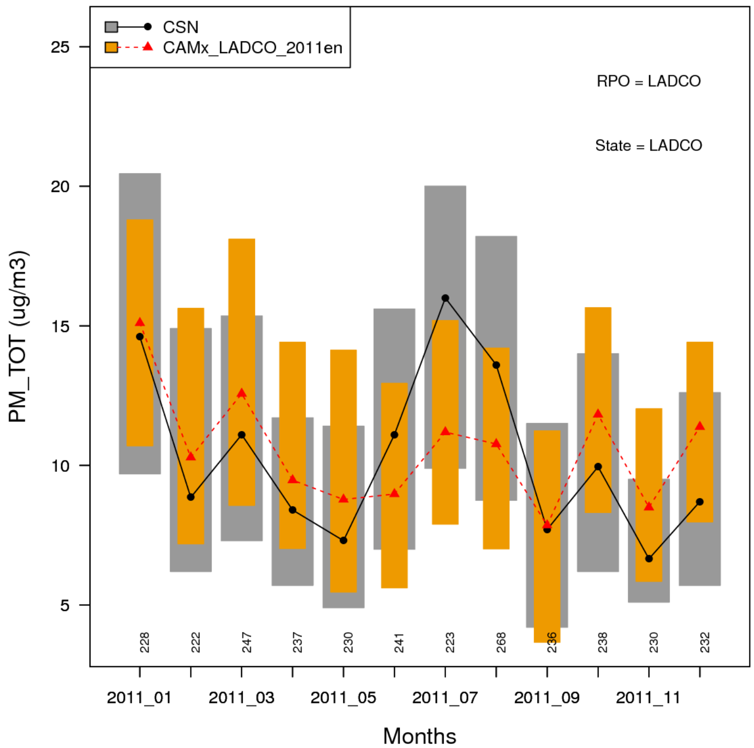


Figure S 5-4. Monthly 2011 $PM_{2.5}$ boxplot of CSN locations in the LADCO region

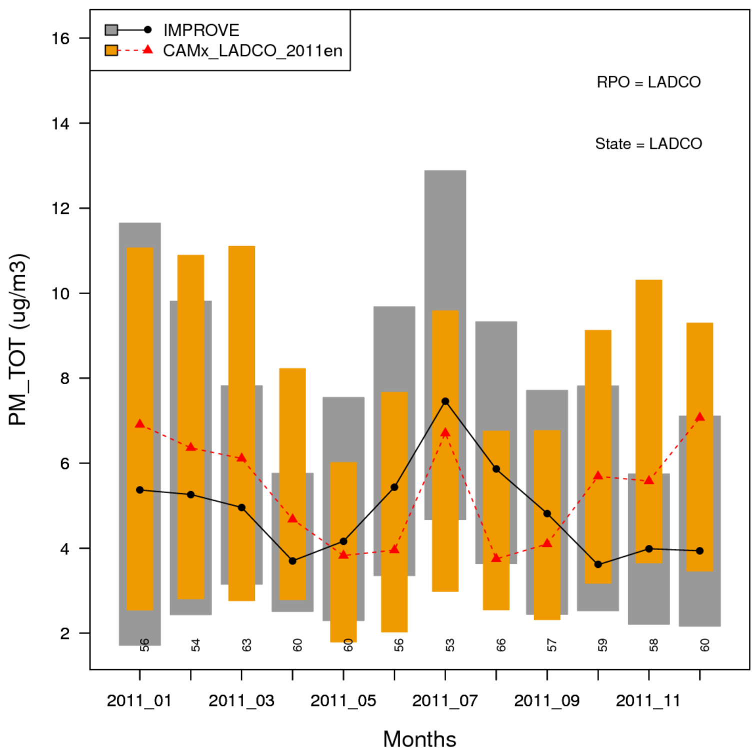


Figure S 5-5. Monthly 2011 $PM_{2.5}$ boxplot of IMPROVE locations in the LADCO region

S5.1.2 Sulfate

This section presents the LADCO 2011 CAMx simulation performance for daily average sulfate (SO_4) at individual sites in the LADCO region, monthly averages across the CSN and IMPROVE networks, and seasonal averages at the monitors in the different LADCO member states. Figure S 5-6 is a "bubble" plot of seasonal average NMB at IMPROVE and CSN locations in the LADCO region. Figure S 5-7 and Figure S 5-8 are "boxplots" of monthly average modeled and observed concentrations for the two monitoring networks. See section S5.1.1 for additional details about the format of these plot types.

The spring season bubble plot for sulfate shows that most sites in the middle and northern portions of the map, covering the majority of the area of the LADCO states, fall within the +/- 35% performance criteria for sulfate NMB. A systematic underprediction bias in CAMx is seen at the monitors along the southern tier of the map, including southern Illinois, Indiana, and Ohio, with NMBs at almost all of the monitors exceeding -35%. The winter season sulfate bubble plot shows a fairly severe CAMx underprediction bias (NMB > -30%) across most of the monitors in the region. A bright spot in the wintertime bubble plot is that the CAMx predictions for sulfate at the northern Class I areas in Michigan and Minnesota acheived the model performance benchmarks for sulfate.

The boxplot in Figure S 5-7 shows that regionwide CAMx underpredicts sulfate in all months at the CSN monitors. Figure S 5-8 shows more mixed performance at the IMPROVE monitors in the region with CAMx generally underpredicting sulfate in the winter (NMB = -23.6%) and overpredicting sulfate during most of the spring months.

Table S 5-4 shows the CAMx sulfate performance statistics by season and state for monitors in the IMPROVE network. Focusing on the statistics in Michigan and Minnesota, the two LADCO member states with Class I areas subject to the RHR, shows that CAMx performance in the springtime acheived the NMB performance goal (10%) for both states (MI = +9.6%; MN = +4%). The wintertime performance for sulfate is good for the MI IMPROVE site (NMB = +3.3%) and acceptable for the MN IMPROVE sites (NMB= -21%).

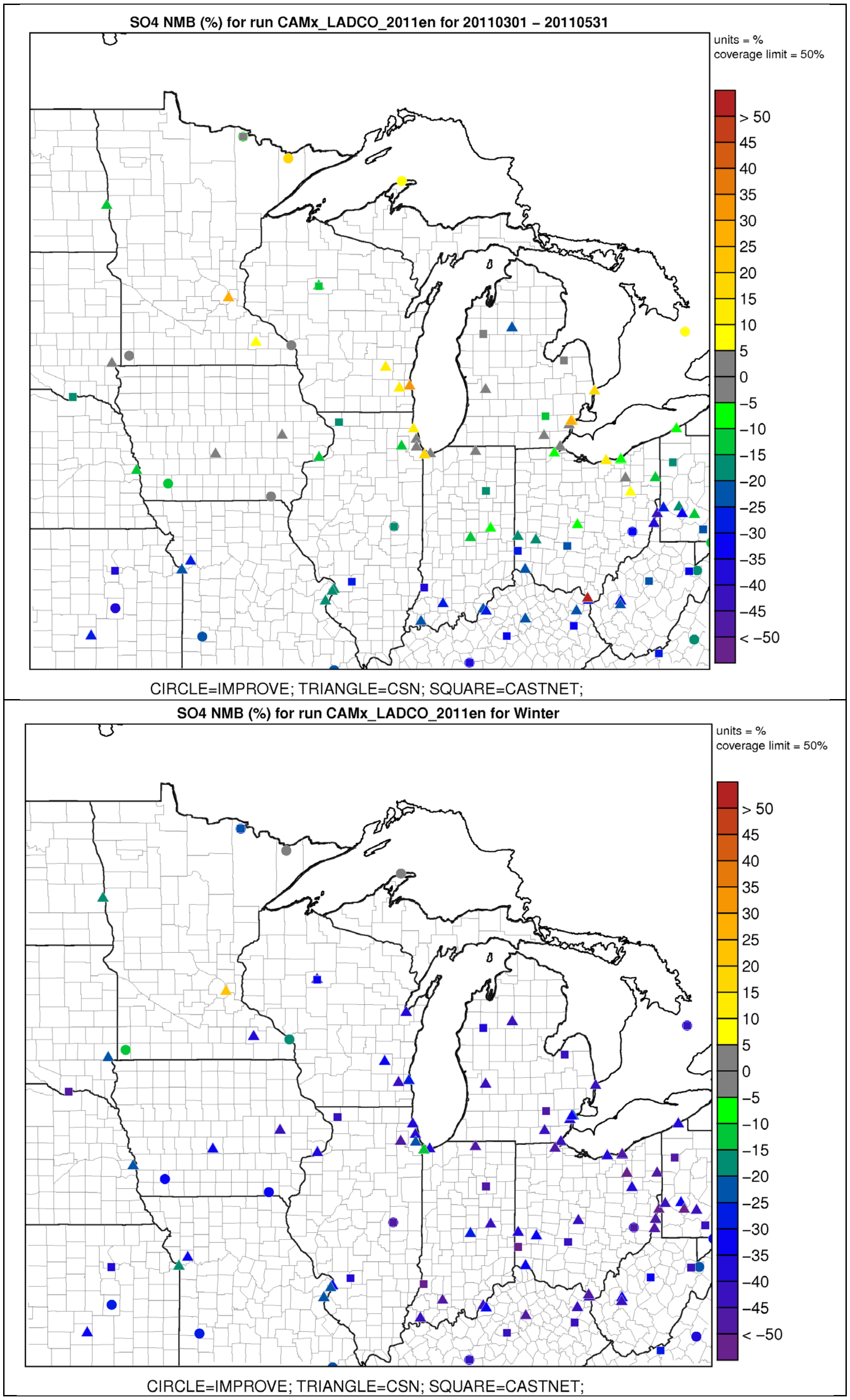


Figure S 5-6. Sulfate 2011 seasonal average NMB for the spring (top) and winter (bottom)

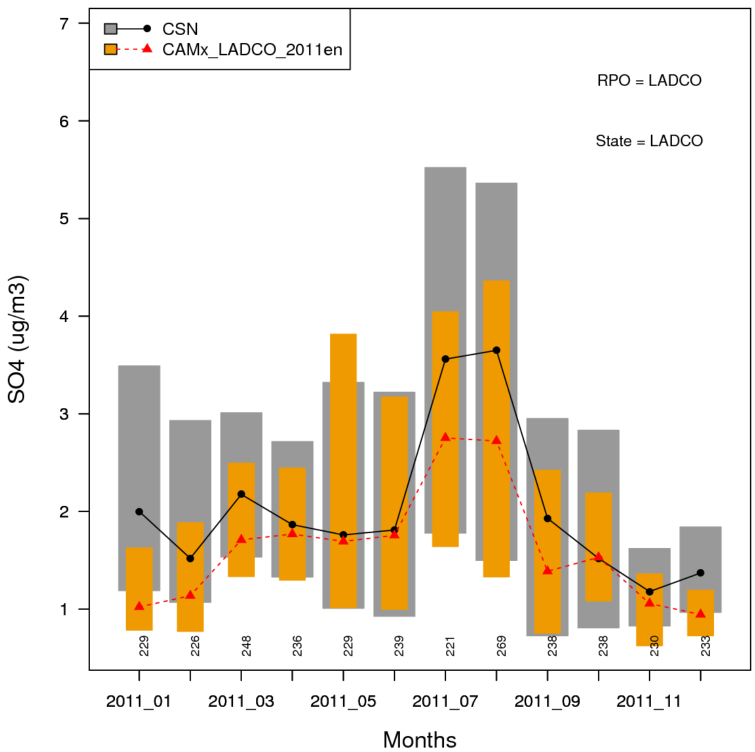


Figure S 5-7. Monthly SO_4 boxplot of CSN locations in the LADCO region

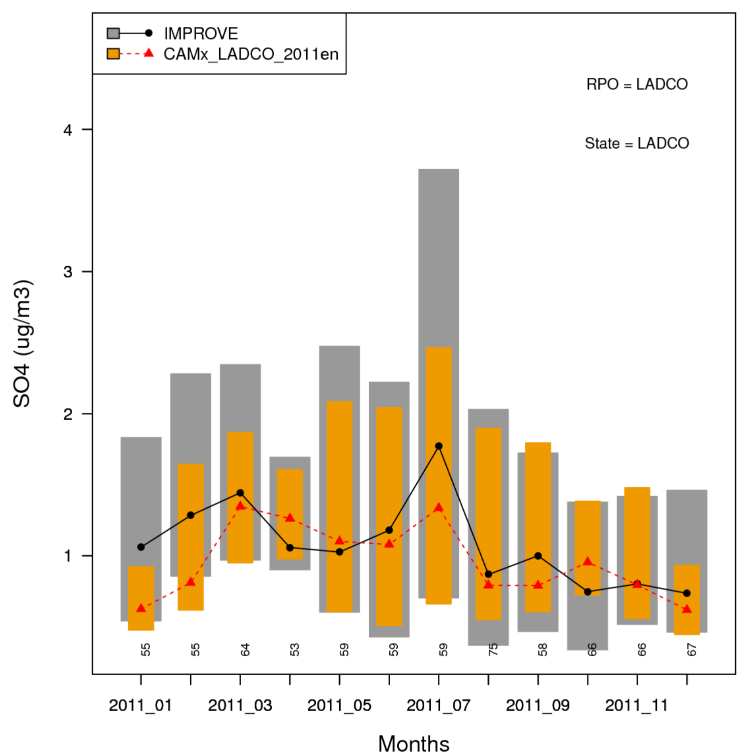


Figure S 5-8. Monthly SO_4 boxplot of IMPROVE locations in the LADCO region

S5.1.3 Nitrate

This section presents the LADCO 2011 CAMx simulation performance for daily average nitrate (NO_3) at individual sites in the LADCO region, monthly averages across the CSN and IMPROVE networks, and seasonal averages at the monitors in the different LADCO member states. Figure S 5-9 is a "bubble" plot of seasonal average NMB at IMPROVE and CSN locations in the LADCO region. Figure S 5-10 and Figure S 5-11 are "boxplots" of monthly average modeled and observed concentrations for the two monitoring networks. See section S5.1.1 for additional details about the format of these plot types.

The spring season bubble plot for nitrate shows that the LADCO 2011 CAMx simulation overpredicted nitrate across most of the LADCO region. The simulation achieved low NMB values at monitors in the region west of Lake Michigan (NMB < +/-15%), with higher biases (NMB > +/40%) in the eastern and southern portions of the LADCO region. The winter season nitrate bubble plot shows that the simulation had an underprediction bias across most of the monitors in the region. An exception to this pattern is at the northern Class I areas where the CAMx simulation had a significant overprediction bias at the IMPROVE monitors in Michigan (NMB = 45%) and Minnesota (NMB = 36%).

The boxplot in Figure S 5-10 shows that during the winter and spring, when the highest nitrate values are observed, the LADCO 2011 CAMx simulation tended to overpredict nitrate at the CSN monitors. January is an exception, and as the single month with the highest observed nitrate concentrations in the region, the simulation underpredicted the observations during January. Figure S 5-11 shows that the CAMx simulation overpredicted winter and spring season nitrate at the IMPROVE monitors across the region. While the highest biases occur in March and December, the CAMx nitrate NMBs were relatively low in January, February, and April.

Table S 5-6 shows the CAMx nitrate performance statistics by season and state for monitors in the IMPROVE network. Focusing on the statistics in Michigan and Minnesota shows that the CAMx nitrate estimates in the springtime achieved the NMB performance goal (15%) for Minnesota monitors (NMB = +11.7%) and are within the performance criteria (65%) for Michigan (NMB = -33.7%). The wintertime performance for nitrate is acceptable for the Minnesota IMPROVE sites (NMB= +39%). The LADCO 3011 CAMx simulation severely overpredicted wintertime nitrate at the Michigan IMPROVE monitors (NMB = +91%).

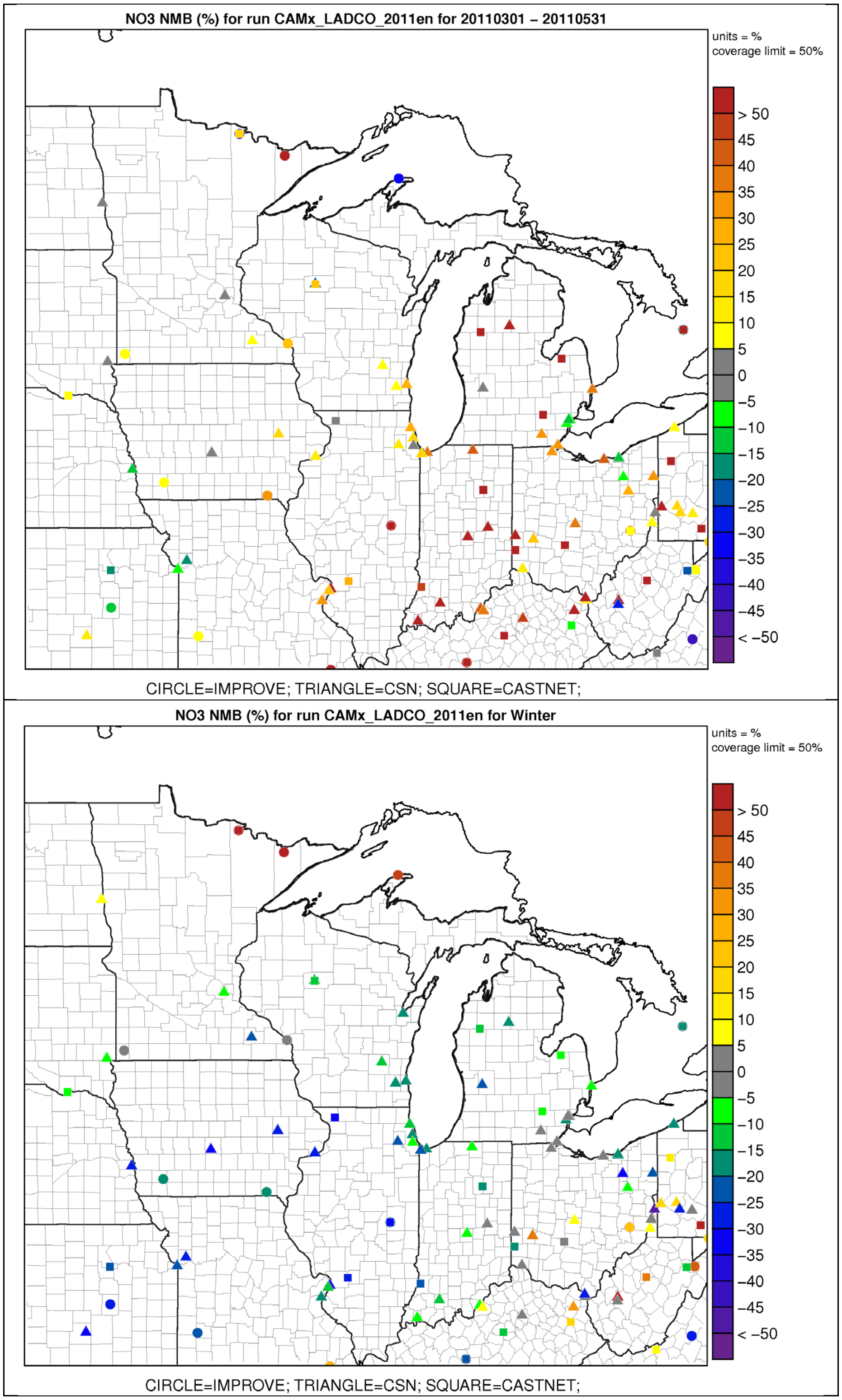


Figure S 5-9. Nitrate 2011 seasonal average NMB for the spring (top) and winter (bottom)

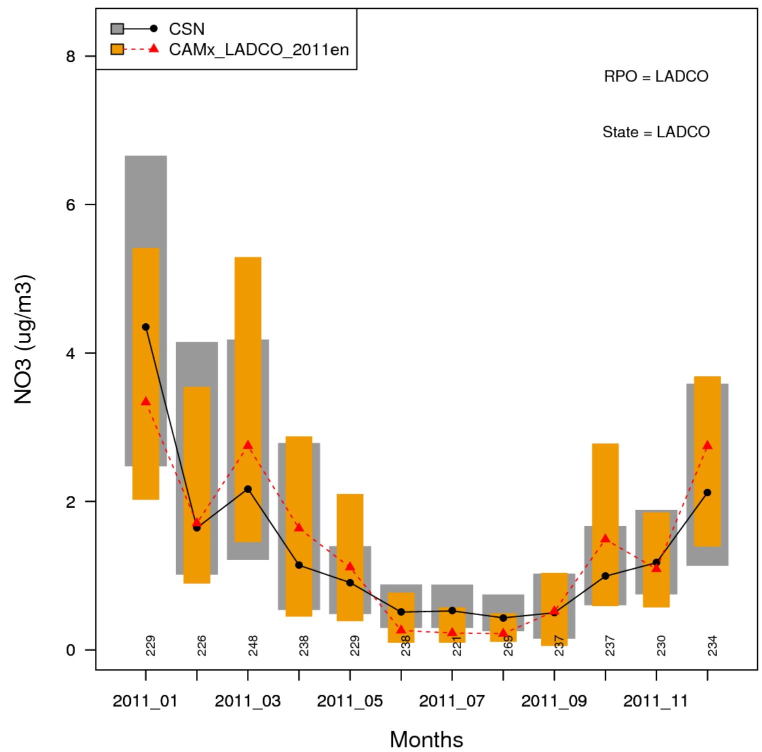


Figure S 5-10. Monthly 2011 NO_3 boxplot of CSN locations in the LADCO region

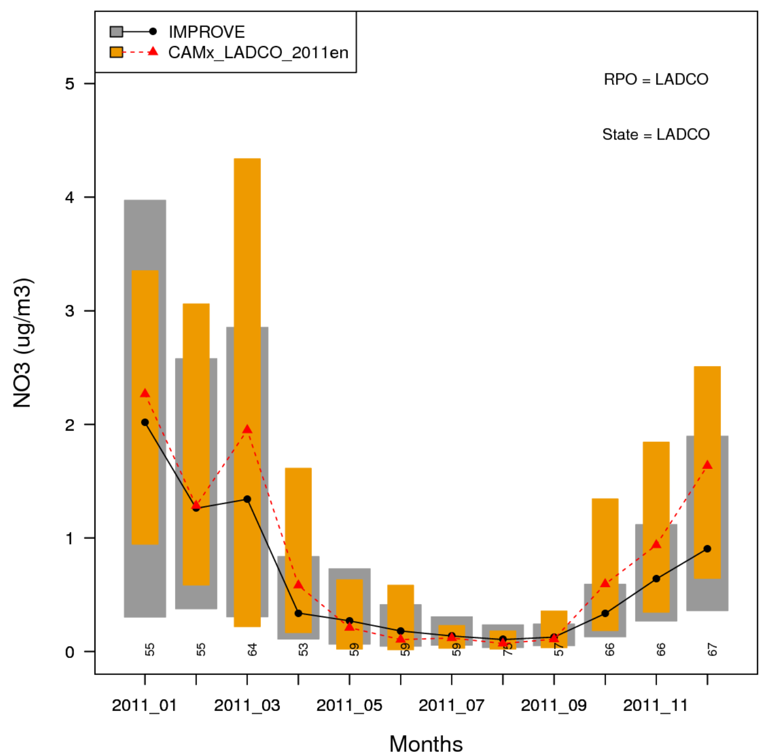


Figure S 5-11. Monthly 2011 NO_3 boxplot of IMPROVE locations in the LADCO region

S5.1.4 Carbonaceous Aerosols

This section presents the LADCO 2011 CAMx simulation performance for total carbonaceous aerosol (TC = EC + OC) at individual sites in the LADCO region, monthly averages across the CSN and IMPROVE networks, and seasonal averages at the monitors in the different LADCO member states. Figure S 5-12 is a "bubble" plot of seasonal average NMB at IMPROVE and CSN locations in the LADCO region. Figure S 5-13 and Figure S 5-14 are "boxplots" of monthly average modeled and observed concentrations for the two monitoring networks. See section S5.1.1 for additional details about the format of these plot types.

The spring season bubble plot for TC shows that the LADCO 2011 CAMx simulation overpredicted carbonaceous aerosols across most of the LADCO region. The simulation had particularly high seasonal average NMBs at the CSN monitors (NMB = +75%). The CAMx simulation acheived relatively good springtime TC performance at the IMPROVE monitors in the region (NMB +9.5%). The winter season TC bubble plot shows that the simulation had an overprediction bias for TC across all of the monitors in the LADCO region. The CAMx wintertime TC estimates at the IMPROVE monitors (NMB = +76.5%) and at the CSN monitors (NMB = +138%) were well outside of the NMB performance criteria for the carbonaceous aerosols (40-50%).

The boxplot in Figure S 5-13 shows that the highest TC values observed in the CSN monitors occurred during the summer and fall when biogenic emissions and wildfires are at their peak. CAMx estimated summertime TC at the CSN monitors fairly well (regional NMB = +9.8%), and also captured the monthly variability in the fall months. This plot illustrates the significant deficiency in the CAMx predictions of winter and spring season carbonaceous aerosols, with the model overpredicting TC (NMB > 75%) through these seasons. Figure S 5-14 shows that the IMPROVE network observed similar monthly variability in TC as the CSN monitors, with concentrations peaking in the summer and dropping in the winter. Like at the CSN monitors the LADCO 2011 CAMx simulation also overpredicted winter season TC at the IMPROVE monitors in the region.

Table S 5-8 shows the CAMx TC performance statistics by season and state for monitors in the IMPROVE network. CAMx springtime TC estimates at IMPROVE monitors in Michigan (NMB = +14.6%) and Minnesota (NMB = +17.5%) meet the NMB performance goal (15-20%). The CAMx simulation severely overpredicted wintertime TC at the Michigan (NMB = +82%) and Minnesota (NMB = +98.8%) IMPROVE monitors.

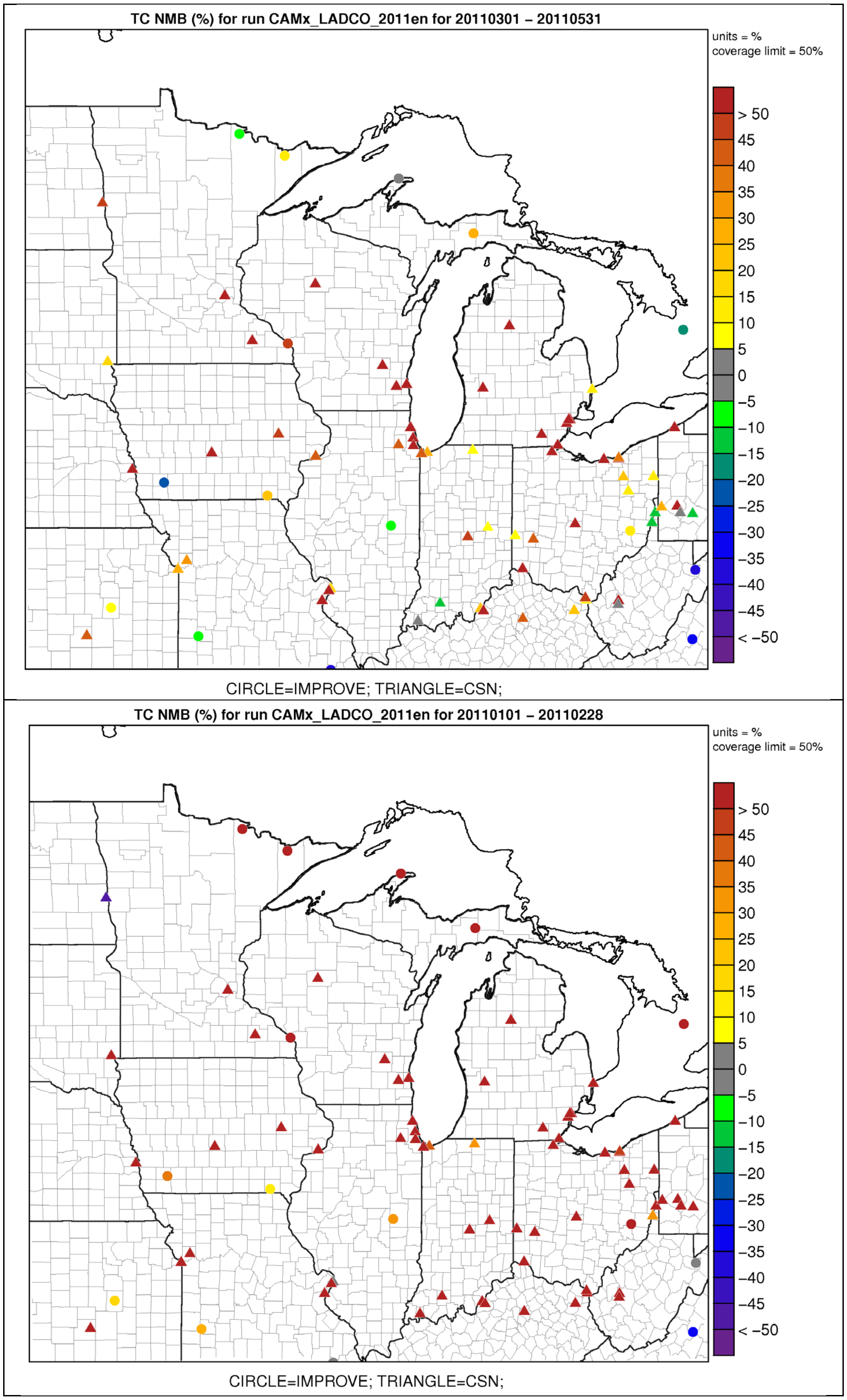


Figure S 5-12. Carbonaceous aerosol 2011 seasonal average NMB for the spring (top) and winter (bottom)

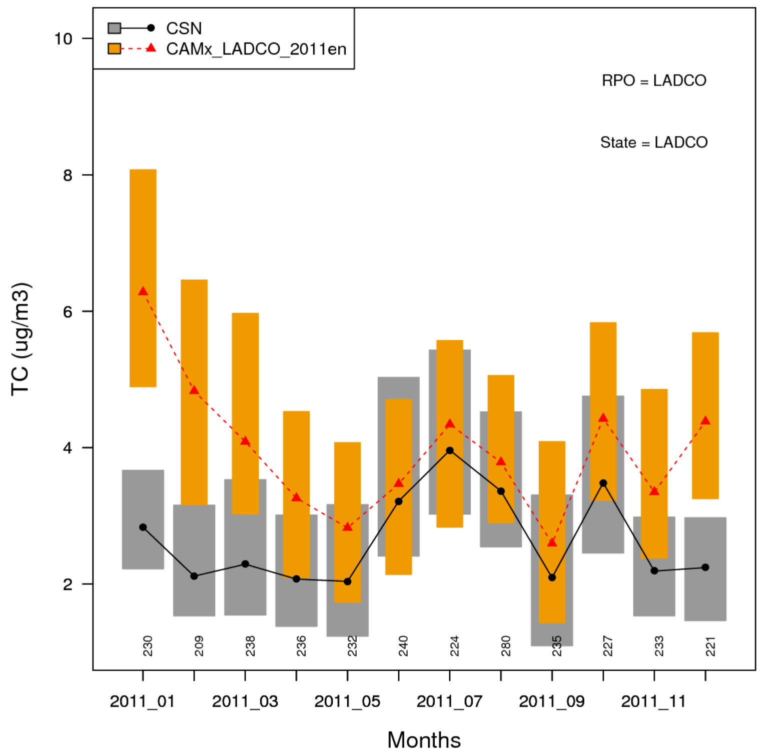


Figure S 5-13. Monthly 2011 TC boxplot of CSN locations in the LADCO region

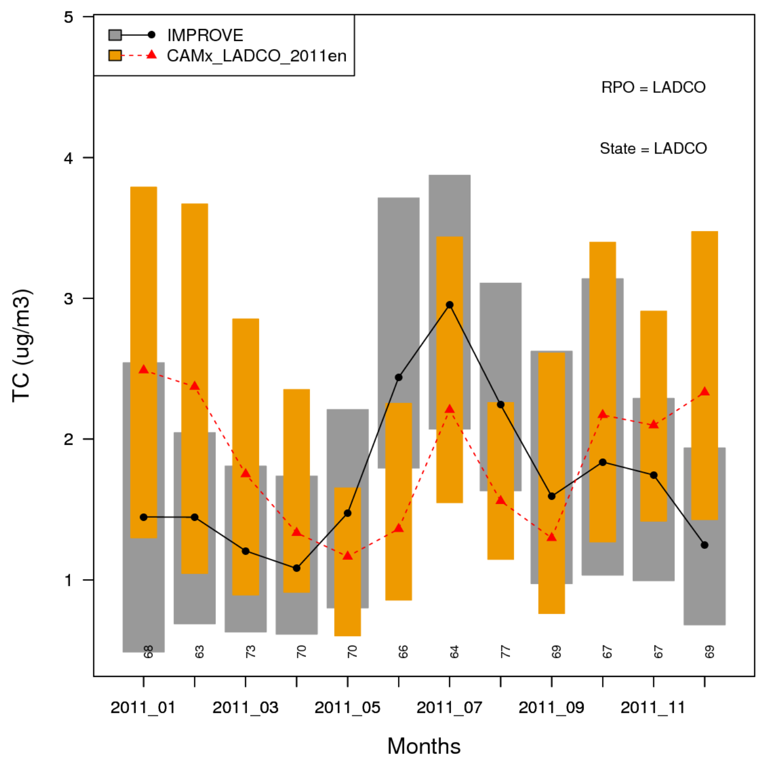


Figure S 5-14. Monthly 2011 TC boxplot of IMPROVE locations in the LADCO region

S5.1.5 LADCO CAMx 2011 Simulation Seasonal and State MPE Tables

Table S 5-1. CSN 2011 $PM_{2.5}$ seasonal MPE statistics

State	Season	Obs (µg/m³)	CAMx (µg/m³)	NMB (%)	NME (%)	r
IL	Fall	8.90	11.31	27.00	41.04	0.73
	Spring	11.86	13.91	20.06	34.42	0.83
	Summer	14.36	12.12	-15.11	26.06	0.71
	Winter	12.73	14.35	13.83	33.69	0.65
IN	Fall	8.75	9.58	9.90	32.35	0.76
	Spring	11.27	12.77	12.79	30.38	0.72
	Summer	16.19	12.40	-22.96	26.81	0.82
	Winter	12.14	13.20	8.75	28.49	0.81
MI	Fall	8.34	9.87	18.69	35.44	0.82
	Spring	8.76	10.61	20.50	34.04	0.68
	Summer	13.40	9.08	-32.64	35.06	0.73
	Winter	9.90	11.28	13.56	30.65	0.86
MN	Fall	8.74	14.04	61.05	63.03	0.78
	Spring	9.18	13.75	48.70	51.07	0.87
	Summer	9.55	9.76	3.87	32.03	0.49
	Winter	12.73	20.81	63.76	70.49	0.67
OH	Fall	9.71	9.29	-2.76	30.57	0.78
	Spring	9.83	10.96	20.71	45.00	0.64
	Summer	15.27	11.72	-22.09	31.34	0.76
	Winter	12.75	12.25	-1.15	26.46	0.81
WI	Fall	7.83	8.43	7.25	27.50	0.83
	Spring	8.64	9.81	12.66	33.70	0.85
	Summer	10.32	7.80	-24.71	36.11	0.71
	Winter	10.30	10.01	-2.89	24.23	0.86
LADCO	Fall	8.71	10.42	20.19	38.32	0.78
	Spring	9.92	11.97	22.57	38.10	0.76
	Summer	13.18	10.48	-18.94	31.23	0.70
	Winter	11.76	13.65	15.97	35.67	0.78

Table S 5-2. IMPROVE 2011 $PM_{2.5}$ seasonal MPE statistics

State	Season	Obs (μg/m³)	CAMx (μg/m³)	NMB (%)	NME (%)	r
IL	Fall	6.84	8.55	25.06	39.86	0.77
	Spring	8.20	10.92	33.16	48.44	0.66
	Summer	10.95	8.66	-20.92	24.53	0.89
	Winter	10.23	9.84	-3.77	28.85	0.66
MI	Fall	4.15	3.81	-8.37	46.13	0.68
	Spring	3.69	3.27	-11.21	21.07	0.90
	Summer	5.48	3.36	-38.74	46.01	0.71
	Winter	3.02	3.97	31.53	44.53	0.89
MN	Fall	5.06	7.79	50.80	79.17	0.75
	Spring	4.09	5.05	17.30	35.92	0.77
	Summer	5.39	4.04	-26.78	33.30	0.64
	Winter	5.07	7.17	52.11	60.53	0.66
OH	Fall	6.46	7.63	18.18	34.36	0.80
	Spring	7.37	7.01	-4.96	34.29	0.58
	Summer	12.22	8.36	-31.61	31.89	0.83
	Winter	7.91	10.81	36.75	39.38	0.84
LADCO	Fall	5.63	6.94	21.42	49.88	0.75
	Spring	5.84	6.56	8.57	34.93	0.73
	Summer	8.51	6.10	-29.51	33.93	0.77
	Winter	6.56	7.95	29.16	43.32	0.76

Table S 5-3. CSN 2011 SO_4 seasonal MPE statistics

State	Season	Obs (µg/m³)	CAMx (µg/m³)	NMB (%)	NME (%)	r
IL	Fall	1.70	1.51	-11.25	37.43	0.78
	Spring	2.46	2.33	-4.06	24.84	0.83
	Summer	2.95	2.49	-15.10	30.30	0.76
	Winter	1.95	1.26	-35.31	47.02	0.60
IN	Fall	1.98	1.58	-20.04	30.51	0.79
	Spring	2.84	2.54	-9.19	29.54	0.76
	Summer	4.22	3.29	-20.29	30.64	0.84
	Winter	2.30	1.42	-37.96	45.43	0.69
MI	Fall	1.70	1.54	-9.24	28.08	0.84
	Spring	2.04	2.17	5.80	36.85	0.64
	Summer	2.90	2.27	-21.45	31.40	0.84
	Winter	1.62	0.99	-38.78	45.04	0.73
MN	Fall	1.31	1.41	12.32	41.20	0.76
	Spring	1.58	1.85	17.73	31.86	0.84
	Summer	1.61	1.59	4.97	28.10	0.87
	Winter	1.59	1.44	-6.59	48.75	0.57
OH	Fall	2.12	1.66	-19.69	28.59	0.89
	Spring	2.58	2.40	2.15	46.22	0.63
	Summer	4.21	3.48	-16.08	30.10	0.81
	Winter	2.40	1.30	-44.25	46.46	0.73
WI	Fall	1.38	1.22	-11.34	30.03	0.91
	Spring	1.73	1.91	10.89	41.83	0.73
	Summer	2.02	1.85	-7.18	33.82	0.67
	Winter	1.59	1.01	-37.04	47.05	0.63
LADCO	Fall	1.70	1.49	-9.87	32.64	0.83
	Spring	2.20	2.20	3.89	35.19	0.74
	Summer	2.99	2.50	-12.52	30.72	0.80
	Winter	1.91	1.24	-33.32	46.63	0.66

Table S 5-4. IMPROVE 2011 SO_4 seasonal MPE statistics

State	Season	Obs (μg/m³)	CAMx (μg/m³)	NMB (%)	NME (%)	r
IL	Fall	1.83	1.67	-8.68	39.27	0.49
	Spring	2.17	2.14	-1.06	36.75	0.63
	Summer	3.26	2.25	-30.94	35.59	0.90
	Winter	2.17	1.27	-41.40	44.19	0.66
MI	Fall	0.81	0.94	15.67	42.25	0.83
	Spring	1.09	1.19	9.61	25.14	0.86
	Summer	0.85	1.08	27.29	47.55	0.88
	Winter	0.84	0.83	-1.26	45.46	0.76
MN	Fall	0.91	1.02	14.79	43.29	0.73
	Spring	1.14	1.18	3.94	32.42	0.86
	Summer	1.14	1.09	1.11	37.88	0.72
	Winter	1.05	0.92	-11.91	55.75	0.43
OH	Fall	2.14	2.01	-6.26	23.73	0.91
	Spring	2.68	1.90	-29.16	35.02	0.76
	Summer	4.83	3.42	-29.24	30.99	0.85
	Winter	2.46	1.63	-33.74	35.97	0.83
LADCO	Fall	1.42	1.41	3.88	37.13	0.74
	Spring	1.77	1.60	-4.17	32.33	0.78
	Summer	2.52	1.96	-7.95	38.00	0.84
	Winter	1.63	1.16	-22.08	45.34	0.67

Table S 5-5. 2011 NO_3 seasonal MPE statistics

State	Season	Obs (µg/m³)	CAMx (µg/m³)	NMB (%)	NME (%)	r
IL	Fall	1.17	1.45	25.51	64.17	0.70
	Spring	2.35	2.83	26.82	46.06	0.89
	Summer	0.73	0.32	-55.20	57.58	0.54
	Winter	3.86	3.15	-18.12	33.50	0.80
IN	Fall	1.10	1.39	26.19	57.99	0.74
	Spring	1.91	2.93	59.54	77.26	0.78
	Summer	0.64	0.55	-11.82	61.46	0.49
	Winter	3.54	3.16	-10.04	36.05	0.73
MI	Fall	1.24	1.51	27.80	57.02	0.77
	Spring	1.81	2.00	15.60	55.24	0.73
	Summer	0.64	0.38	-32.58	71.98	0.39
	Winter	2.80	2.58	-7.43	32.11	0.87
MN	Fall	1.47	2.01	36.44	49.40	0.97
	Spring	2.20	2.21	0.20	27.10	0.94
	Summer	0.50	0.40	-24.31	40.87	0.88
	Winter	3.97	3.38	-14.71	43.41	0.60
OH	Fall	1.09	1.17	6.37	53.96	0.58
	Spring	1.68	2.09	36.77	79.71	0.64
	Summer	0.63	0.52	-20.18	55.62	0.65
	Winter	3.10	2.75	-9.93	38.41	0.75
WI	Fall	1.38	1.63	19.65	50.92	0.81
	Spring	2.32	2.45	4.49	40.66	0.85
	Summer	0.58	0.54	-5.41	66.05	0.60
	Winter	3.17	2.65	-16.48	27.69	0.88
LADCO	Fall	1.24	1.53	23.66	55.58	0.76
	Spring	2.05	2.42	23.91	54.34	0.80
	Summer	0.62	0.45	-24.92	58.92	0.59
	Winter	3.41	2.94	-12.78	35.19	0.77

Table S 5-6. IMPROVE 2011 NO_3 seasonal MPE statistics

State	Season	Obs ($\mu g/m^3$)	CAMx ($\mu g/m^3$)	NMB (%)	NME (%)	r
IL	Fall	1.07	1.69	58.17	85.12	0.76
	Spring	1.73	3.13	80.96	94.33	0.80
	Summer	0.44	0.28	-37.23	63.79	0.34
	Winter	3.73	3.00	-19.66	30.27	0.76
MI	Fall	0.27	0.35	31.17	48.11	0.94
	Spring	0.41	0.27	-33.71	44.52	0.98
	Summer	0.05	0.06	23.83	103.15	0.69
	Winter	0.64	0.92	45.09	78.89	0.79
MN	Fall	0.74	1.22	75.86	83.29	0.94
	Spring	1.26	1.36	11.69	50.76	0.93
	Summer	0.21	0.32	34.39	92.23	0.57
	Winter	1.80	2.05	36.51	62.80	0.69
OH	Fall	0.35	0.52	49.79	86.69	0.68
	Spring	0.65	0.89	35.48	91.08	0.38
	Summer	0.18	0.15	-13.60	44.93	0.72
	Winter	1.33	1.81	36.11	70.61	0.58
LADCO	Fall	0.61	0.94	53.75	75.80	0.83
	Spring	1.01	1.41	23.61	70.17	0.77
	Summer	0.22	0.20	1.85	76.03	0.58
	Winter	1.87	1.95	24.51	60.64	0.70

Table S 5-7. CSN total 2011 TC seasonal MPE statistics

State	Season	Obs (µg/m³)	CAMx (µg/m³)	NMB (%)	NME (%)	r
IL	Fall	3.22	4.16	34.77	44.42	0.77
	Spring	3.05	4.66	60.13	68.46	0.69
	Summer	4.35	4.92	13.63	32.73	0.53
	Winter	3.21	6.30	117.36	131.60	0.67
IN	Fall	2.85	3.29	19.40	39.48	0.80
	Spring	2.85	3.35	17.54	35.95	0.79
	Summer	4.31	4.40	1.40	24.87	0.69
	Winter	2.87	5.35	88.19	93.99	0.71
MI	Fall	2.59	3.76	47.53	52.17	0.82
	Spring	2.09	3.50	69.67	72.89	0.74
	Summer	3.71	3.47	-7.22	25.56	0.74
	Winter	2.34	5.17	125.27	125.93	0.77
MN	Fall	2.71	6.71	145.20	145.20	0.51
	Spring	2.08	6.29	199.14	200.23	0.47
	Summer	3.07	4.92	58.23	62.08	0.55
	Winter	2.58	11.23	332.84	332.84	0.88
OH	Fall	3.00	3.61	21.92	38.74	0.84
	Spring	2.56	3.50	38.07	51.22	0.66
	Summer	4.16	4.11	-0.55	28.08	0.70
	Winter	2.99	5.26	77.74	84.60	0.64
WI	Fall	2.32	3.10	35.59	46.51	0.75
	Spring	1.77	2.96	65.48	75.16	0.72
	Summer	3.24	3.05	-6.57	36.06	0.64
	Winter	2.16	4.04	88.36	93.56	0.68
LADCO	Fall	2.78	4.10	50.73	61.09	0.75
	Spring	2.40	4.04	75.00	83.98	0.68
	Summer	3.81	4.15	9.82	34.89	0.64
	Winter	2.69	6.23	138.29	143.75	0.72

Table S 5-8. IMPROVE 2011 TC seasonal MPE statistics

State	Season	Obs ($\mu g/m^3$)	CAMx ($\mu g/m^3$)	NMB (%)	NME (%)	r
IL	Fall	2.43	2.24	-7.61	25.31	0.82
	Spring	2.56	2.36	-7.58	29.64	0.72
	Summer	3.65	2.71	-25.68	31.42	0.78
	Winter	2.28	3.00	31.48	37.27	0.59
MI	Fall	1.95	1.74	-6.65	44.41	0.85
	Spring	1.03	1.19	14.60	38.13	0.74
	Summer	2.86	1.54	-46.09	49.22	0.59
	Winter	0.88	1.68	91.90	92.26	0.93
MN	Fall	5.09	7.22	34.39	80.06	0.42
	Spring	1.25	1.56	17.47	51.91	0.47
	Summer	2.74	1.75	-35.26	43.19	0.50
	Winter	1.26	2.61	106.90	107.41	0.68
OH	Fall	2.08	3.29	58.24	66.94	0.79
	Spring	2.18	2.47	13.68	44.82	0.60
	Summer	3.05	2.80	-8.24	33.60	0.53
	Winter	2.81	4.94	75.73	75.73	0.91
LADCO	Fall	2.89	3.62	19.59	54.18	0.72
	Spring	1.75	1.90	9.54	41.13	0.63
	Summer	3.08	2.20	-28.82	39.36	0.60
	Winter	1.81	3.05	76.50	78.17	0.78

S5.2 2016 CAMx Model Performance Evaluation Results

The CAMx MPE results for 2016 are presented in this section. The results are first presented as annual averages for all CSN and IMPROVE monitoring locations in the LADCO region to provide an overview of the CAMx model's skill in simulating $PM_{2.5}$. We use seasonal and regional MPE metrics to identify how well the model can estimate PM concentrations during different times of the year. We then present model performance for different $PM_{2.5}$ components (total $PM_{2.5}$, sulfate, nitrate, and total carbonaceous aerosols[15]) to quantify how well the model can simulate the key light scattering species that most contribute to visibility impairment.

The "Soccer Goal (i.e., soccer) plots in Figure S 5-15 and Figure S 5-16 show seasonal and regional average CAMx NMB and NME relative to the model performance goals by Emery et al. (2017). The LADCO 2016 CAMx simulation springtime predictions were close to the NMB performance goals for sulfate (NMB = +9.4%) and nitrate (NMB = -12.2%) at the IMPROVE monitors. For the more urban CSN monitors, the simulation springtime predictions were within the less stringent performance criteria for nitrate (NMB = +20.5%), but outside of the criteria for sulfate (NMB = +36%). The CAMx simulation overpredicted the total carbonaceous (TC) aerosols in the spring season at both the CSN (NMB = +48.5%) and IMPROVE (NMB = +29%) networks. As the CAMx elemental carbon predictions had very low biases on average for the two networks, the positive NMBs in TC were driven primarily by the organic carbon aerosols (IMPROVE = +32%; CSN = +74%).

Figure S 5-16 shows that the winter season CAMx performance for the 2016 simulation is reasonable for the inorganic aerosols and poor for the organic aerosols. On average, CAMx predicted wintertime sulfate at both the CSN and IMPROVE networks well (NMB < +10%). Nitrate, which is the most important contributor to wintertime haze in the region, was underpredicted on average by the CAMx simulation at both the IMPROVE (NMB = -23.5%) and CSN (NMB = -8.8%) networks. The LADCO 2016 CAMx simulation overpredicted organic aerosols so badly in the 2016 wintertime period that the TC symbols are not visible in Figure S 5-16 for either the IMPROVE (NMB = +115.7%) or CSN (NMB = +144%) networks.

The following sections present additional details about the CAMx 2016 model performance for the different PM species that contribute to haze impairment in the LADCO region.

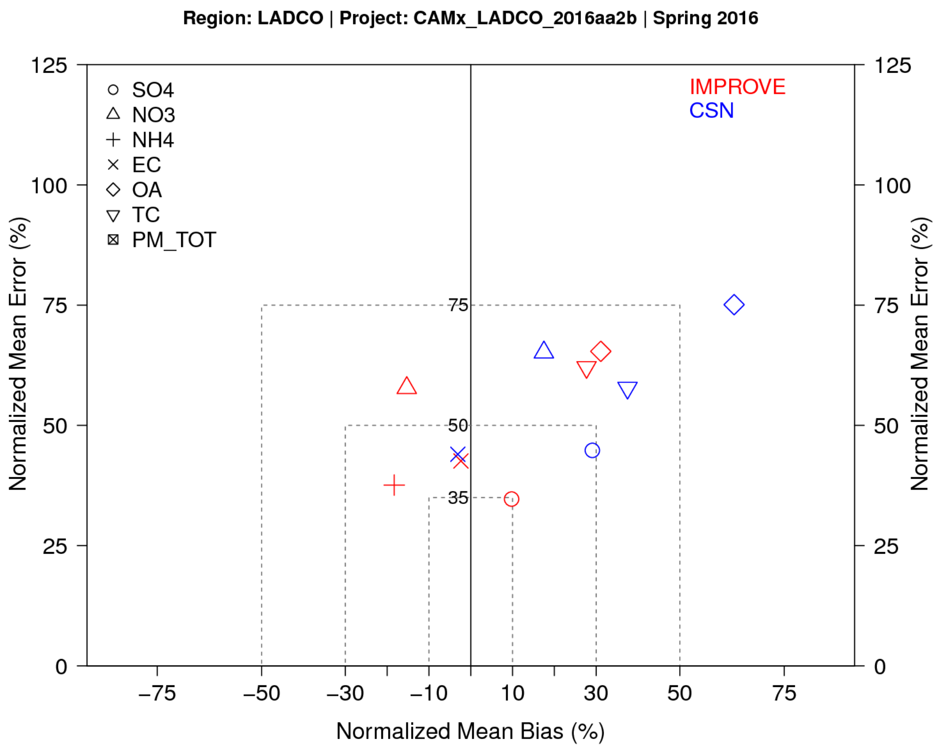


Figure S 5-15. Spring 2016 LADCO region PM performance soccer plot

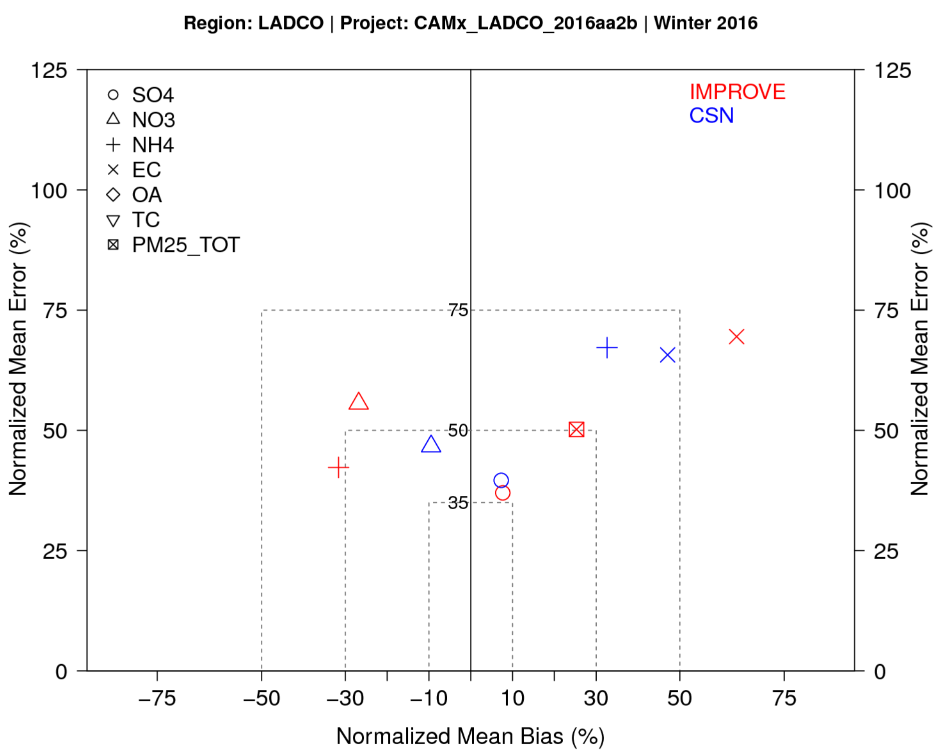


Figure S 5-16. Winter 2016 LADCO region PM performance soccer plot

S5.2.1 Total $PM_{2.5}$

This section presents the LADCO 2016 CAMx simulation performance for daily average $PM_{2.5}$ at individual sites in the LADCO region, monthly averages across the CSN and IMPROVE networks, and seasonal averages at the monitors in the different LADCO member states. Figure S 5-17 is a “bubble” plot of seasonal average daily average total $PM_{2.5}$ NMB at IMPROVE and CSN locations in the LADCO region. The symbols on the plot show the color coded average NMB values at each monitor. The spring season bubble plot in the figure does not indicate much of a spatial pattern in the CAMx predictions of $PM_{2.5}$. While the LADCO 2016 CAMx simulation overpredicted the observations at most sites, there are several sites scattered across the domain with negative NMBs. The CAMx simulation springtime $PM_{2.5}$ predictions at most of the monitors in the region achieved the NMB performance criteria (+/- 30%). Notable exceptions include the high NMBs (>+40%) at the CSN monitors in the Twin Cities area and at the Boundary Waters IMPROVE monitor.

The winter season bubble plot in Figure S 5-17 shows that the CAMx simulation generally overpredicted $PM_{2.5}$ during that season at monitors in both the CSN and IMPROVE networks. The LADCO 2016 CAMx winter season simulation did not achieve the performance criteria for total $PM_{2.5}$ at the IMPROVE monitors in either Minnesota or Michigan, the two states in the LADCO region with Class I areas subject to the RHR.

Figure S 5-18 and Figure S 5-19 are “boxplots” of 2016 monthly average modeled and observed concentrations for the CSN and IMPROVE monitoring networks, respectively. The red line shows the CAMx monthly average predicted concentration and the orange boxes show the CAMx 25th and 75th percentile concentration distributions. Similarly the black line and grey boxes show the same metrics for the observations.

The LADCO 2016 CAMx simulation overpredicted total $PM_{2.5}$ at the CSN sites fall all months except June. Relative to the observations, the simulation had a higher positive bias in total $PM_{2.5}$ during the winter months at the CSN sites (NMB = +34%) than at the IMPROVE sites (NMB = +29%). CAMx also better simulated total $PM_{2.5}$ on average at the IMPROVE sites (+15.5%) than at the CSN sites (NMB =+23%) during the spring months.

Table S 5-10 shows the LADCO CAMx simulation total $PM_{2.5}$ performance statistics by season and state for monitors in the IMPROVE network. Focusing on the statistics in Michigan and Minnesota shows that CAMx performance in the springtime acheived the total $PM_{2.5}$ NMB performance criteria (30%) for both states (MI = +28%; MN = +29%). The wintertime NMB performance for total $PM_{2.5}$ is slightly worse (MI = +32%; MN = +33%), but close to achieving the performance criteria .

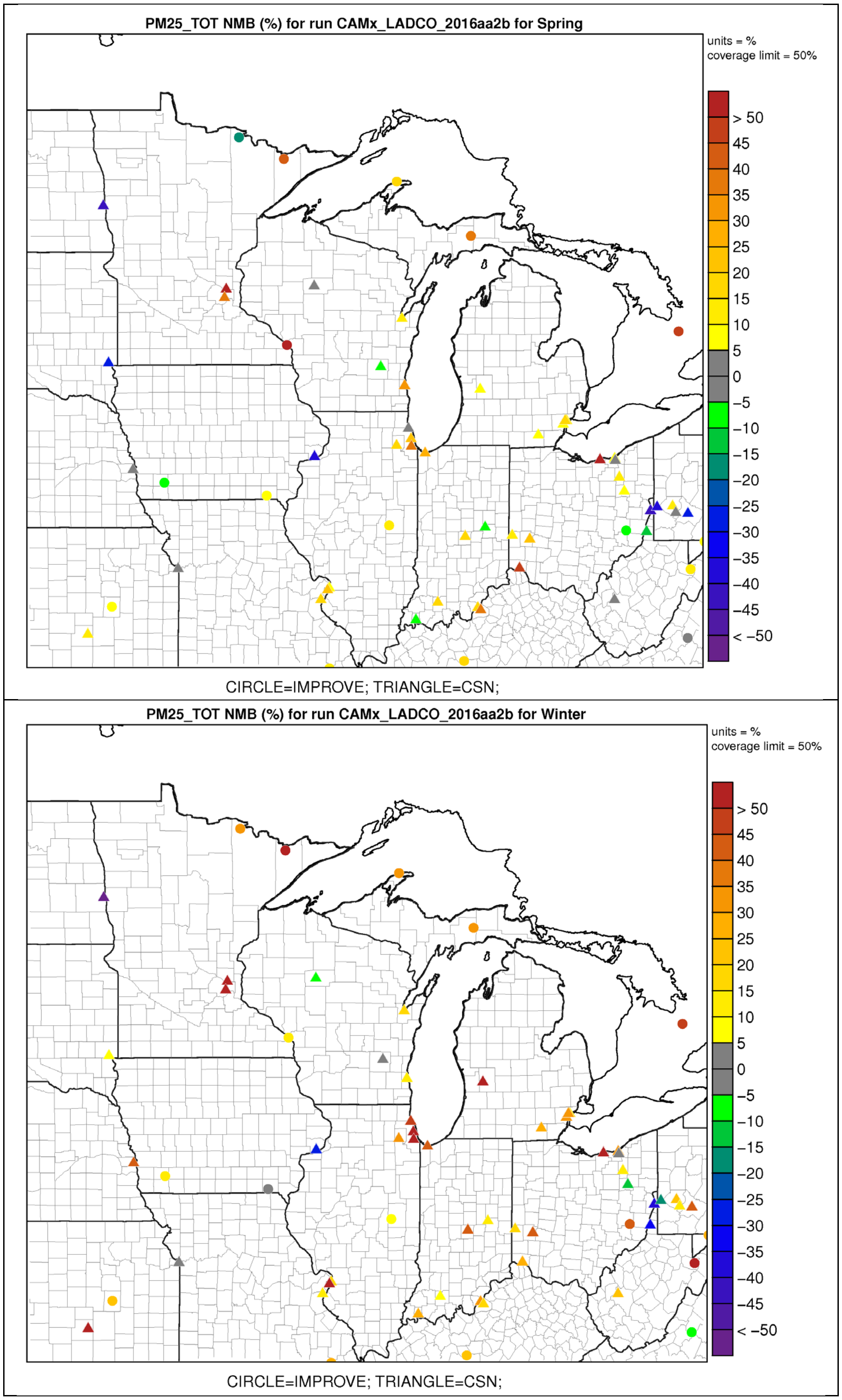


Figure S 5-17. Total $PM_{2.5}$ 2016 seasonal average NMB for the spring (top) and winter (bottom)

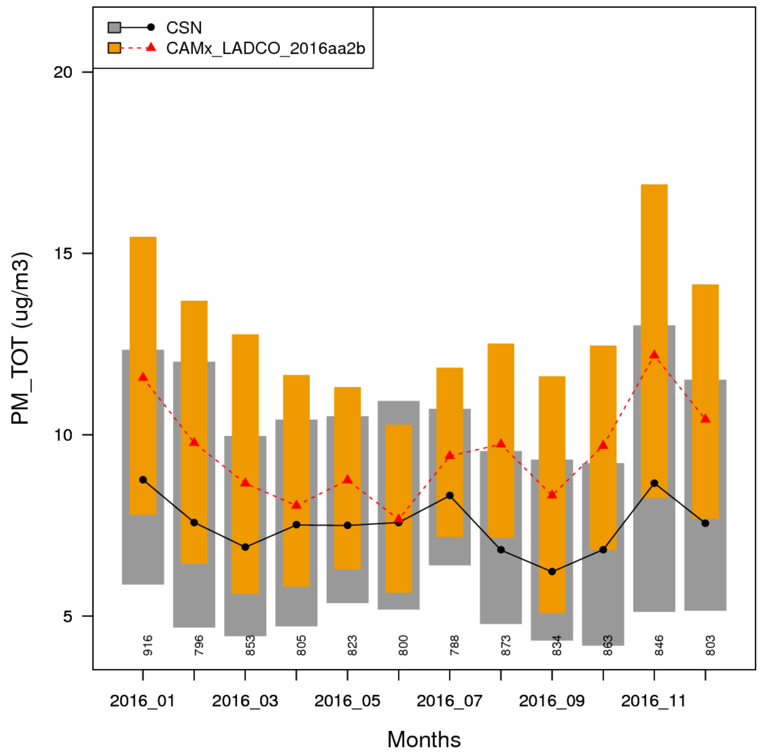


Figure S 5-18. Monthly 2016 $PM_{2.5}$ boxplot of CSN locations in the LADCO region

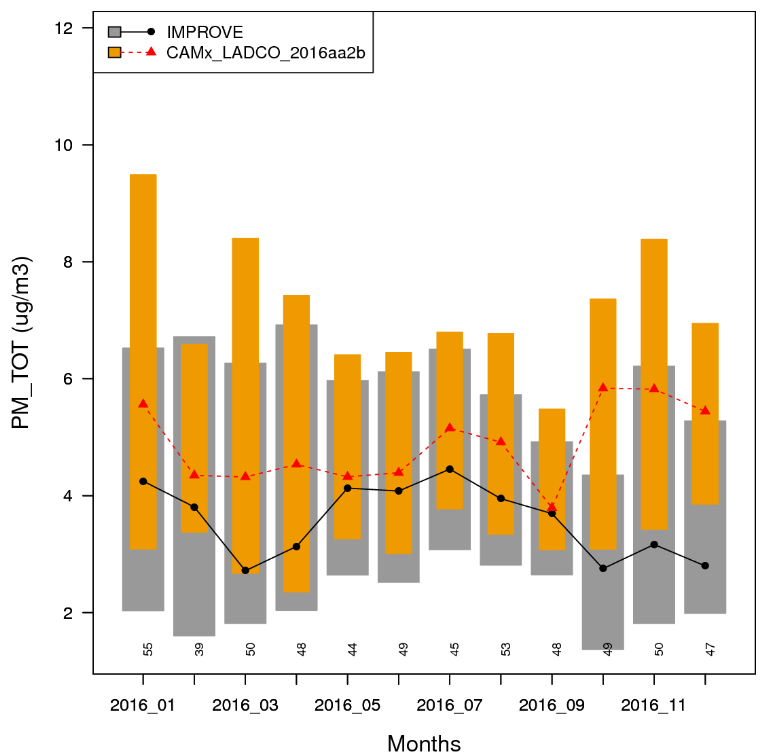


Figure S 5-19. Monthly 2016 $PM_{2.5}$ boxplot of IMPROVE locations in the LADCO region

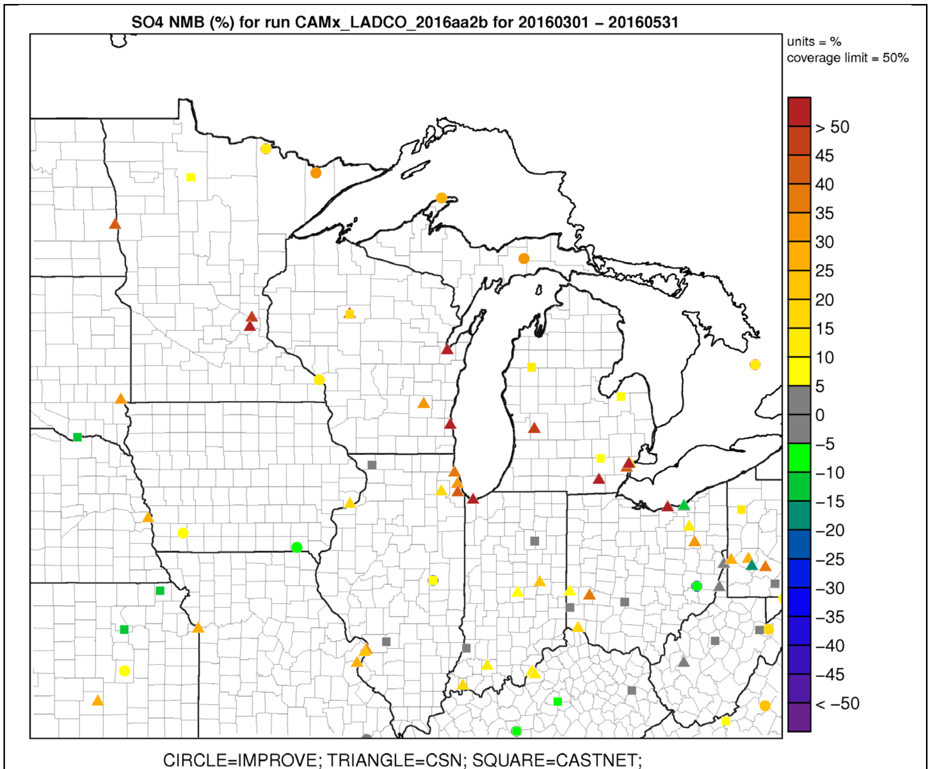
S5.2.2 Sulfate

This section presents the LADCO 2016 CAMx simulation performance for daily average sulfate (SO_4) at individual sites in the LADCO region, monthly averages across the CSN and IMPROVE networks, and seasonal averages at the monitors in the different LADCO member states. Figure S 5-20 is a "bubble" plot of seasonal average NMB at IMPROVE and CSN locations in the LADCO region. Figure S 5-21 and Figure S 5-22 are "boxplots" of monthly average modeled and observed concentrations for the two monitoring networks. See section S5.1.1 for additional details about the format of these plot types.

The spring season bubble plot for sulfate shows that while most of the monitoring stations in the LADCO states fall within the +/- 35% performance criteria for sulfate NMB, the 2016 CAMx simulation achieved the +/-10% performance goal for sulfate at very few of the monitor locations. The 2016 CAMx simulation overpredicted springtime sulfate (LADCO average IMPROVE NMB = +9.4%) at all but a few sites in Ohio, and at some sites outside of the LADCO member states. The winter season sulfate bubble plot shows that the 2016 CAMx simulation slightly underpredicted sulfate along the southern part of the map (NMBs < -10%); the CAMx simulation tended to overpredict wintertime sulfate at sites in the central and northern parts of the LADCO region. The CAMx wintertime sulfate overprediction was the worst at the CSN sites in the Twin Cities are of Minnesota (NMB = +46.7%)

The boxplot in Figure S 5-21 shows that regionwide the CAMx 2016 simulation overpredicted sulfate in all months at the CSN monitors, with the best model performance achieved in the winter (NMB = +18%). Figure S 5-22 also shows that the CAMx simulation overpredicted sulfate at the IMPROVE monitors in most months. Although the seasonal average biases in the spring (NMB = +9.4%) and the winter (NMB = +7.2%) are relatively low, Figure S 5-22 illustrates that offsetting biases within each period distort the seasonal average biases. In the wintertime for example, the high positive bias in February is attenuated by a negative bias in January, and a low positive bias in December.

Table S 5-12 shows the LADCO 2016 CAMx simulation sulfate performance statistics by season and state for monitors in the IMPROVE network. Focusing on the statistics in Michigan and Minnesota shows that CAMx performance in the springtime was close to the NMB performance criteria (30%) for both states (MI = +30.5%; MN = +25.7%). The CAMx simulation of wintertime sulfate bias is acceptable for the IMPROVE locations in both states (MI = +29.5%; MN = +12%).



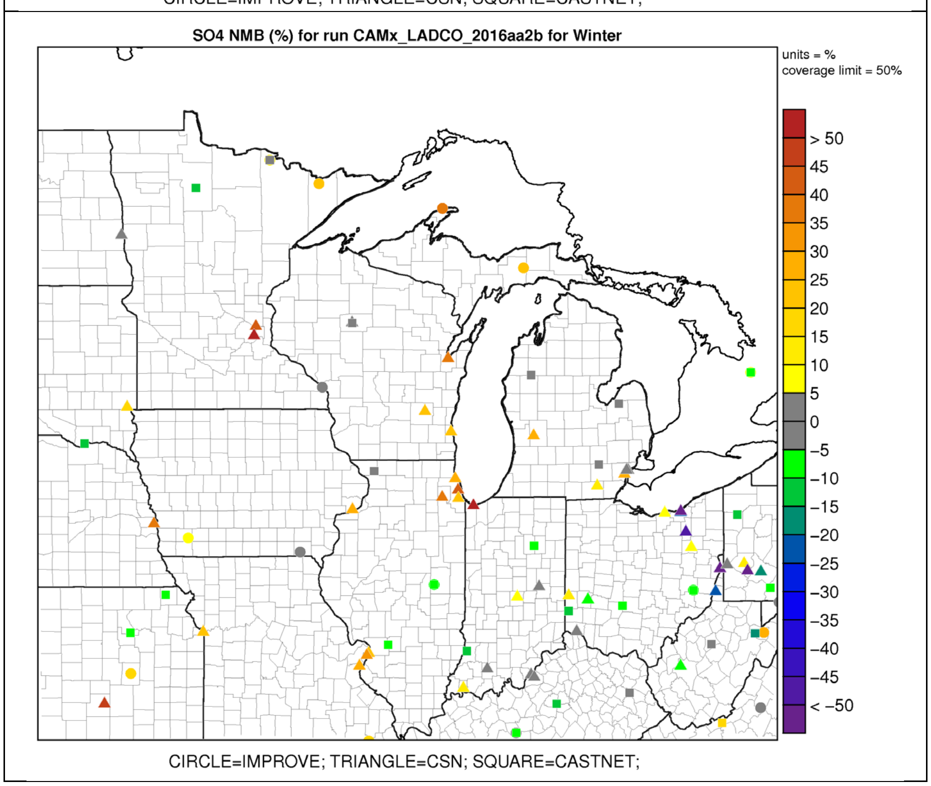


Figure S 5-20. Sulfate 2016 seasonal average NMB for the spring (top) and winter (bottom)

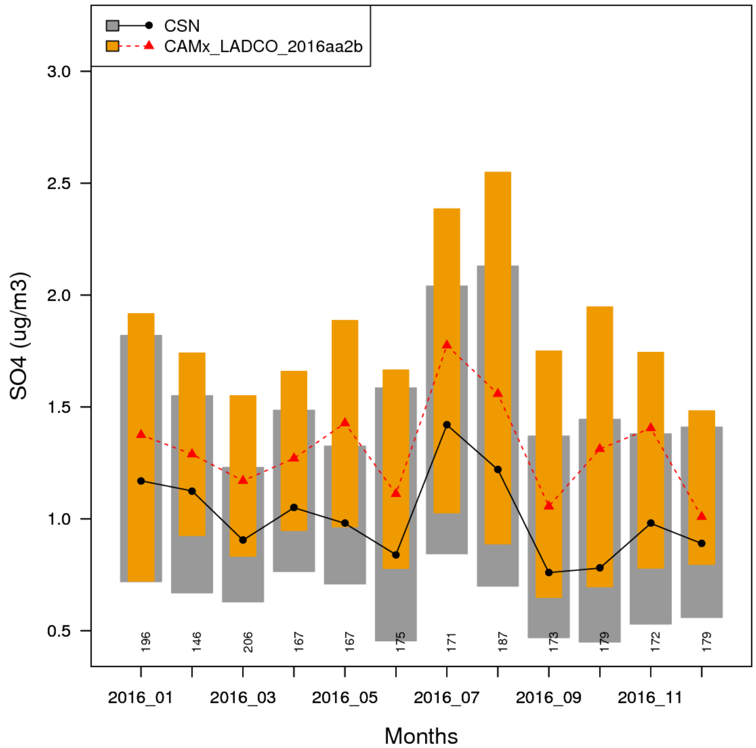


Figure S 5-21. Monthly 2016 SO_4 boxplot of CSN locations in the LADCO region

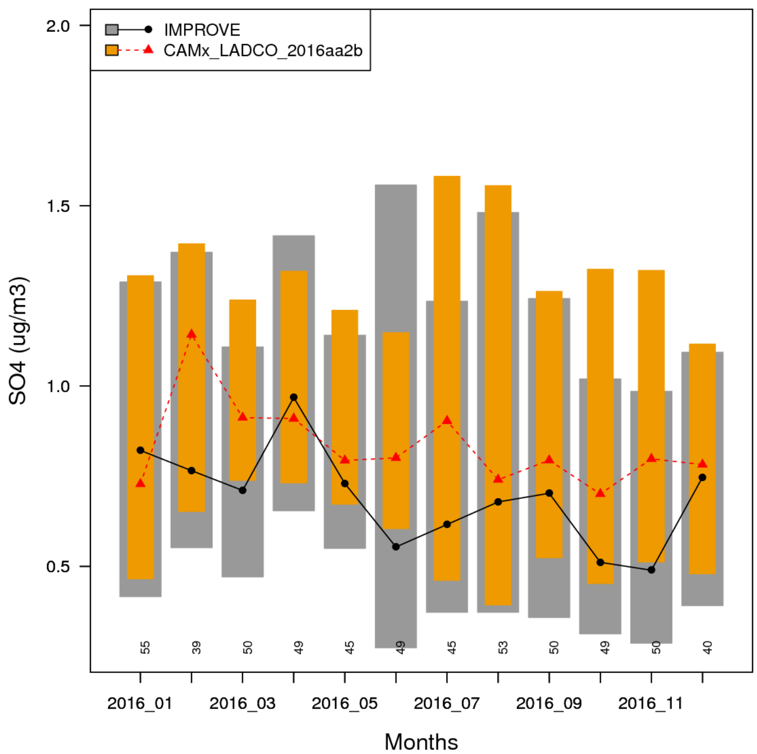


Figure S 5-22. Monthly 2016 SO_4 boxplot of IMPROVE locations in the LADCO region

S5.2.3 Nitrate

This section presents the LADCO 2016 CAMx simulation performance for daily average nitrate (NO_3) at individual sites in the LADCO region, monthly averages across the CSN and IMPROVE networks, and seasonal averages at the monitors in the different LADCO member states. Figure S 5-9 is a "bubble" plot of seasonal average NMB at IMPROVE and CSN locations in the LADCO region. Figure S 5-10 and Figure S 5-11 are "boxplots" of monthly average modeled and observed concentrations for the two monitoring networks. See section S5.1.1 for additional details about the format of these plot types.

The spring season bubble plot for nitrate shows that LADCO 2016 CAMx simulation performance was mixed across the LADCO region. The 2016 simulation tended to overpredict springtime nitrate at the more urban CSN monitors (regionwide NMB = +20.5%). While the simulation had a regional underprediction bias in the spring at the IMPROVE monitors (NMB = -12.2%), there was a slight overprediction bias at the northern Class I areas in Minnesota and Michigan. The winter season nitrate bubble plot shows that the LADCO 2016 CAMx simulation had an underprediction bias across most of the monitors in the region. On average, the CAMx simulation better predicted wintertime nitrate at the more urban CSN monitors (NMB = -8.8%) compared to the IMPROVE monitors (-23.5%).

Figure S 5-10 and Figure S 5-11 show that the LADCO 2016 CAMx simulation reproduced the observed monthly average nitrate profiles at both the CSN and IMPROVE networks, respectively. The CAMx simulation overpredicted nitrate at the CSN locations in all months other than February. Figure S 5-11 shows that for the IMPROVE monitor locations the LADCO 2016 CAMx simulation underpredicted winter season (NMB = -23.5%) and spring season (NMB = -12%) nitrate. The low wintertime average biases for the CAMx simulation at both the CSN and IMPROVE network monitor locations are somewhat misleading because the February underpredictions are offset by overpredictions in December.

Table S 5-14 shows the CAMx nitrate performance statistics by season and state for monitors in the IMPROVE network. The NMB statistics for the IMPROVE sites in Michigan and Minnesota indicate very good CAMx nitrate predictions in the springtime (Minnesota = -6%; Michigan = +2%). The wintertime performance for nitrate is acceptable for both the Minnesota (NMB= -25%) and Michigan (NMB = -31%) IMPROVE locations.

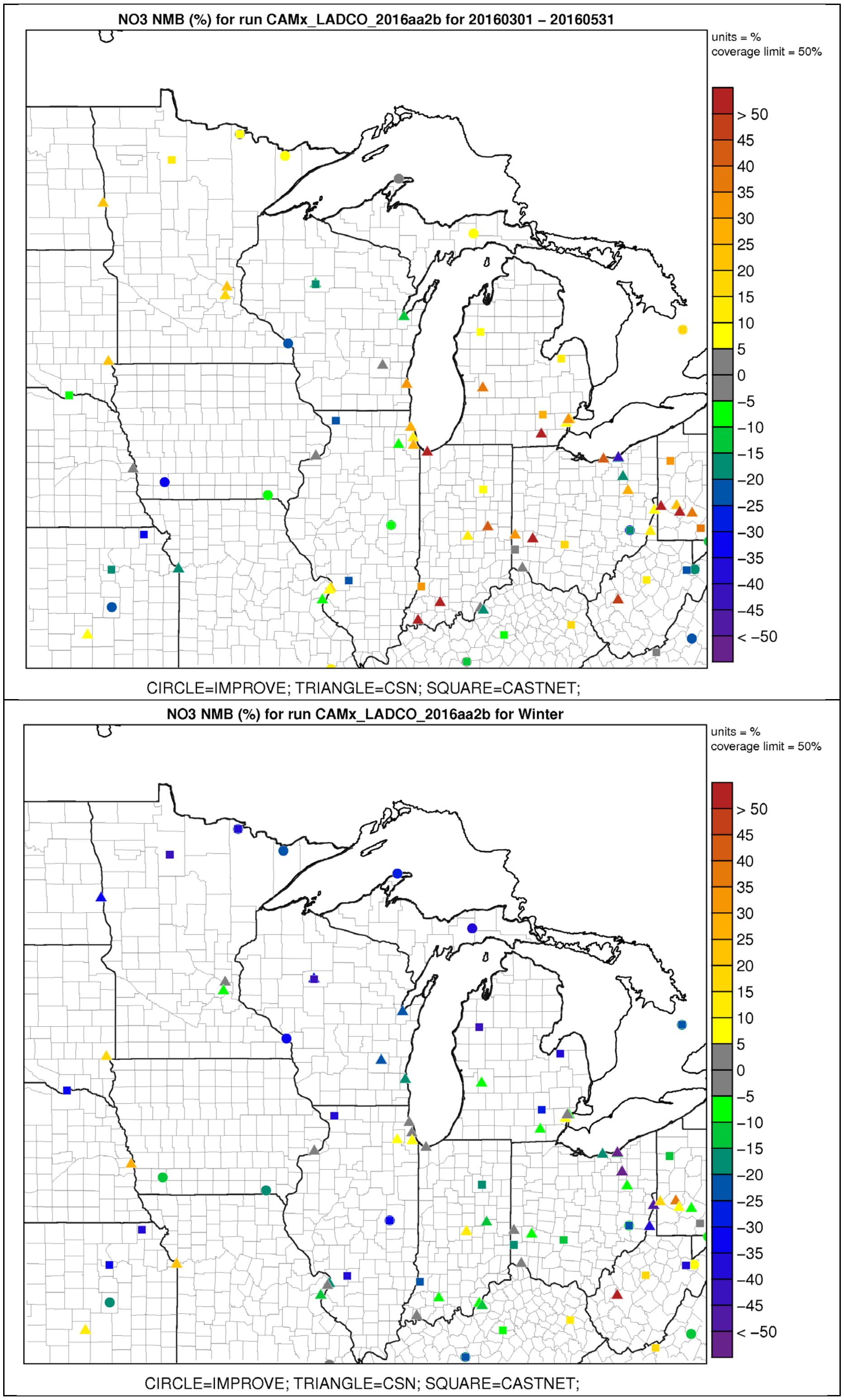


Figure S 5-23. Nitrate 2016 seasonal average NMB for the spring (top) and winter (bottom)

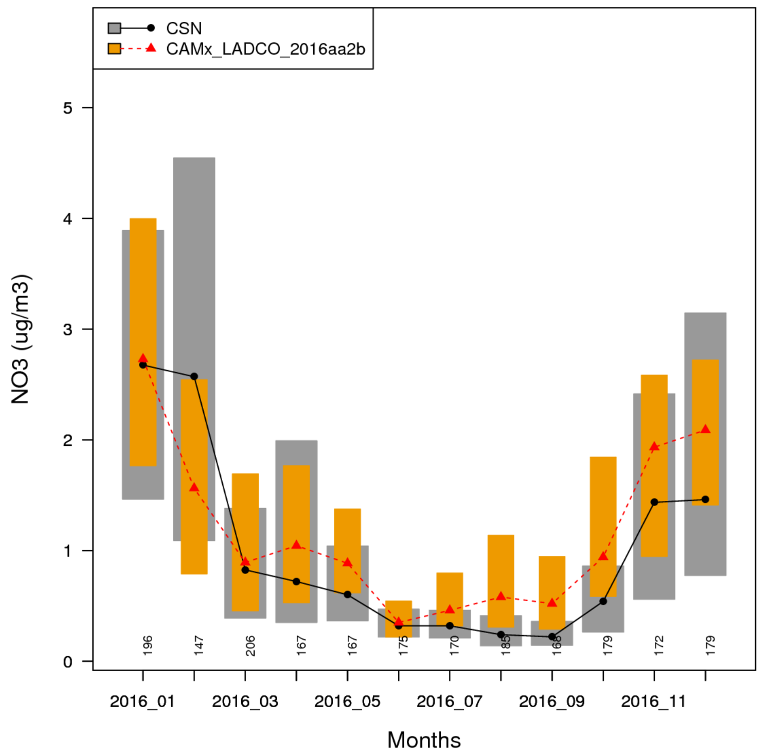


Figure S 5-24. Monthly 2016 NO_3 boxplot of CSN locations in the LADCO region

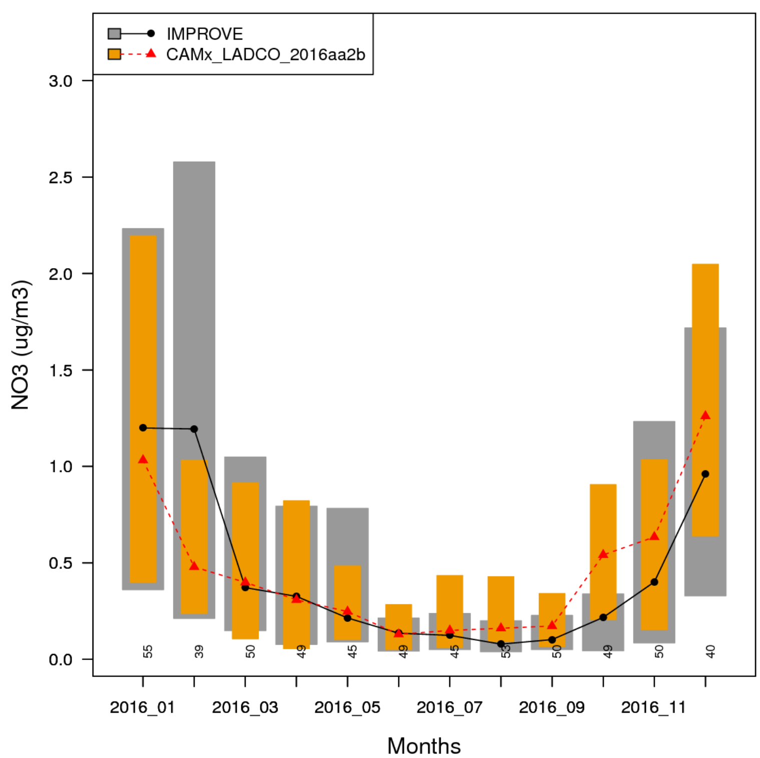


Figure S 5-25. Monthly 2016 NO_3 boxplot of IMPROVE locations in the LADCO region

S5.2.4 Carbonaceous Aerosols

This section presents the LADCO 2016 CAMx simulation performance for total carbonaceous aerosol (TC = EC + OC) at individual sites in the LADCO region, monthly averages across the CSN and IMPROVE networks, and seasonal averages at the monitors in the different LADCO member states. Figure S 5-26 is a "bubble" plot of seasonal average NMB at IMPROVE and CSN locations in the LADCO region. Figure S 5-27 and Figure S 5-28 are "boxplots" of monthly average modeled and observed concentrations for the two monitoring networks. See section S5.1.1 for additional details about the format of these plot types.

The spring season bubble plot for TC shows that the LADCO 2016 CAMx simulation overpredicted carbonaceous aerosols across most of the LADCO region. The springtime overpredictions were within the performance benchmarks for carbonaceous aerosols at both the CSN (NMB = +48%) and IMPROVE (NMB = +29%) network locations. The winter season TC bubble plot shows that the CAMx simulation has a severe overprediction bias (NMB > +110%) for TC across all of the monitors in the LADCO region. The CAMx wintertime TC estimates at the IMPROVE monitors (NMB = +115.7%) and at the CSN monitors (NMB = +144.4%) were well outside of the NMB performance criteria for the carbonaceous aerosols (40-50%).

The boxplot in Figure S 5-27 shows that the highest regional average observed and simulated TC concentrations at the CSN monitors during 2016 occurred in November. Although the CAMx simulation overpredicted the TC concentrations, it is encouraging that the model reproduced the November concentration spike. This concentration spike reflects a PM pollution episode during the early part of the month that impacted all of the central and southern areas of the LADCO region . Figure S 5-28 shows that the IMPROVE network observed more typical monthly variability in TC than the CSN monitors, with concentrations peaking in the summer and dropping in the winter. The LADCO 2016 CAMx simulation badly overpredicted TC in most months at the IMPROVE monitors in the region.

Table S 5-16 shows the CAMx TC performance statistics by season and state for monitors in the IMPROVE network. The CAMx simulation springtime TC estimates at IMPROVE monitors in Michigan (NMB = +50.9%) and Minnesota (NMB = +45.2%) generally achieved the NMB performance criteria (40-50%). CAMx severely overpredicts wintertime TC at the Michigan (NMB = +119.2%) and Minnesota (NMB = +140.6%) IMPROVE monitors.

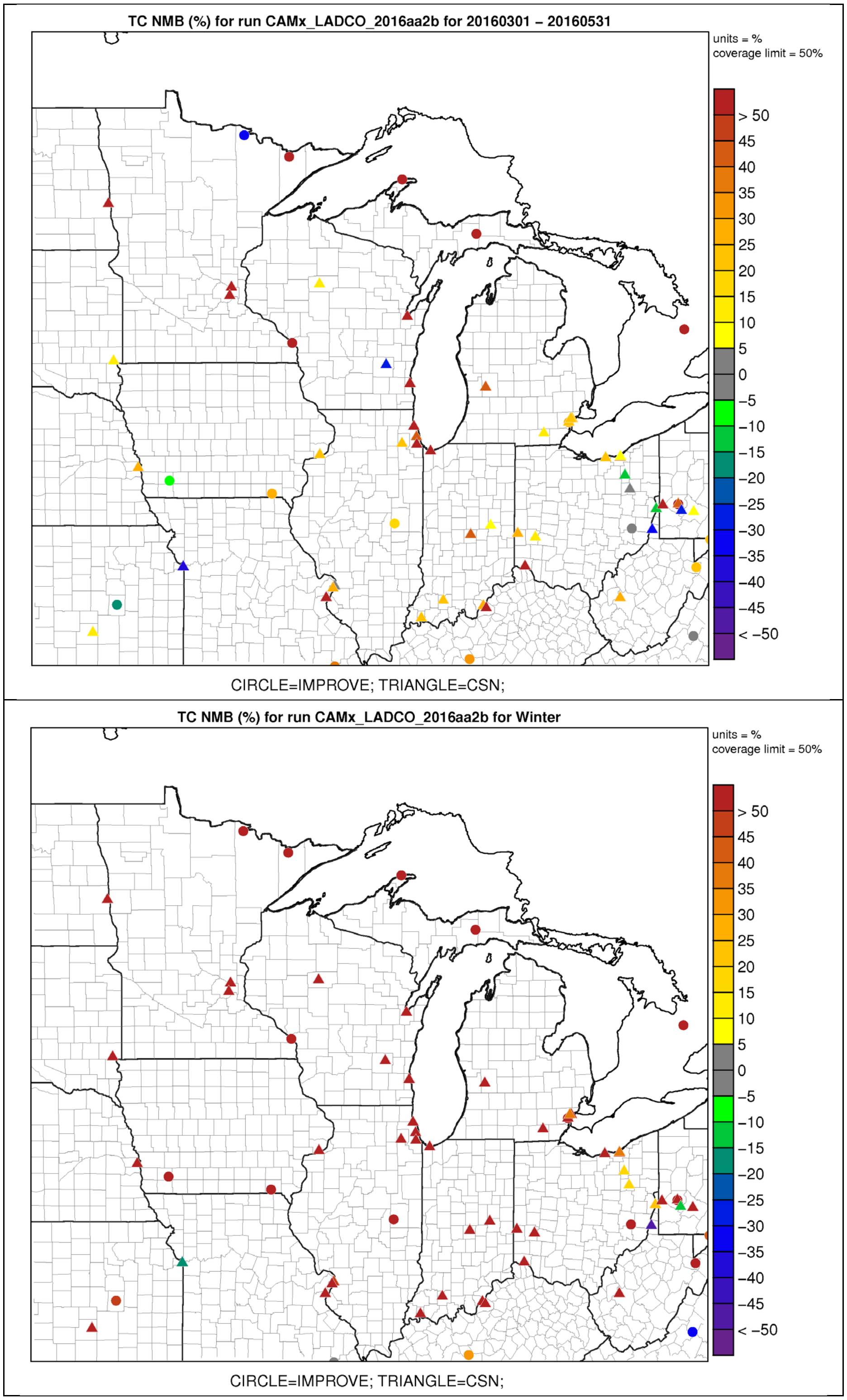


Figure S 5-26. Carbonaceous aerosol 2016 seasonal average NMB for the spring (top) and winter (bottom)

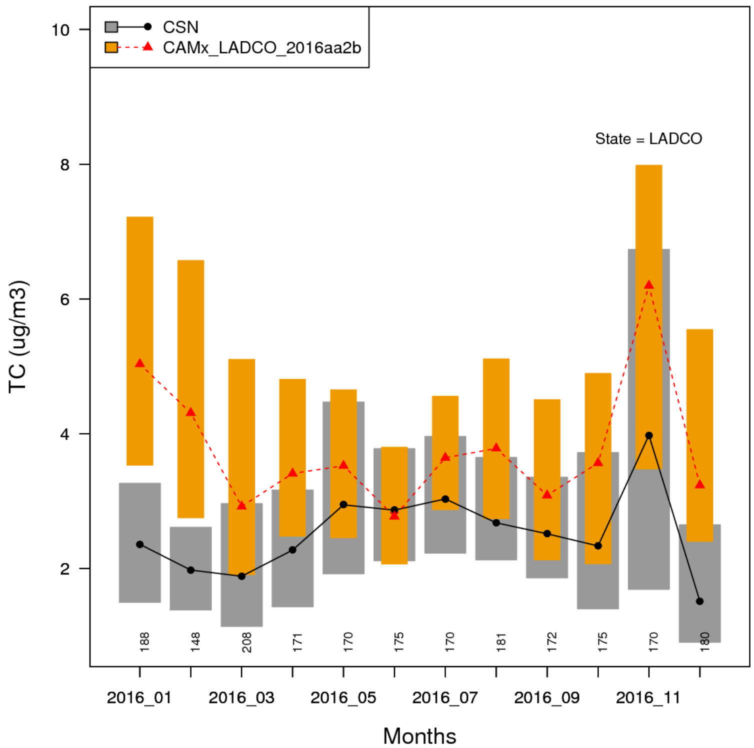


Figure S 5-27. Monthly 2016 TC boxplot of CSN locations in the LADCO region

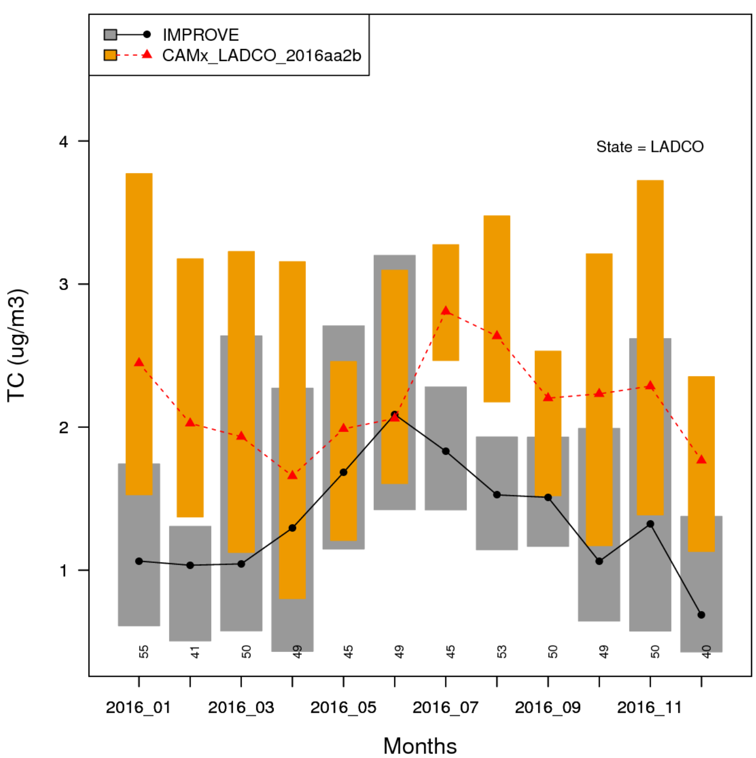


Figure S 5-28. Monthly 2016 TC boxplot of IMPROVE locations in the LADCO region

S5.2.5 LADCO CAMx 2016 Simulation Seasonal and State MPE Tables

Table S 5-9. CSN 2016 $PM_{2.5}$ seasonal MPE statistics

State	Season	Obs ($\mu g/m^3$)	CAMx ($\mu g/m^3$)	NMB (%)	NME (%)	r
IL	Fall	8.67	11.93	38.72	44.63	0.83
	Spring	8.43	10.29	22.37	37.99	0.67
	Summer	9.33	10.30	12.93	32.35	0.62
	Winter	9.31	13.62	46.24	52.25	0.78
IN	Fall	9.12	11.53	27.99	36.25	0.76
	Spring	7.93	9.28	16.43	38.75	0.55
	Summer	8.87	10.43	18.13	31.06	0.66
	Winter	9.34	11.85	26.33	38.40	0.73
MI	Fall	8.87	10.51	19.68	32.50	0.79
	Spring	8.51	9.56	12.62	29.39	0.74
	Summer	9.35	8.23	-10.53	27.31	0.59
	Winter	10.16	11.92	19.74	33.30	0.76
MN	Fall	5.97	12.42	108.86	109.19	0.81
	Spring	6.99	10.98	57.85	72.96	0.48
	Summer	5.43	8.58	58.22	60.77	0.51
	Winter	8.16	15.53	92.71	93.79	0.79
OH	Fall	8.74	10.20	19.74	33.55	0.84
	Spring	8.03	8.90	16.25	36.51	0.68
	Summer	8.50	9.01	8.74	30.39	0.65
	Winter	9.61	10.74	19.40	39.30	0.70
WI	Fall	5.05	7.65	51.53	56.08	0.82
	Spring	7.05	8.14	14.59	35.12	0.77
	Summer	6.11	8.01	31.70	41.44	0.64
	Winter	9.13	9.19	1.01	29.13	0.78
LADCO	Fall	7.74	10.71	44.42	52.03	0.81
	Spring	7.82	9.53	23.35	41.79	0.65
	Summer	7.93	9.09	19.87	37.22	0.61
	Winter	9.28	12.14	34.24	47.69	0.76

Table S 5-10. IMPROVE 2016 $PM_{2.5}$ seasonal MPE statistics

State	Season	Obs (μg/m³)	CAMx (μg/m³)	NMB (%)	NME (%)	r
IL	Fall	6.43	7.68	19.40	29.85	0.81
	Spring	5.96	6.57	10.27	42.87	0.49
	Summer	6.45	7.67	18.76	33.94	0.68
	Winter	7.17	7.75	7.98	39.69	0.58
MI	Fall	2.52	3.55	41.09	51.91	0.75
	Spring	2.67	3.43	28.21	40.61	0.79
	Summer	3.66	3.83	4.64	21.74	0.82
	Winter	2.77	3.66	32.01	54.86	0.68
MN	Fall	2.60	4.32	63.32	70.33	0.64
	Spring	3.84	4.95	28.96	60.06	0.62
	Summer	3.49	4.20	19.62	32.54	0.73
	Winter	3.75	4.69	33.25	57.07	0.60
OH	Fall	6.27	7.55	20.59	33.35	0.78
	Spring	6.23	5.90	-5.33	31.10	0.58
	Summer	6.96	6.86	-1.41	22.83	0.64
	Winter	5.23	7.51	43.70	58.99	0.37
LADCO	Fall	4.45	5.78	36.10	46.36	0.74
	Spring	4.67	5.21	15.53	43.66	0.62
	Summer	5.14	5.64	10.40	27.76	0.72
	Winter	4.73	5.90	29.23	52.65	0.56

Table S 5-11. CSN 2016 SO_4 seasonal MPE statistics

State	Season	Obs ($\mu g/m^3$)	CAMx ($\mu g/m^3$)	NMB (%)	NME (%)	r
IL	Fall	1.21	1.44	27.16	48.93	0.58
	Spring	1.02	1.34	31.92	41.69	0.64
	Summer	1.35	1.82	38.16	46.68	0.71
	Winter	1.09	1.42	30.00	40.86	0.75
IN	Fall	1.31	1.65	29.66	45.02	0.74
	Spring	1.11	1.39	26.05	43.37	0.36
	Summer	1.86	2.29	23.65	40.05	0.78
	Winter	1.27	1.41	11.52	29.53	0.78
MI	Fall	0.98	1.46	49.95	59.47	0.69
	Spring	1.13	1.60	45.61	52.77	0.75
	Summer	1.38	1.61	20.98	40.52	0.71
	Winter	1.28	1.43	13.37	38.75	0.59
MN	Fall	0.58	1.01	75.60	75.60	0.91
	Spring	0.78	1.17	49.81	54.29	0.75
	Summer	0.72	1.00	38.90	47.99	0.80
	Winter	0.85	1.25	46.74	54.17	0.79
OH	Fall	1.19	1.49	27.03	42.63	0.72
	Spring	1.40	1.58	16.19	40.20	0.52
	Summer	1.62	1.78	11.26	28.30	0.81
	Winter	1.82	1.37	-14.80	38.49	0.40
WI	Fall	0.54	1.02	106.64	111.28	0.87
	Spring	0.81	1.20	48.00	54.01	0.65
	Summer	0.94	1.25	32.37	49.46	0.81
	Winter	0.96	1.17	22.54	42.33	0.73
LADCO	Fall	0.97	1.34	52.67	63.82	0.75
	Spring	1.04	1.38	36.26	47.72	0.61
	Summer	1.31	1.62	27.55	42.17	0.77
	Winter	1.21	1.34	18.23	40.69	0.67

Table S 5-12. IMPROVE 2016 SO_4 seasonal MPE statistics

State	Season	Obs (µg/m³)	CAMx (µg/m³)	NMB (%)	NME (%)	r
IL	Fall	1.26	1.33	5.86	27.50	0.87
	Spring	1.18	1.21	2.21	23.03	0.79
	Summer	1.53	1.77	16.19	40.49	0.69
	Winter	1.33	1.26	-5.84	30.62	0.73
MI	Fall	0.48	0.72	51.46	61.17	0.78
	Spring	0.66	0.86	30.51	47.39	0.44
	Summer	0.50	0.66	34.55	46.89	0.85
	Winter	0.64	0.82	29.56	42.44	0.69
MN	Fall	0.49	0.71	45.82	60.99	0.75
	Spring	0.67	0.83	25.75	35.75	0.72
	Summer	0.51	0.69	40.03	51.05	0.83
	Winter	0.74	0.81	11.96	44.04	0.62
OH	Fall	1.30	1.31	1.14	28.10	0.70
	Spring	1.67	1.32	-20.92	31.97	0.45
	Summer	1.71	1.75	2.43	33.22	0.77
	Winter	1.23	1.14	-6.72	27.88	0.68
LADCO	Fall	0.88	1.02	26.07	44.44	0.78
	Spring	1.04	1.05	9.39	34.53	0.60
	Summer	1.06	1.22	23.30	42.91	0.79
	Winter	0.98	1.01	7.24	36.25	0.68

Table S 5-13. CSN 2016 NO_3 seasonal MPE statistics

State	Season	Obs (µg/m³)	CAMx (µg/m³)	NMB (%)	NME (%)	r
IL	Fall	1.04	1.59	53.06	76.24	0.66
	Spring	1.28	1.46	15.28	56.76	0.41
	Summer	0.42	0.80	92.10	113.14	0.26
	Winter	2.72	2.76	0.58	36.57	0.61
IN	Fall	0.87	1.47	65.55	85.03	0.61
	Spring	0.80	1.12	46.38	88.98	0.23
	Summer	0.38	0.94	159.32	178.05	0.26
	Winter	2.52	2.44	-3.21	49.40	0.32
MI	Fall	1.08	1.48	38.32	62.32	0.84
	Spring	1.14	1.45	30.04	76.80	0.50
	Summer	0.54	0.45	-11.88	59.08	0.43
	Winter	3.13	3.03	-3.01	47.58	0.50
MN	Fall	0.64	1.18	88.67	93.97	0.77
	Spring	0.92	1.11	20.28	56.86	0.66
	Summer	0.20	0.42	116.18	140.40	0.20
	Winter	2.28	2.17	-4.73	43.47	0.79
OH	Fall	0.86	1.25	47.49	77.31	0.68
	Spring	0.99	0.99	8.59	65.46	0.35
	Summer	0.41	0.51	24.89	70.36	0.41
	Winter	3.17	2.31	-19.53	57.21	0.19
WI	Fall	0.58	1.00	86.96	100.92	0.80
	Spring	1.25	1.33	2.78	45.85	0.71
	Summer	0.30	0.59	133.59	157.75	0.52
	Winter	2.84	2.19	-23.11	41.63	0.77
LADCO	Fall	0.84	1.33	63.34	82.63	0.73
	Spring	1.06	1.24	20.56	65.12	0.47
	Summer	0.37	0.62	85.70	119.80	0.35
	Winter	2.78	2.48	-8.83	45.98	0.53

Table S 5-14. IMPROVE 2016 NO_3 seasonal MPE statistics

State	Season	Obs (µg/m³)	CAMx (µg/m³)	NMB (%)	NME (%)	r
IL	Fall	0.93	0.94	1.99	52.87	0.58
	Spring	1.30	1.14	-12.43	60.45	0.44
	Summer	0.35	0.69	95.02	122.69	0.22
	Winter	2.70	1.91	-29.33	54.02	0.24
MI	Fall	0.20	0.24	19.32	109.96	0.57
	Spring	0.26	0.27	2.31	55.54	0.88
	Summer	0.07	0.09	24.66	80.35	0.47
	Winter	0.75	0.50	-31.19	67.40	0.63
MN	Fall	0.25	0.48	95.25	136.72	0.49
	Spring	0.52	0.42	-6.14	61.19	0.57
	Summer	0.09	0.17	76.63	97.62	0.67
	Winter	1.31	0.93	-25.20	61.41	0.49
OH	Fall	0.56	0.58	3.41	77.08	0.53
	Spring	0.61	0.41	-32.53	58.21	0.29
	Summer	0.18	0.21	16.99	53.88	0.46
	Winter	1.44	1.32	-8.47	57.92	0.47
LADCO	Fall	0.48	0.56	29.99	94.16	0.54
	Spring	0.67	0.56	-12.20	58.85	0.54
	Summer	0.17	0.29	53.32	88.63	0.45
	Winter	1.55	1.17	-23.55	60.19	0.46

Table S 5-15. CSN total 2016 TC seasonal MPE statistics

State	Season	Obs (μg/m³)	CAMx (μg/m³)	NMB (%)	NME (%)	r
IL	Fall	3.67	4.44	22.42	39.71	0.75
	Spring	2.68	3.68	38.16	52.47	0.63
	Summer	3.32	3.61	8.28	27.86	0.45
	Winter	2.28	5.10	133.38	134.30	0.86
IN	Fall	3.76	4.51	24.12	42.21	0.72
	Spring	2.63	3.50	32.02	50.58	0.67
	Summer	2.99	3.72	23.30	33.51	0.57
	Winter	2.63	4.86	86.74	93.80	0.69
MI	Fall	3.12	4.00	28.65	40.22	0.73
	Spring	2.83	3.63	28.55	46.46	0.75
	Summer	3.28	3.46	5.69	29.78	0.47
	Winter	2.54	4.75	94.51	95.24	0.84
MN	Fall	2.70	6.98	162.81	162.81	0.78
	Spring	2.50	6.05	142.58	151.40	0.35
	Summer	2.55	4.46	75.68	76.66	0.46
	Winter	1.88	9.43	407.25	407.25	0.78
OH	Fall	3.82	4.23	11.99	29.83	0.89
	Spring	3.16	3.65	20.00	43.40	0.67
	Summer	3.44	3.34	-0.27	32.31	0.52
	Winter	2.89	4.33	54.02	59.78	0.85
WI	Fall	1.99	2.68	36.28	47.26	0.76
	Spring	2.46	3.09	29.56	56.25	0.71
	Summer	2.35	2.98	22.63	38.70	0.37
	Winter	1.64	3.13	90.43	91.70	0.68
LADCO	Fall	3.18	4.47	47.71	60.34	0.77
	Spring	2.71	3.93	48.48	66.76	0.63
	Summer	2.99	3.59	22.55	39.80	0.47
	Winter	2.31	5.27	144.39	147.01	0.78

Table S 5-16. IMPROVE 2016 TC seasonal MPE statistics

State	Season	Obs (μg/m³)	CAMx (μg/m³)	NMB (%)	NME (%)	r
IL	Fall	2.49	2.86	14.76	26.72	0.87
	Spring	2.02	2.34	15.77	41.11	0.54
	Summer	2.05	2.73	33.41	45.49	0.53
	Winter	1.56	2.90	85.36	86.43	0.73
MI	Fall	1.90	2.64	54.40	60.96	0.80
	Spring	1.61	2.26	50.90	66.10	0.69
	Summer	2.28	2.93	32.61	40.84	0.66
	Winter	1.32	2.69	119.21	119.21	0.81
MN	Fall	1.19	2.01	69.72	80.19	0.63
	Spring	1.85	2.48	45.17	86.68	0.57
	Summer	1.79	2.54	43.72	59.37	0.35
	Winter	0.83	1.96	140.44	140.59	0.69
OH	Fall	2.72	3.76	38.04	50.52	0.77
	Spring	2.66	2.77	4.15	34.73	0.66
	Summer	2.43	3.34	37.54	59.81	0.27
	Winter	1.55	3.38	117.78	120.42	0.68
LADCO	Fall	2.08	2.82	44.23	54.60	0.77
	Spring	2.03	2.46	29.00	57.16	0.62
	Summer	2.14	2.89	36.82	51.38	0.45
	Winter	1.32	2.73	115.70	116.66	0.72