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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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).

[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 98th 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.

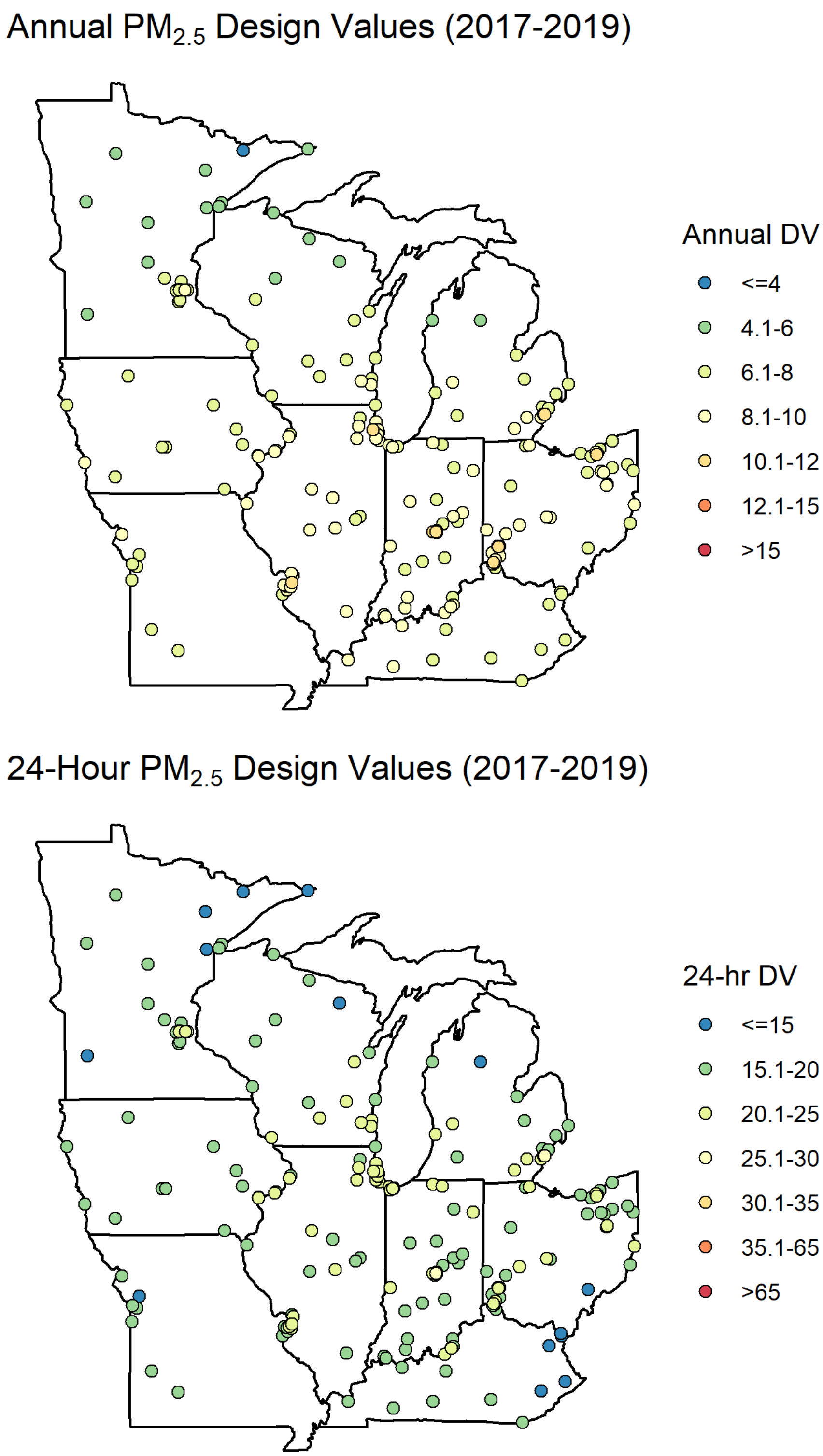

Figure 2-1. 2017-2019 annual (top) and 24-hour (bottom) $PM_{2.5}$ design values (DVs) in μg/m^3. For comparison, the annual $PM_{2.5}$ NAAQS is 12 μg/m^3, and the 24-hour NAAQS is 35 μg/m^3.

$PM_{2.5}$ 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.

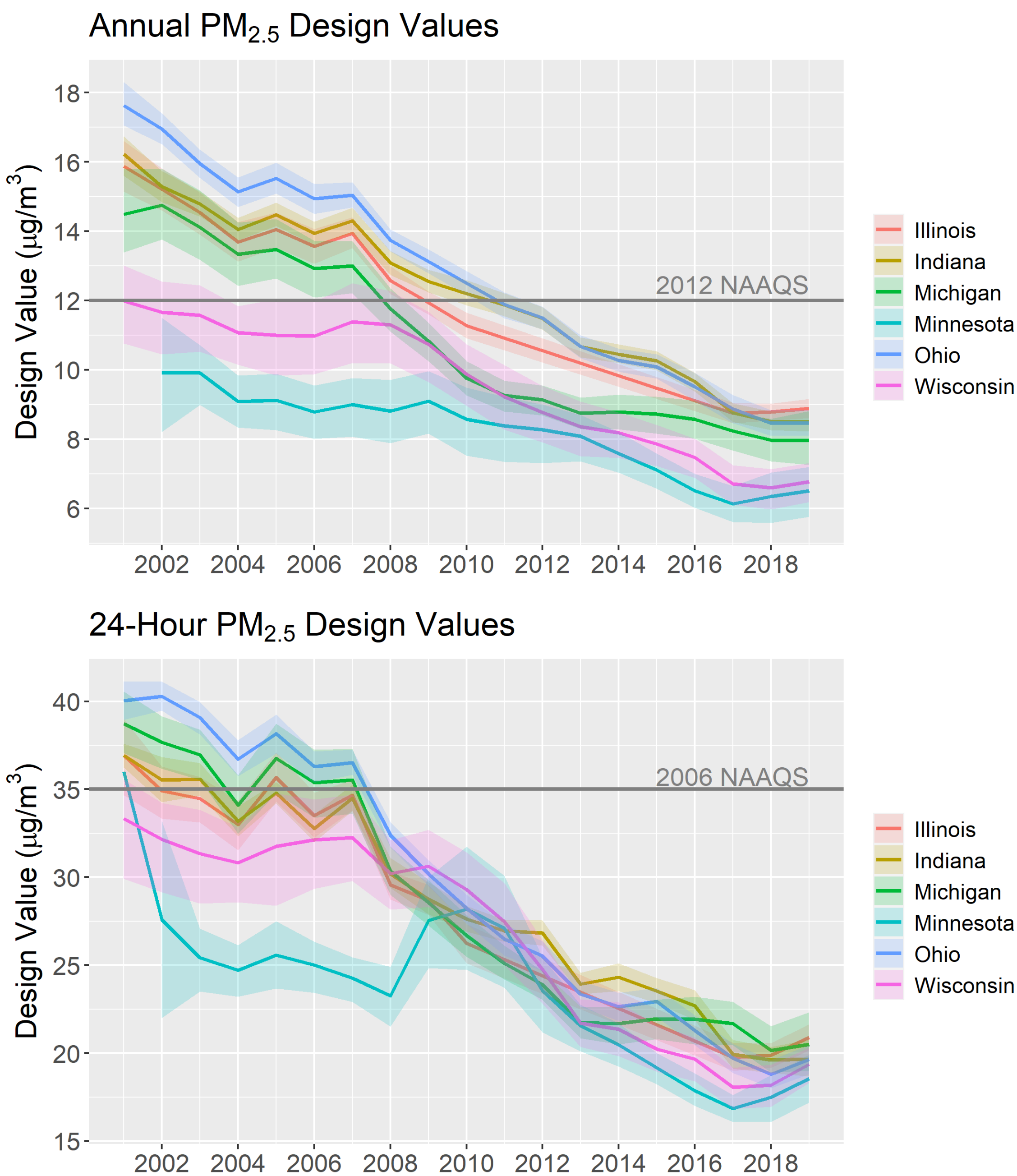

Figure 2-2. Trends in annual (top) and 24-hour (bottom) $PM_{2.5}$ design values in the LADCO states.[7] The levels of the NAAQS are shown for comparison. Dark lines show the state mean, whereas the shaded region shows the 95 percent confidence interval. Plots include monitors with at least six valid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

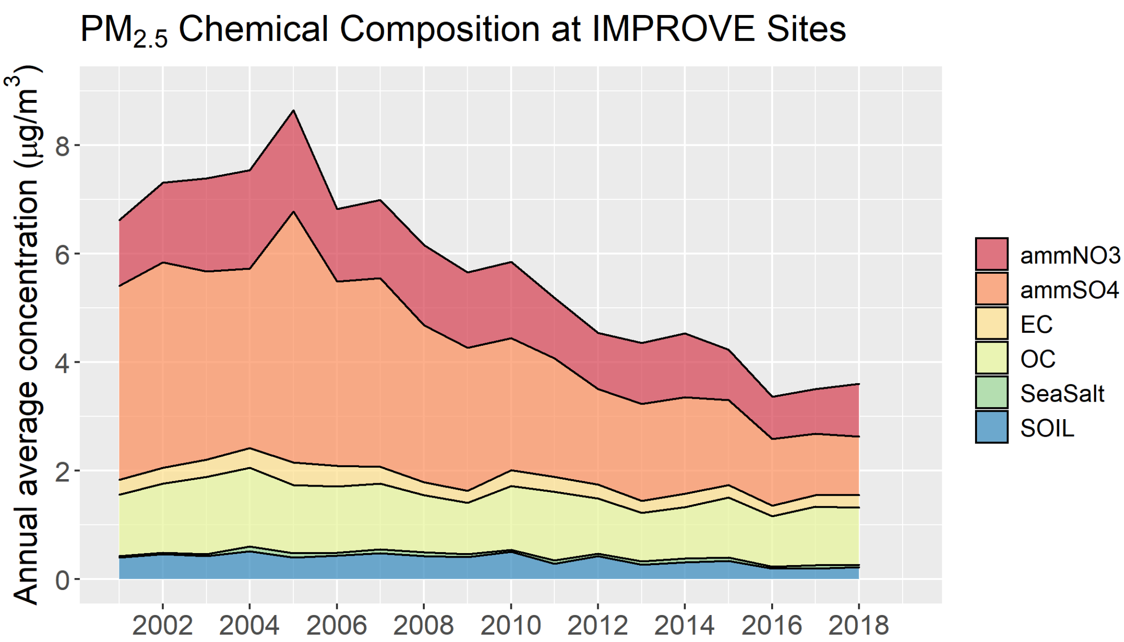

Figure 2-3. Chemical composition of $PM_{2.5}$ at the mostly rural IMPROVE monitoring sites in the LADCO region.[8]

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.

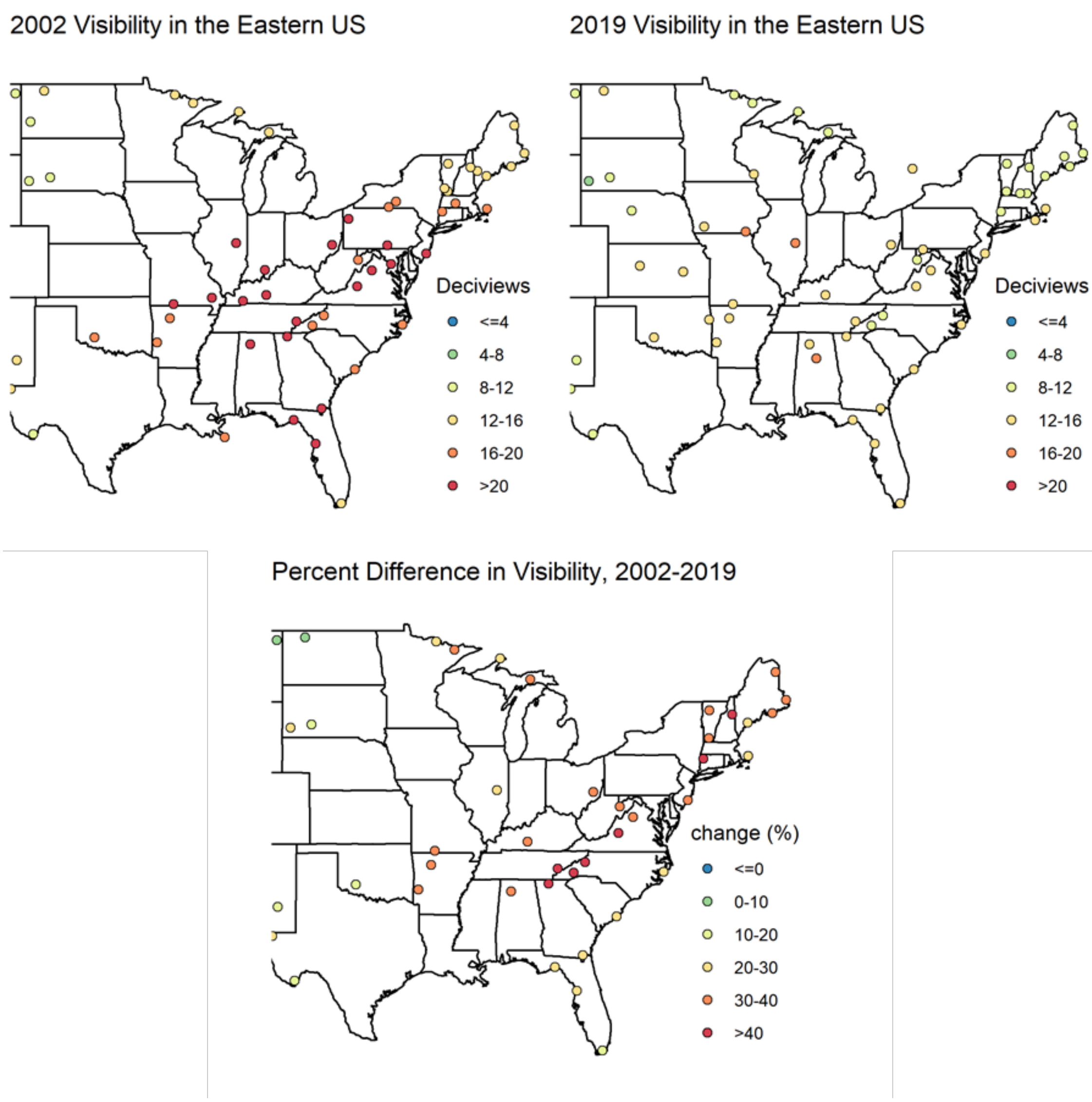

Figure 2-4. Visibility (in deciviews) at sites in the eastern United States in 2002 (left) and 2019 (right), and the percent difference in visibility in these two years (bottom).

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.

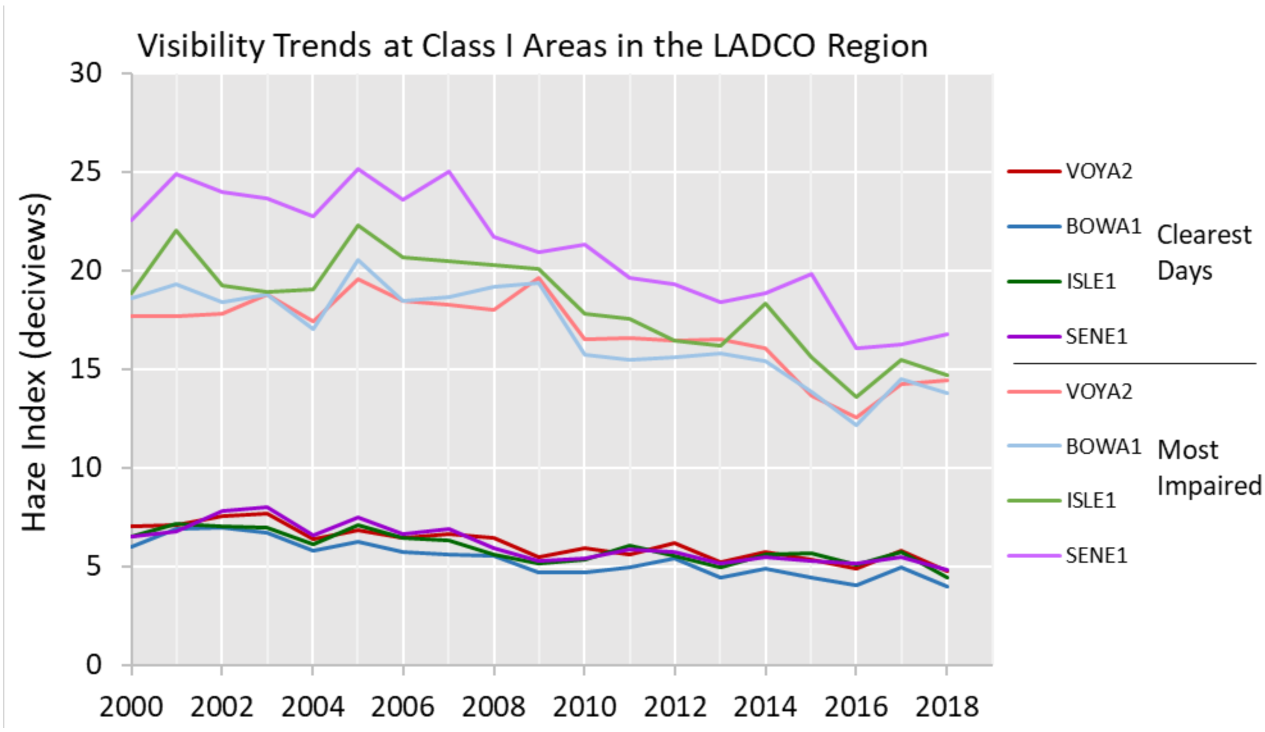

Figure 2-5. Visibility trends (in deciviews) at LADCO Class I Area monitors on the clearest and most impaired days.[12]

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.

Parameter	Light Extinction (Mm^{-1})											
	Voyageurs NP			Boundary Waters			Isle Royale NP			Seney		
	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%**

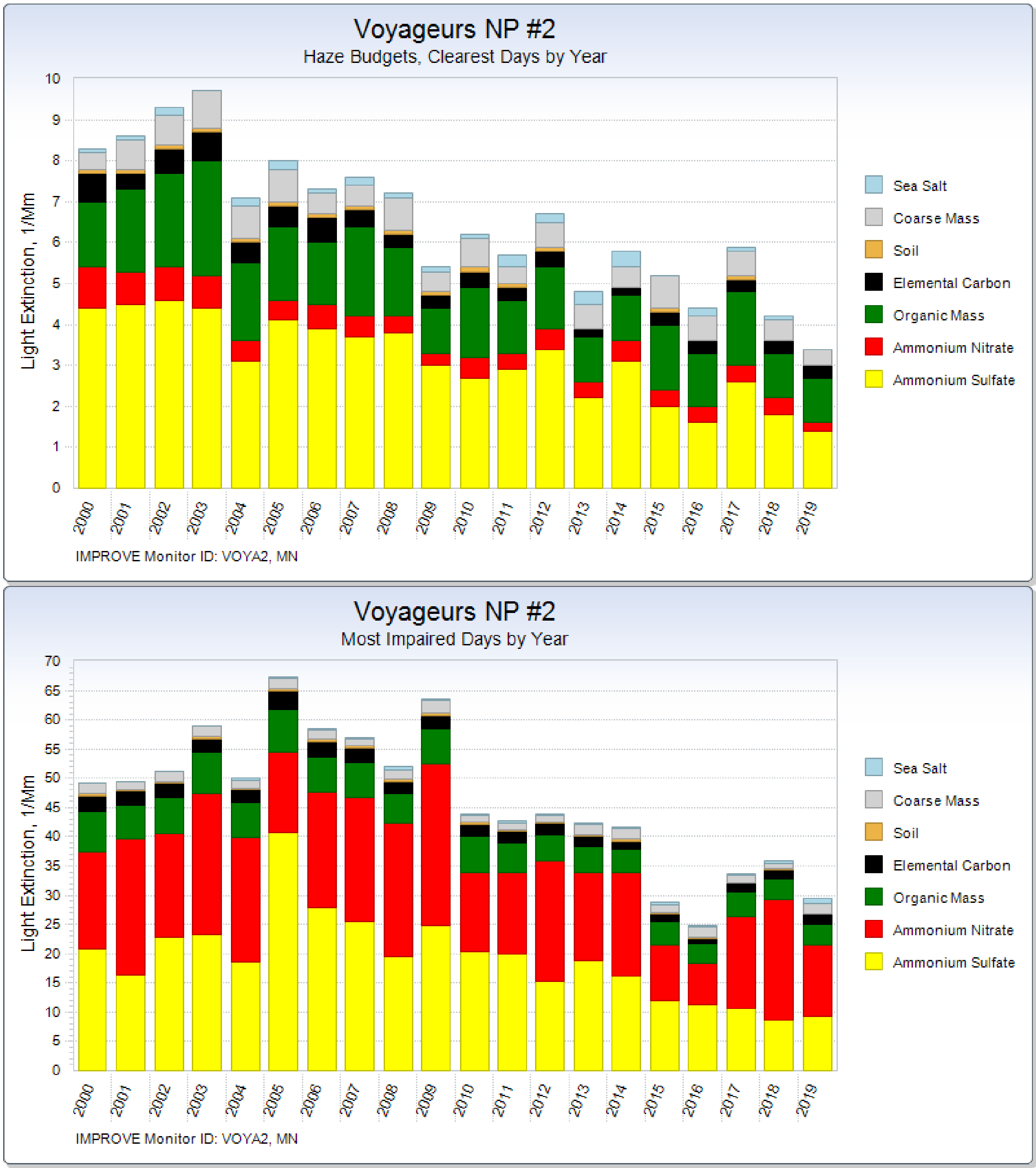

Figure 2-6. Composition of light extinction for Minnesota's Voyageurs National Park, shown for the clearest (top) and most impaired (bottom) days.

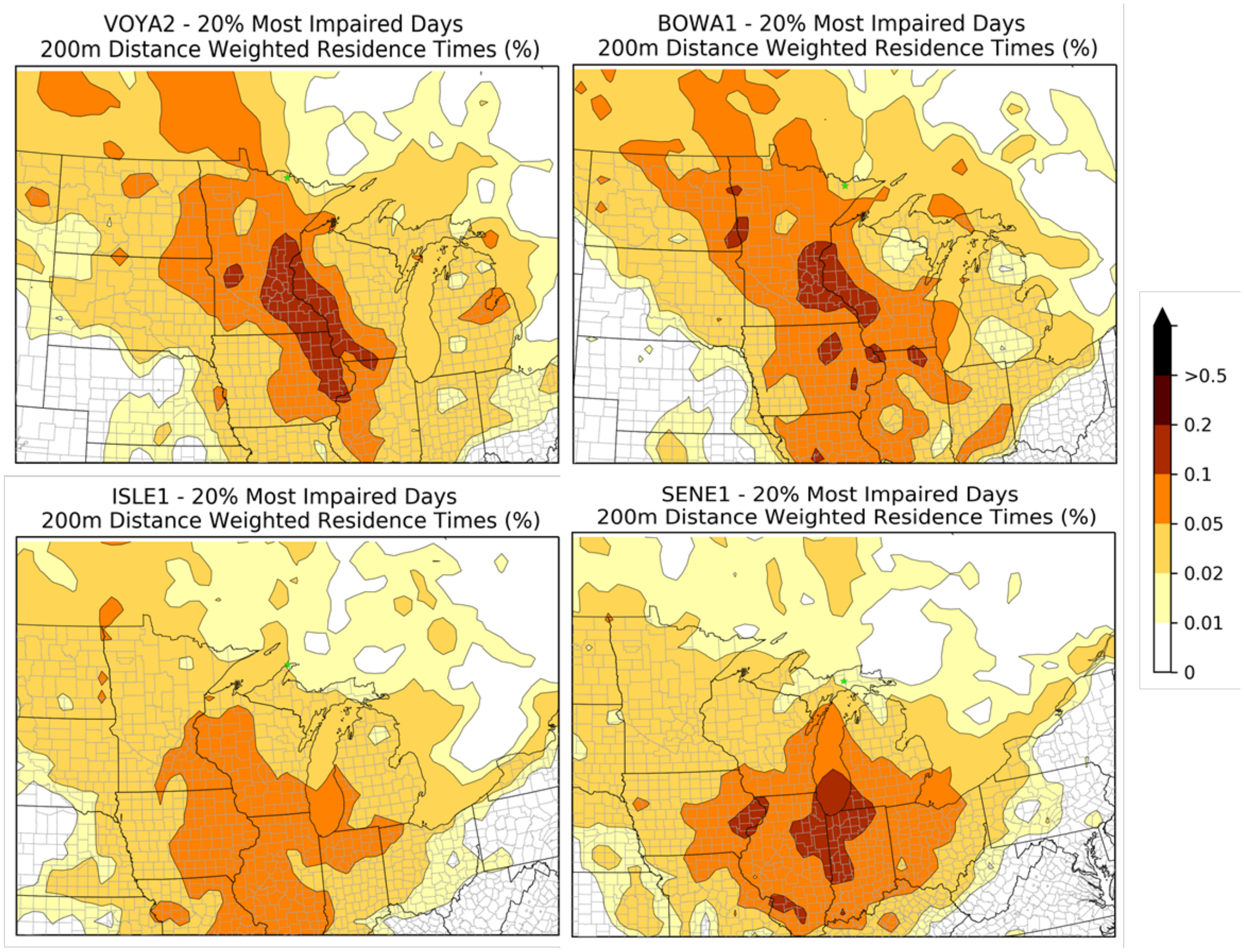

Figure 2-7. Distance weighted residence times for air masses reaching the four LADCO Class I areas on the 20% most impaired days for the years 2012 to 2016. Residence times were determined from 72-hour HYSPLIT back-trajectories ending at 200m altitude.[13]

[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.

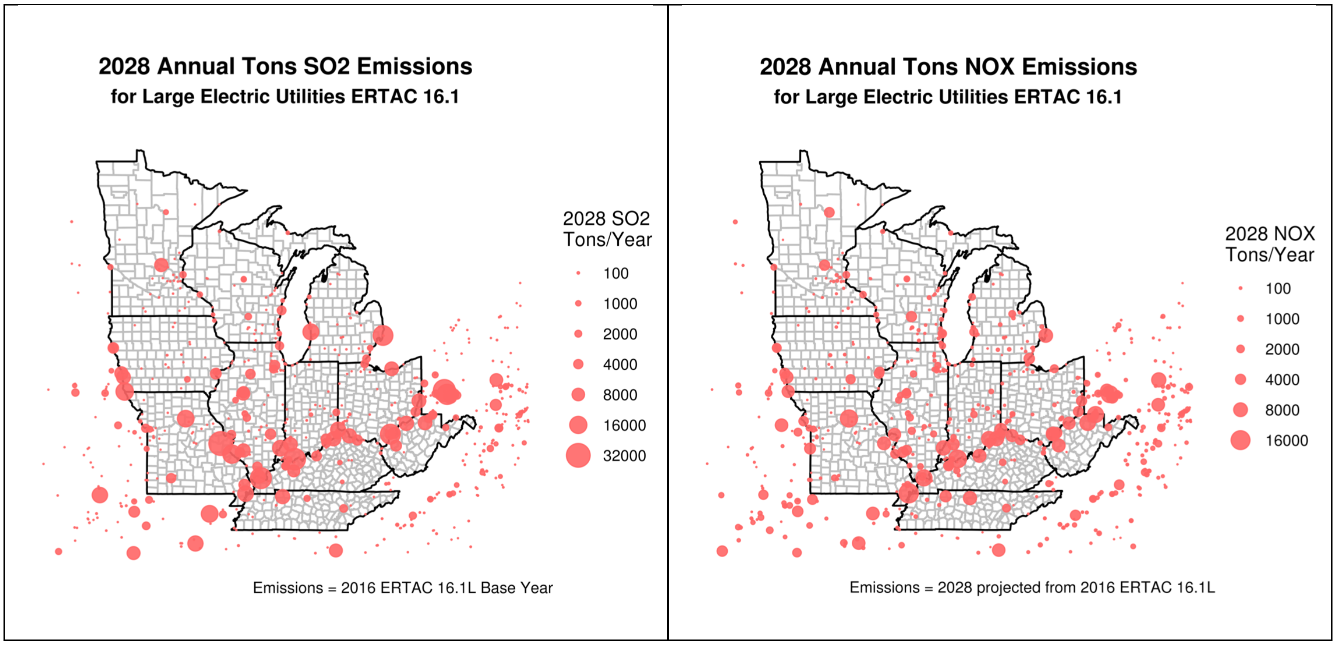

Figure 3-1. ERTAC EGU 16.1 2028 SO_2 (l) and NOx (r) emissions bubble plots

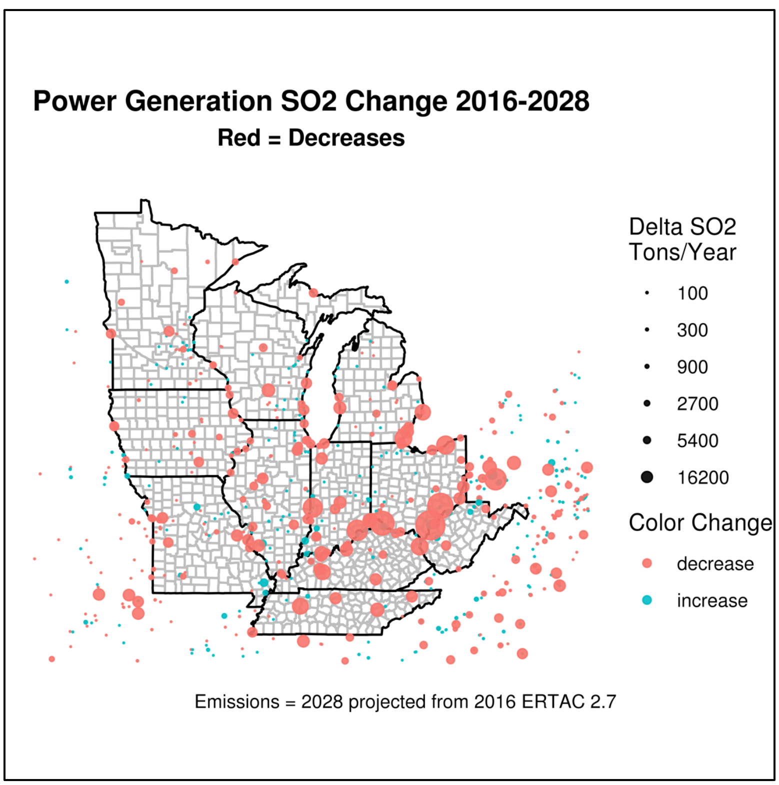

Figure 3-2. ERTAC EGU 16.1 SO_2 emissions difference (2016-2028) bubble plot

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.

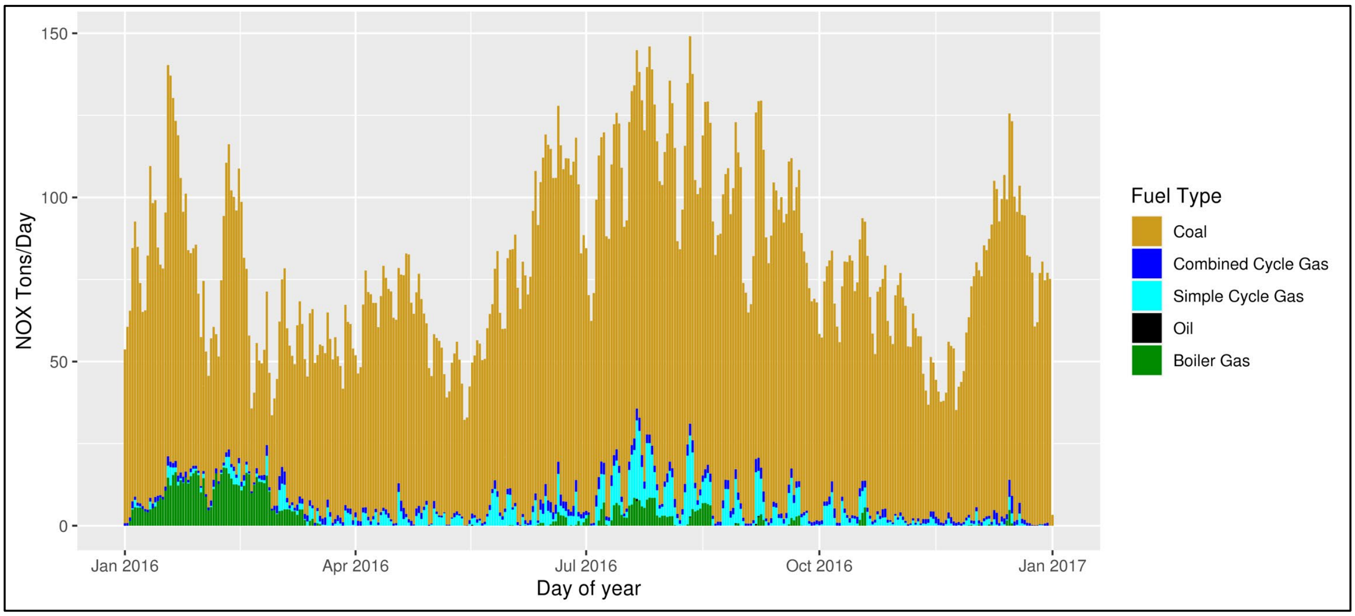

Figure 3-4. Illinois power generation 2016 daily NOx emissions by fuel type

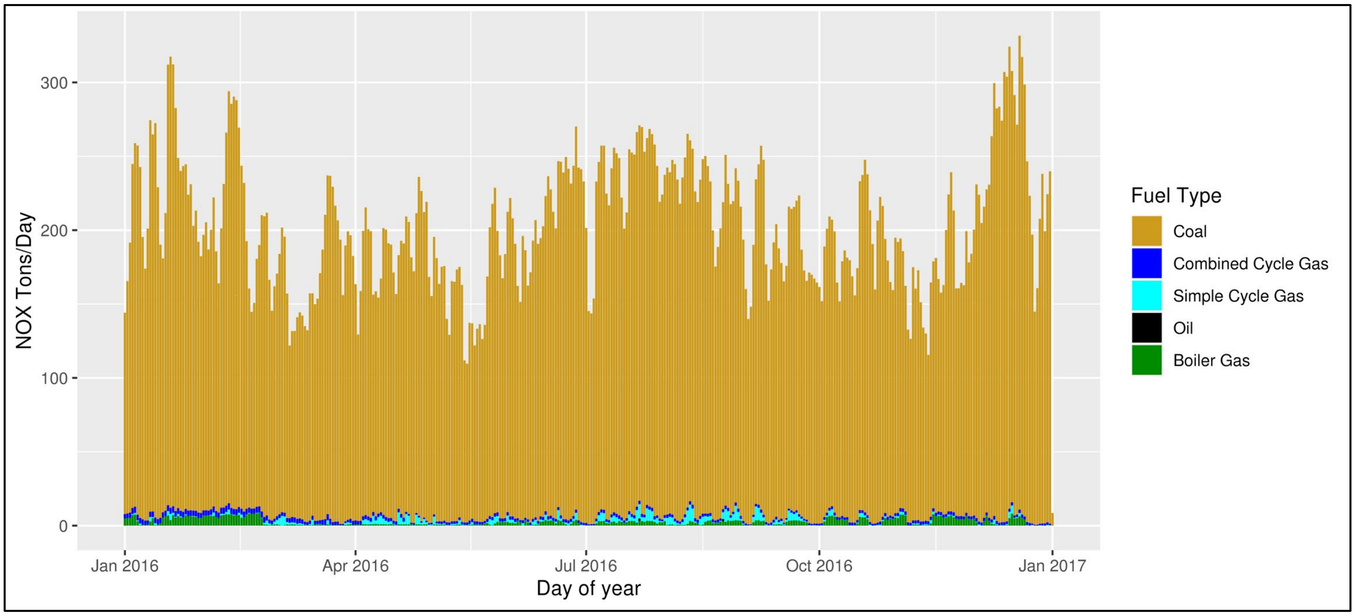

Figure 3-5. Indiana power generation 2016 daily NOx emissions by fuel type

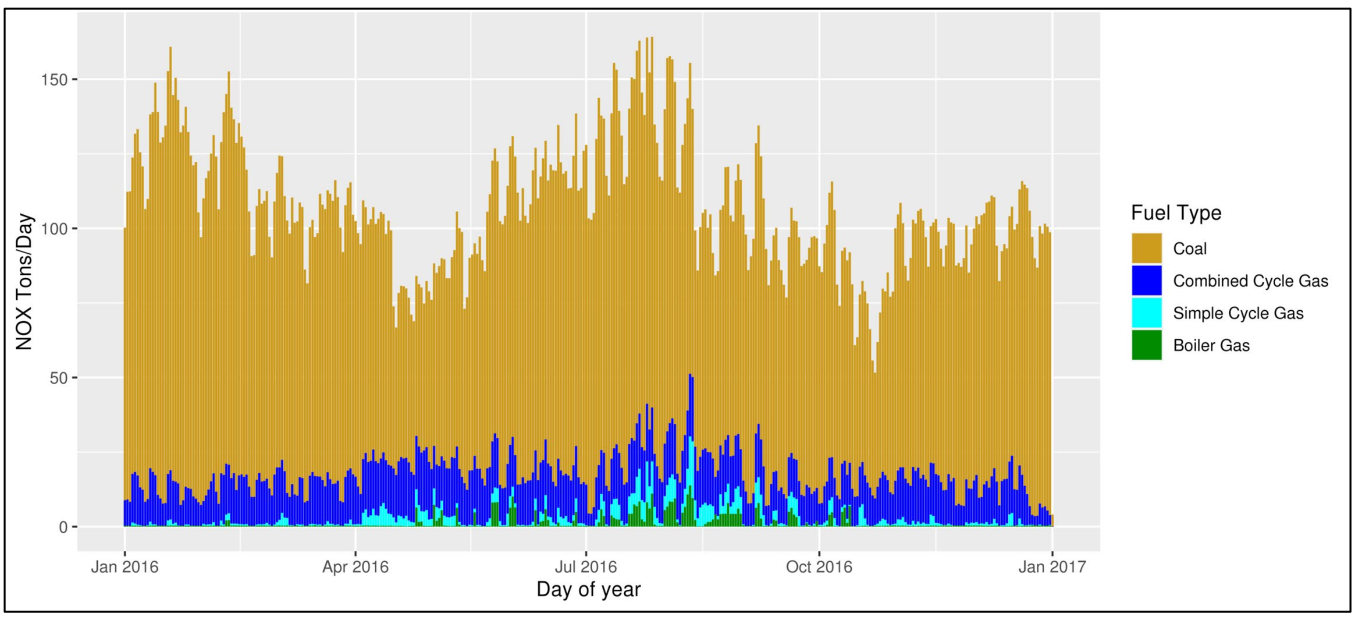

Figure 3-6. Michigan power generation 2016 daily NOx emissions by fuel type

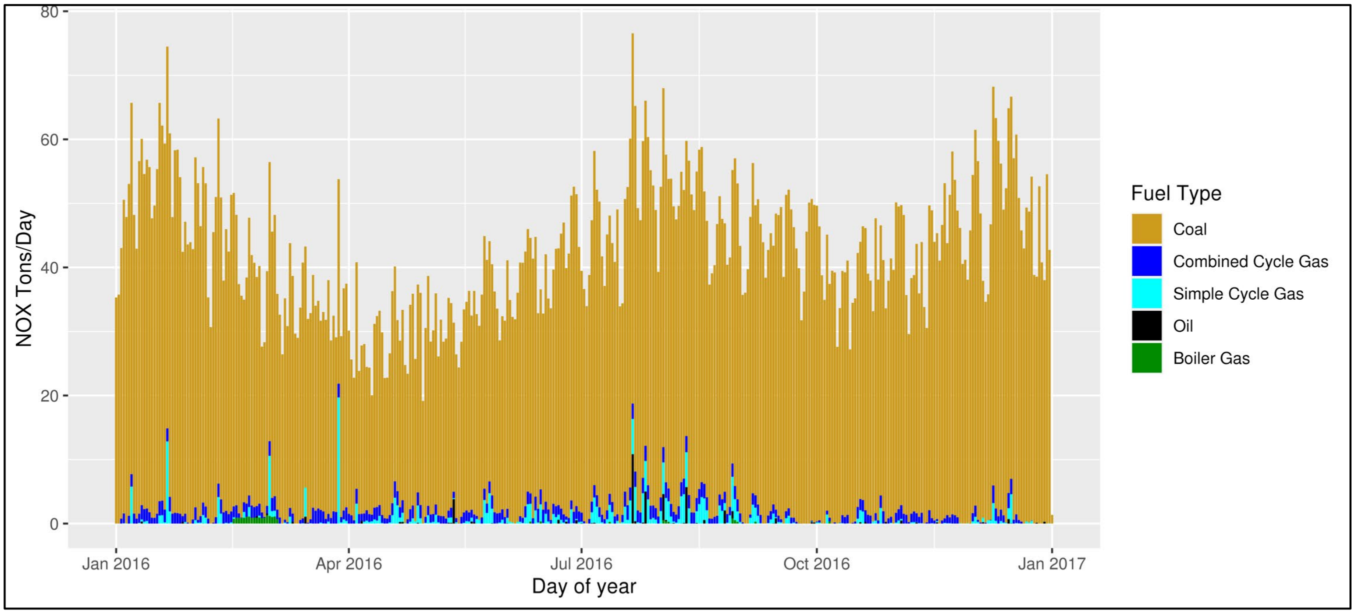

Figure 3-7. Minnesota power generation 2016 daily NOx emissions by fuel type

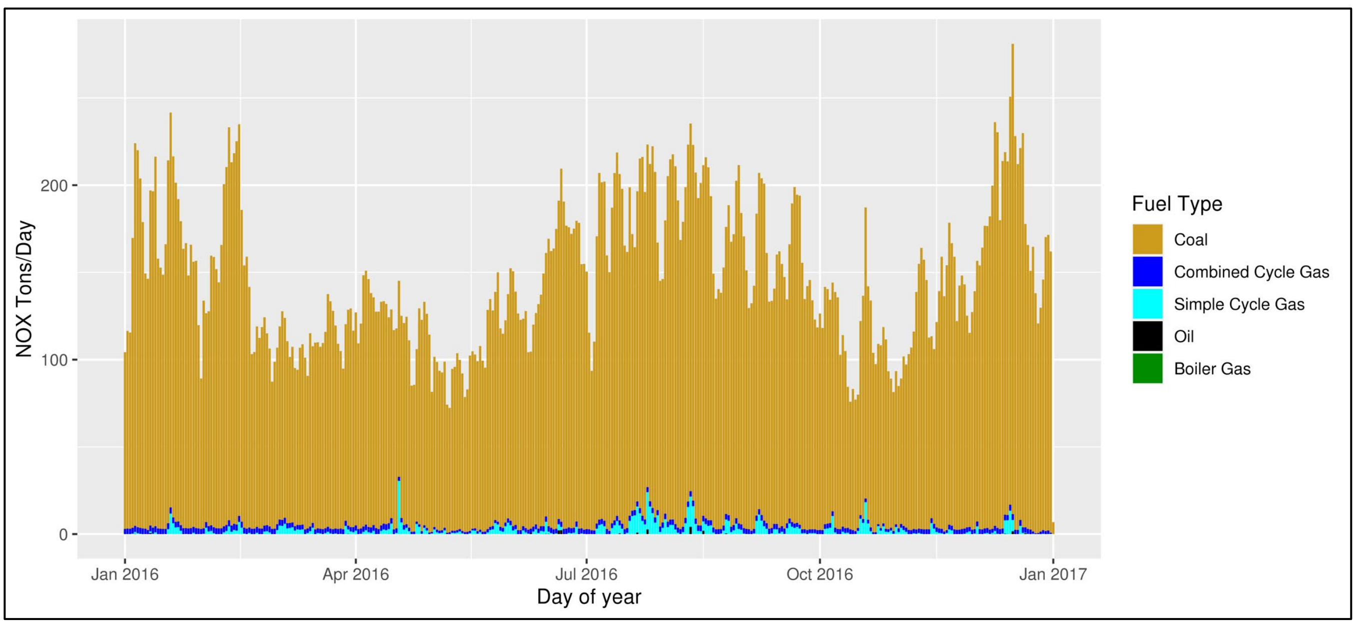

Figure 3-8. Ohio power generation 2016 daily NOx emissions by fuel type

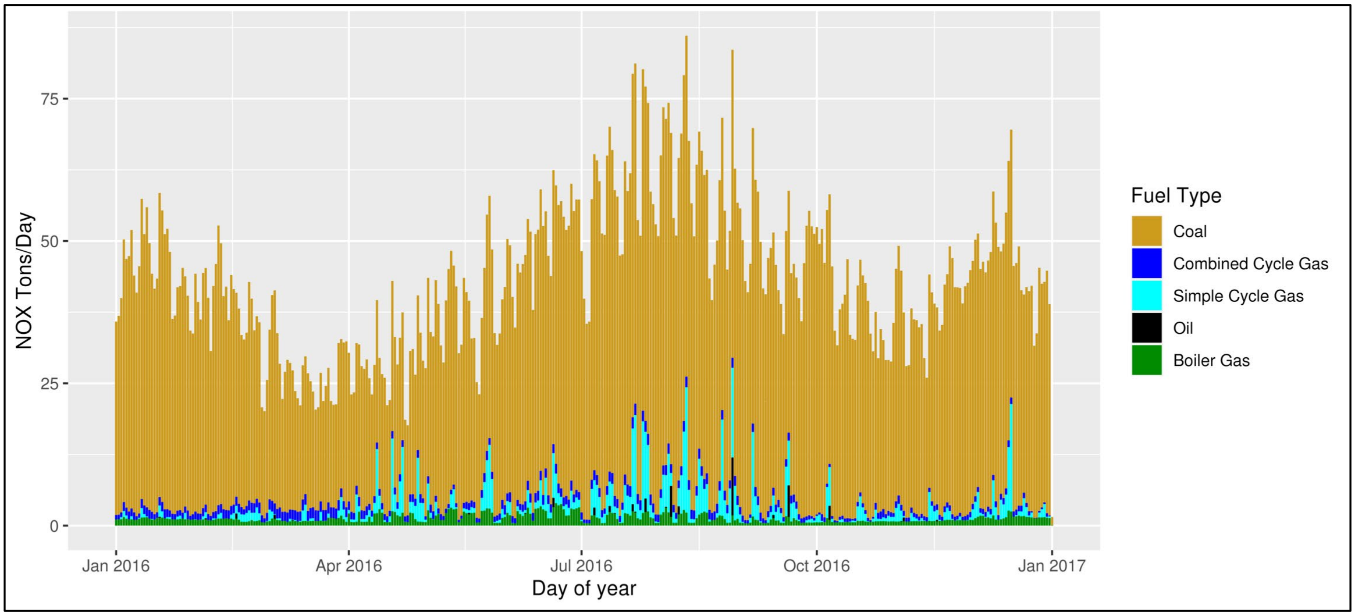

Figure 3-9. Wisconsin power generation 2016 daily NOx emissions by fuel type

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.

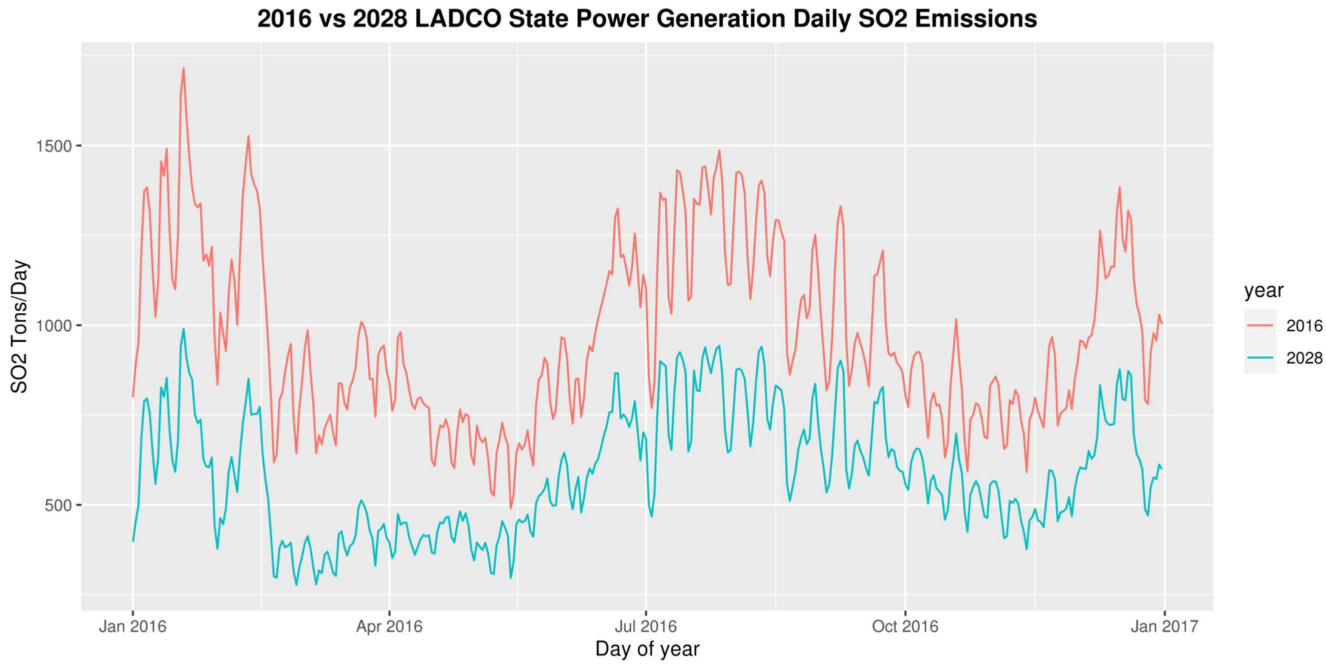

Figure 3-10. Daily total LADCO region SO_2 emissions from EGUs in 2016 and 2028

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.