LADCO | LAKE MICHIGAN AIR DIRECTORS CONSORTIUM

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

TSD SUPPLEMENTAL MATERIALS

Lake Michigan Air Directors Consortium

9501 W. Devon Ave., Suite 701

Rosemont, IL 60018

Please direct question/comments to adelman@ladco.org

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).

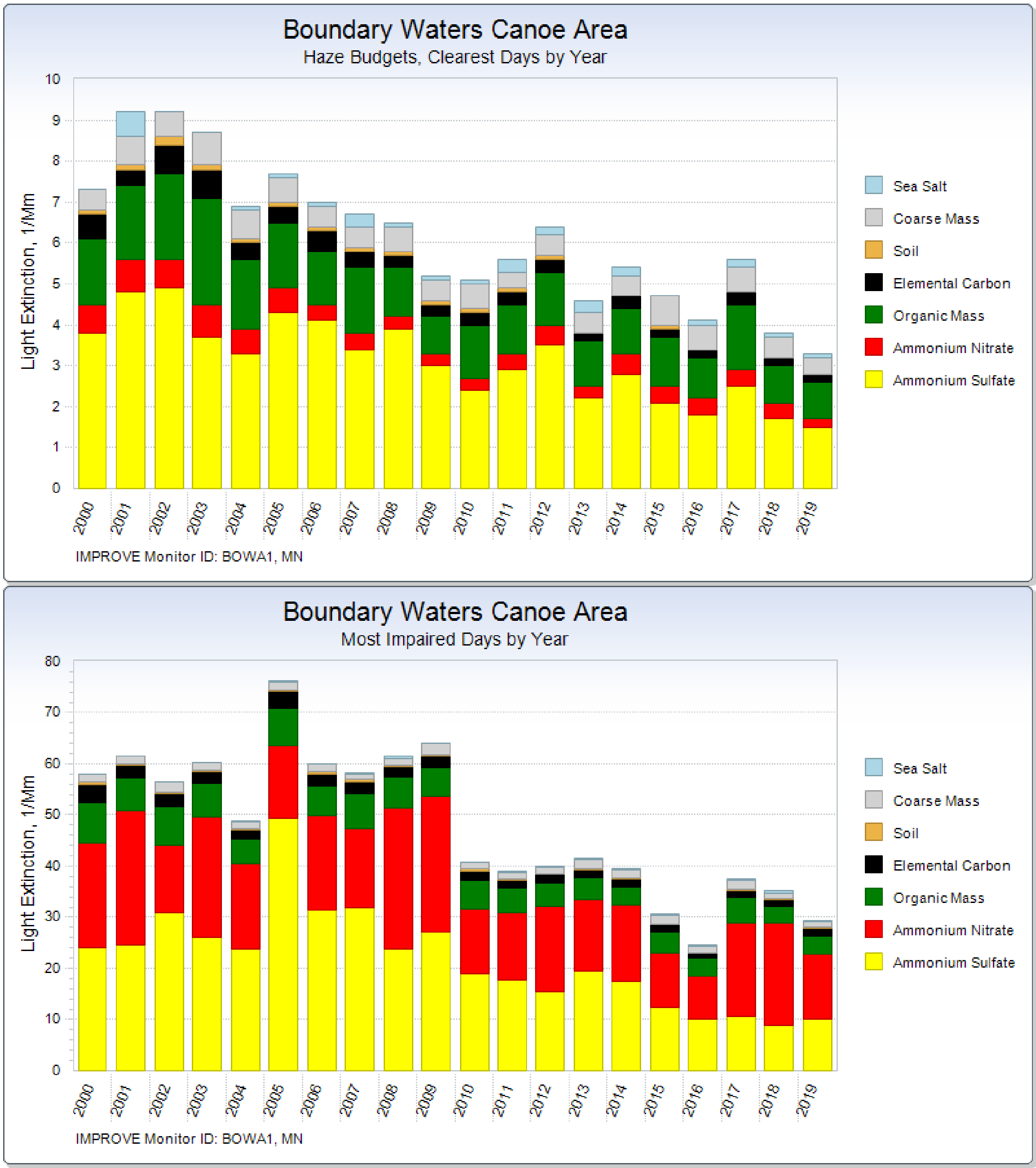


Figure S 1-1. Composition of light extinction for Minnesota's Boundary Waters Canoe Area monitor on the clearest (top) and most impaired (bottom) days.

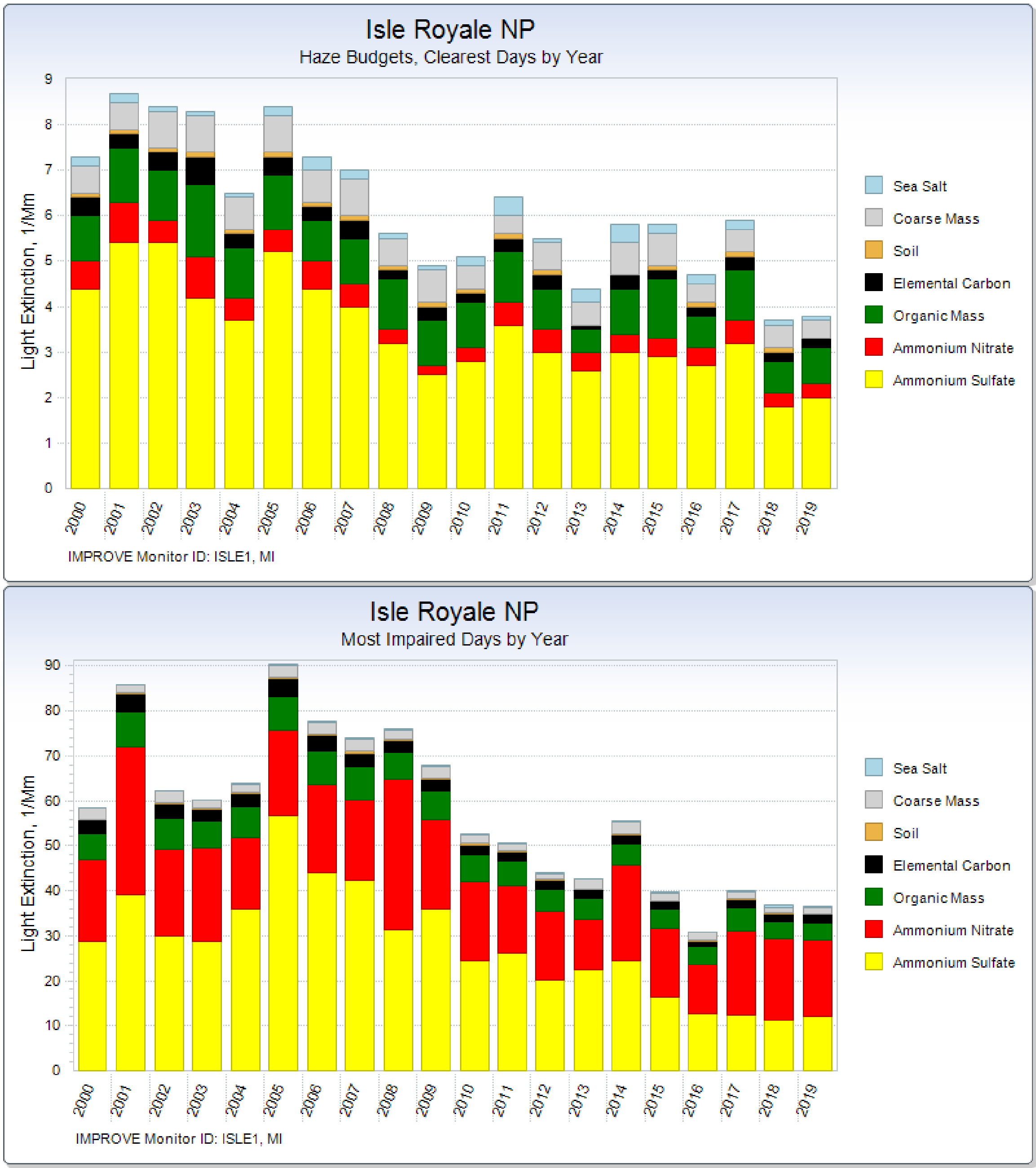
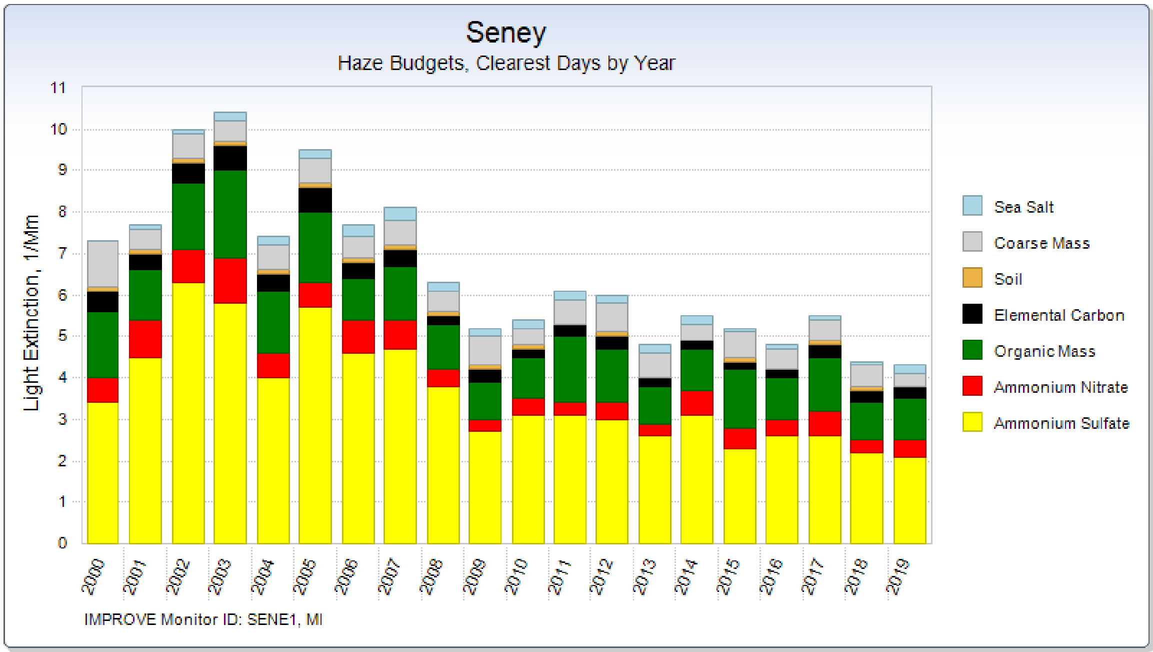


Figure S 1-2. Composition of light extinction for Michigan's Isle Royale National Park monitor on the clearest (top) and most impaired (bottom) days.



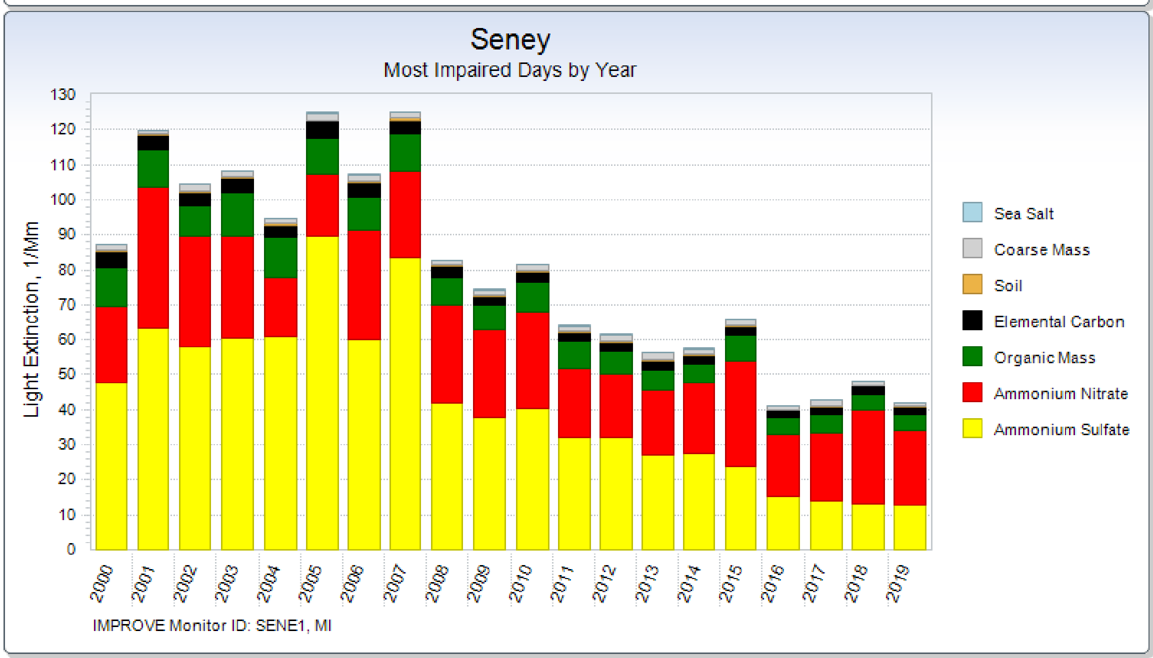


Figure S 1-3. Composition of light extinction for Michigan's Seney monitor on the clearest (top) and most impaired (bottom) days.

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.

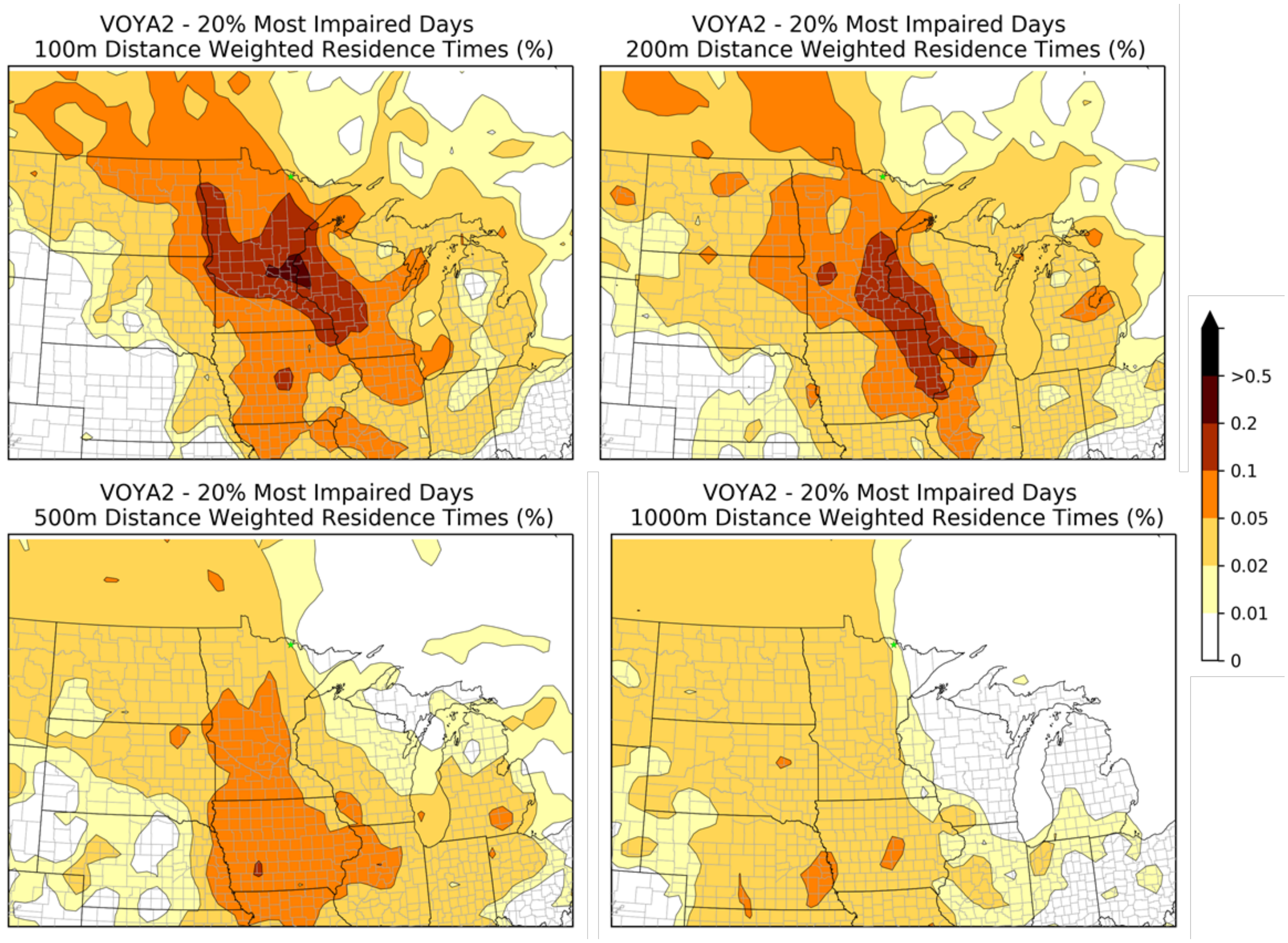


Figure S 2-1. Distance weighted residence times for air masses reaching the Voyageurs National Park monitor at a variety of heights on the 20% most impaired days for the years 2012 to 2016.

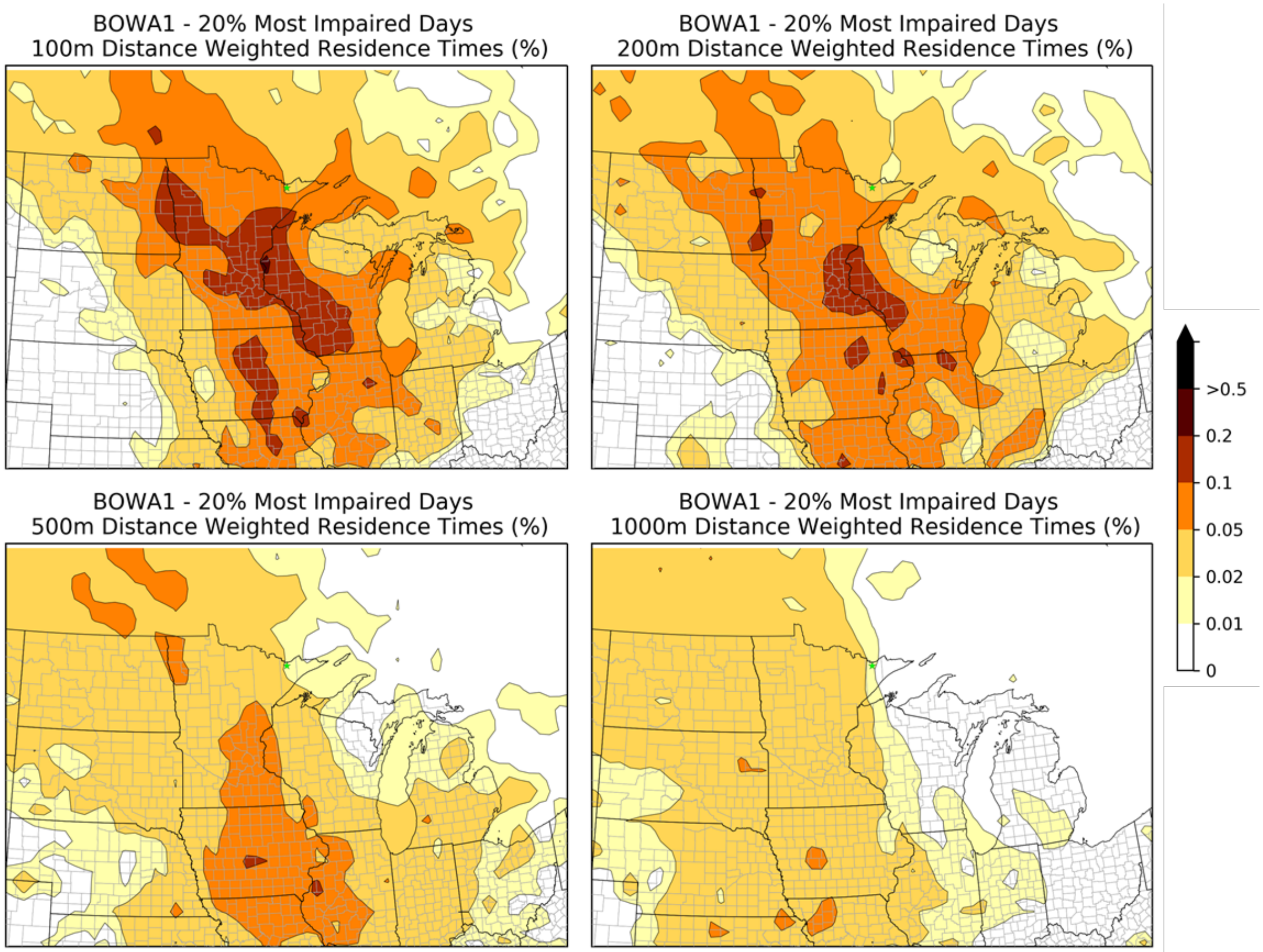


Figure S 2-2. Distance weighted residence times for air masses reaching the Boundary Waters Canoe Area monitor at a variety of heights on the 20% most impaired days for the years 2012 to 2016.

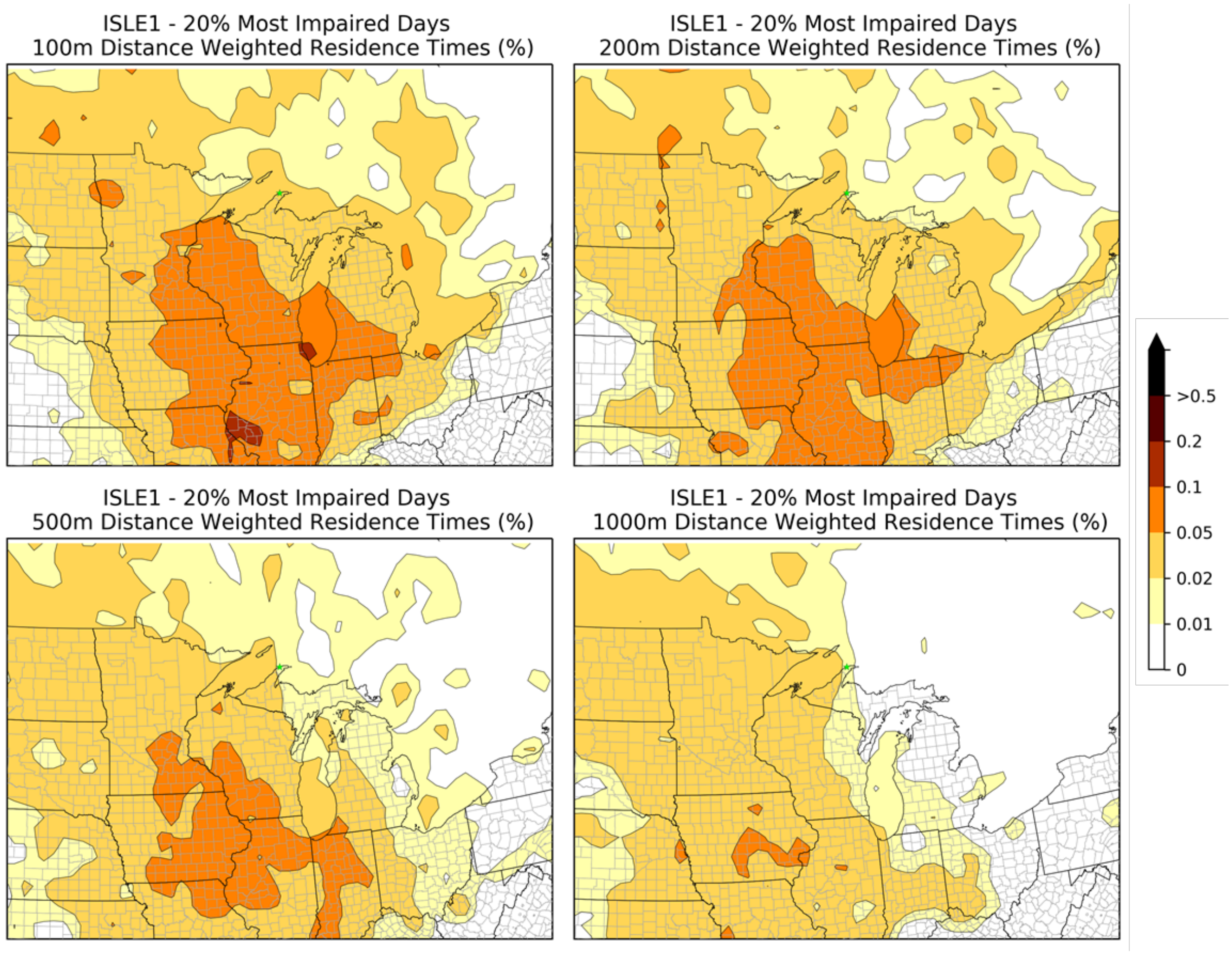


Figure S 2-3. Distance weighted residence times for air masses reaching the Isle Royale National Park monitor at a variety of heights on the 20% most impaired days for the years 2012 to 2016.

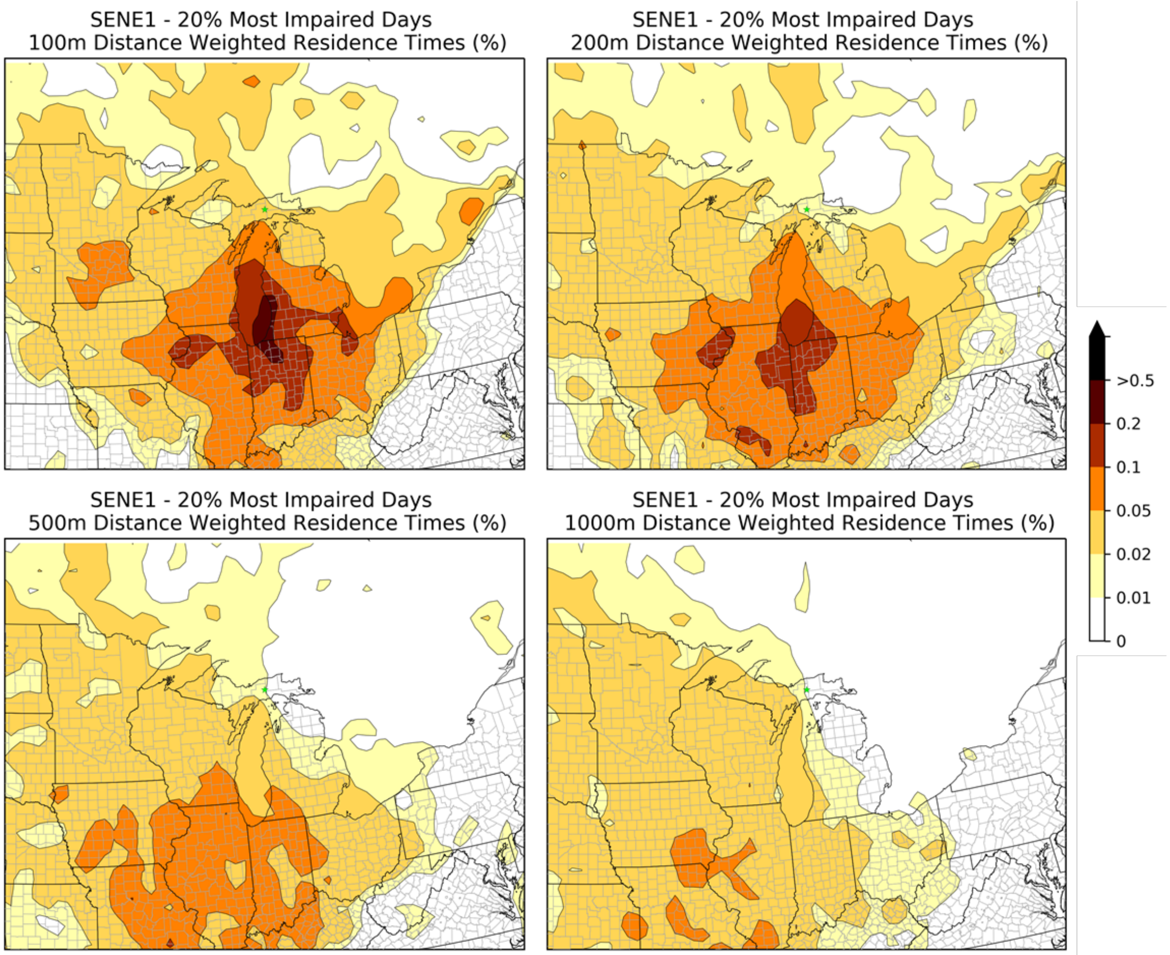


Figure S 2-4. Distance weighted residence times for air masses reaching the Seney National Wildlife Refuge monitor at a variety of heights on the 20% most impaired days for the years 2012 to 2016.

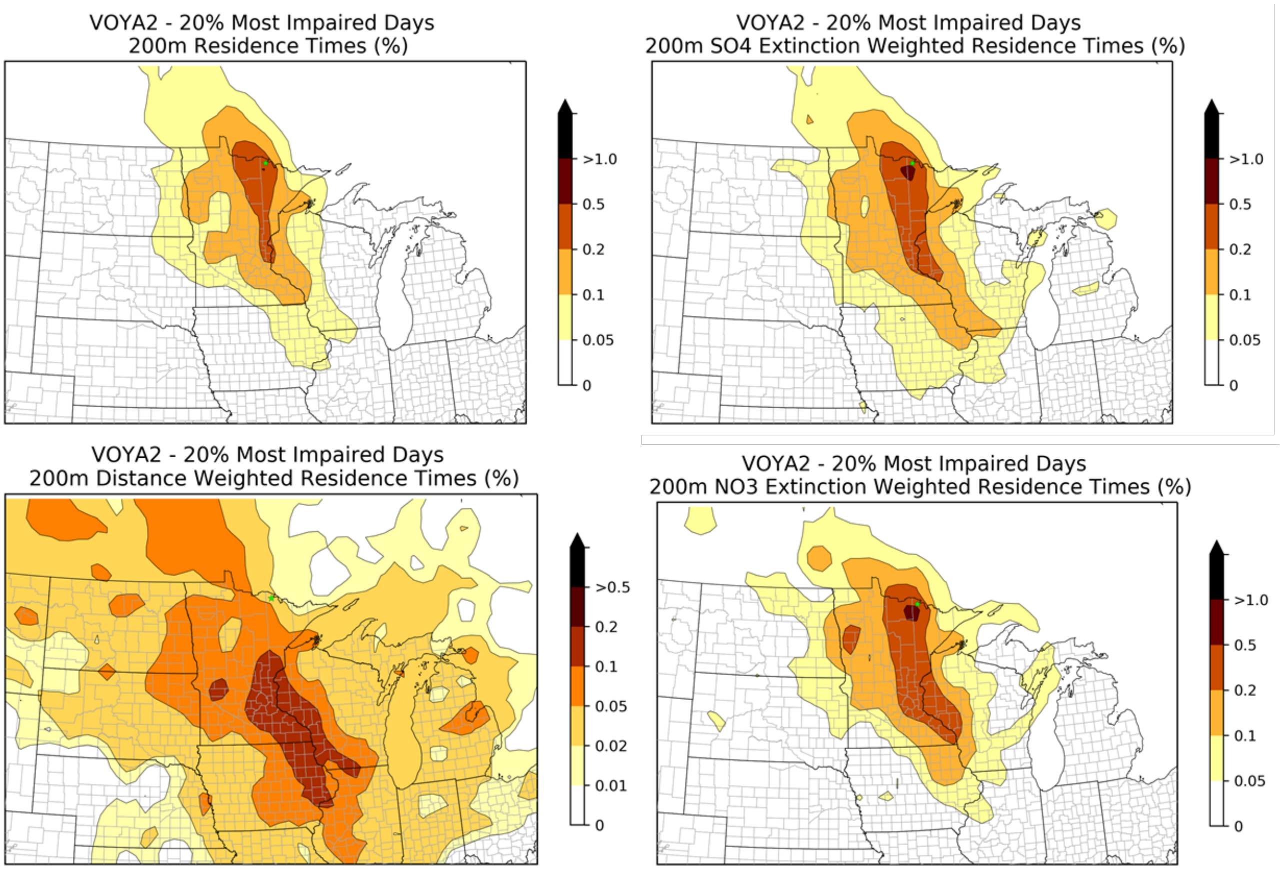


Figure S 2-5. Different measures of residence time for air masses reaching the Voyageurs National Park monitor.

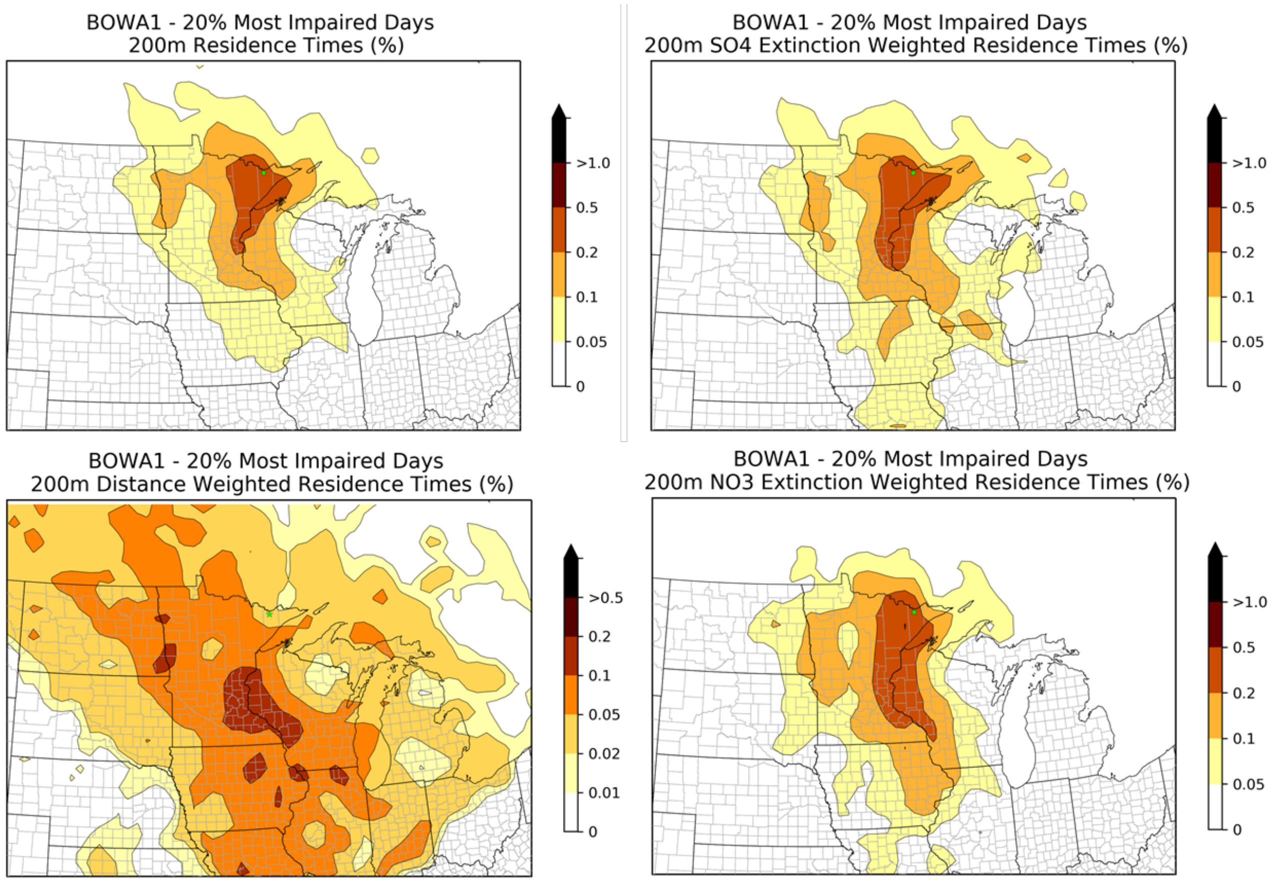


Figure S 2-6. Different measures of residence time for air masses reaching the Boundary Waters Canoe Area monitor.

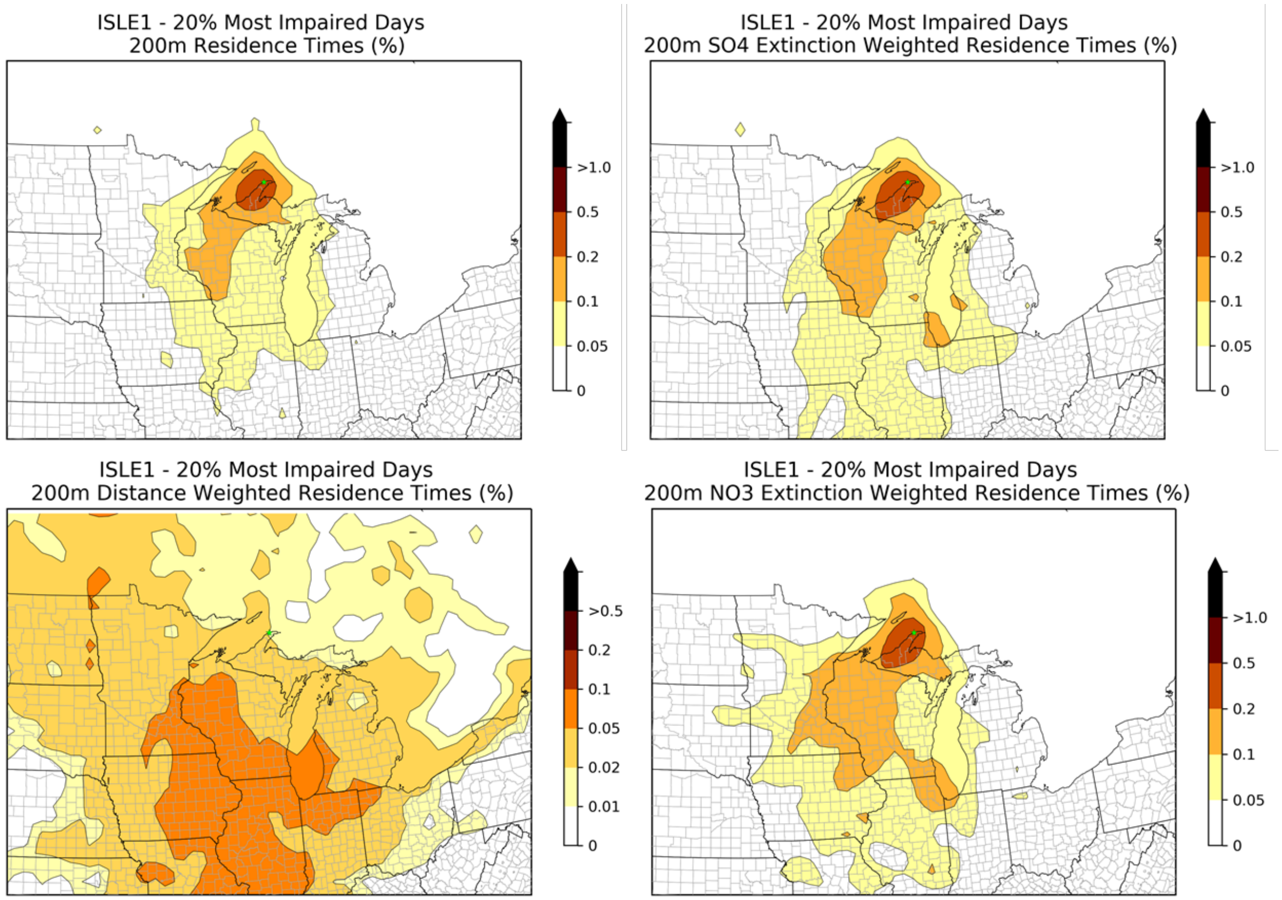


Figure S 2-7. Different measures of residence time for air masses reaching the Isle Royale National Park monitor.

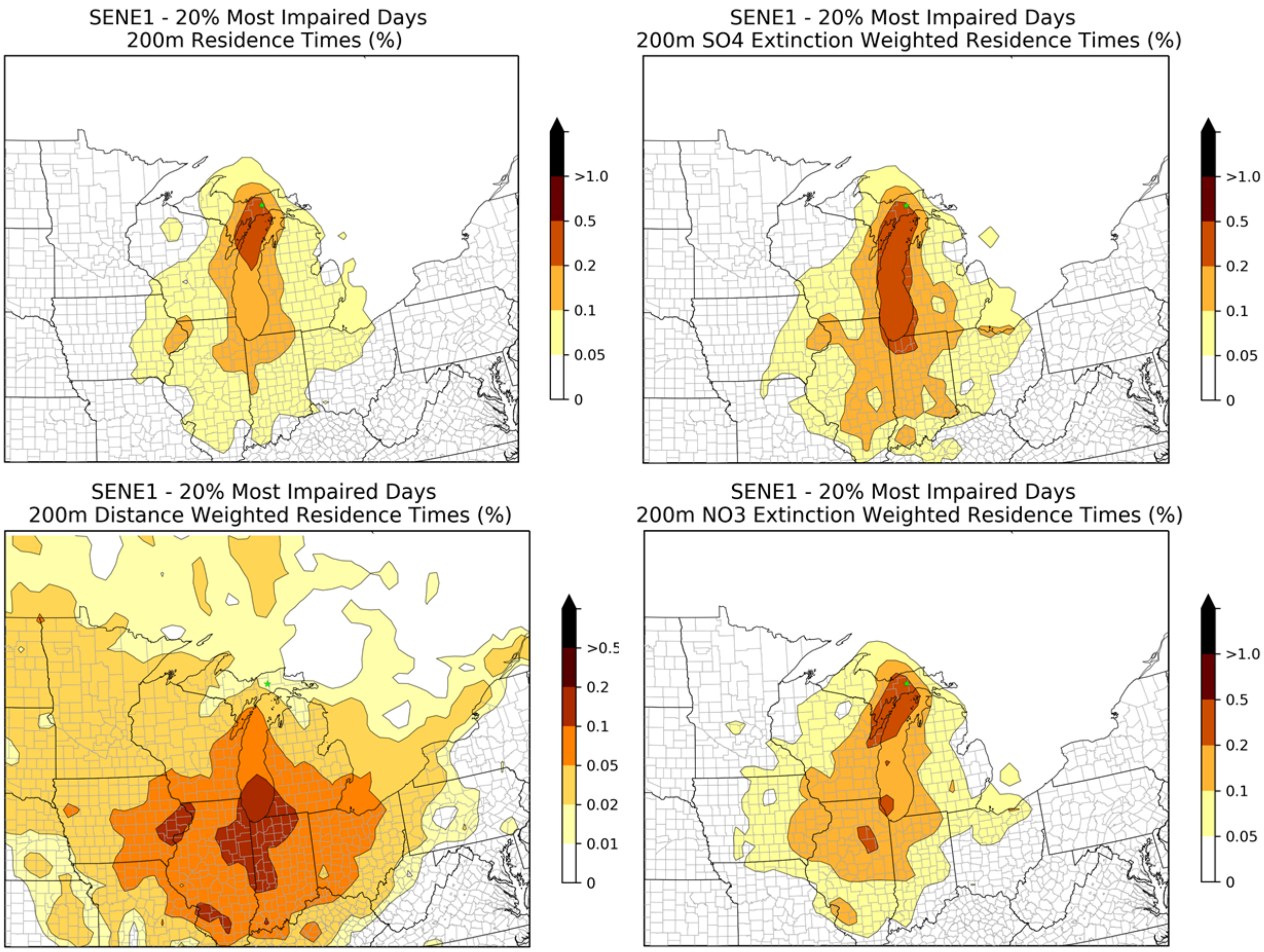


Figure S 2-8. Different measures of residence time for air masses reaching the Seney National Wildlife Area monitor.

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.

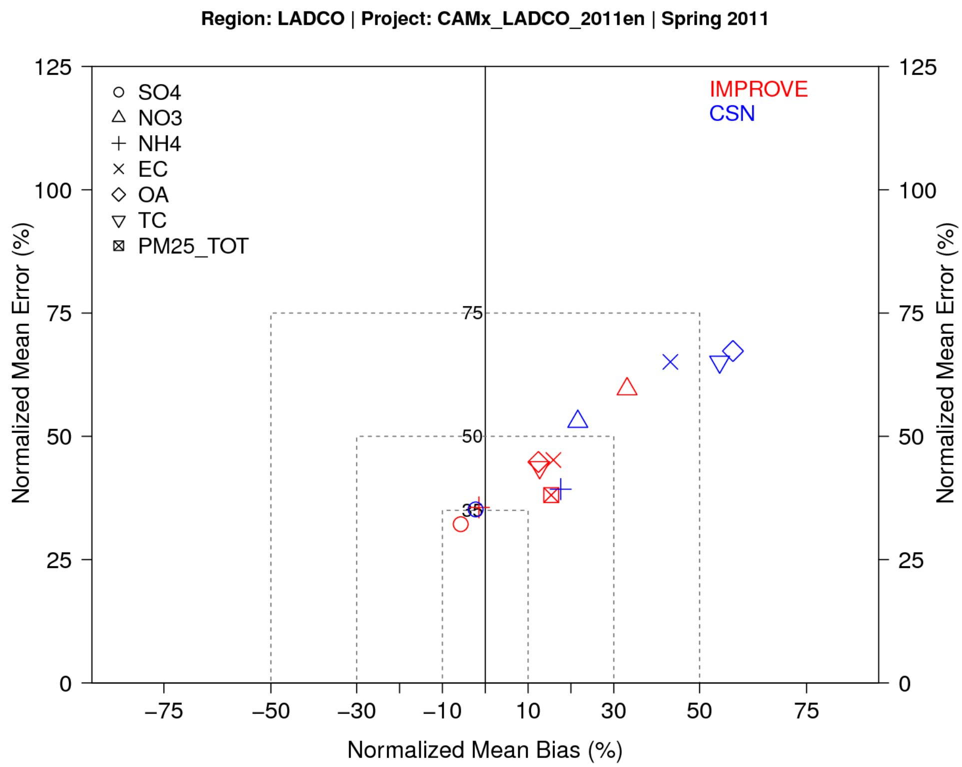


Figure S 5-1. Spring 2011 LADCO region $PM_{2.5}$ performance soccer plot

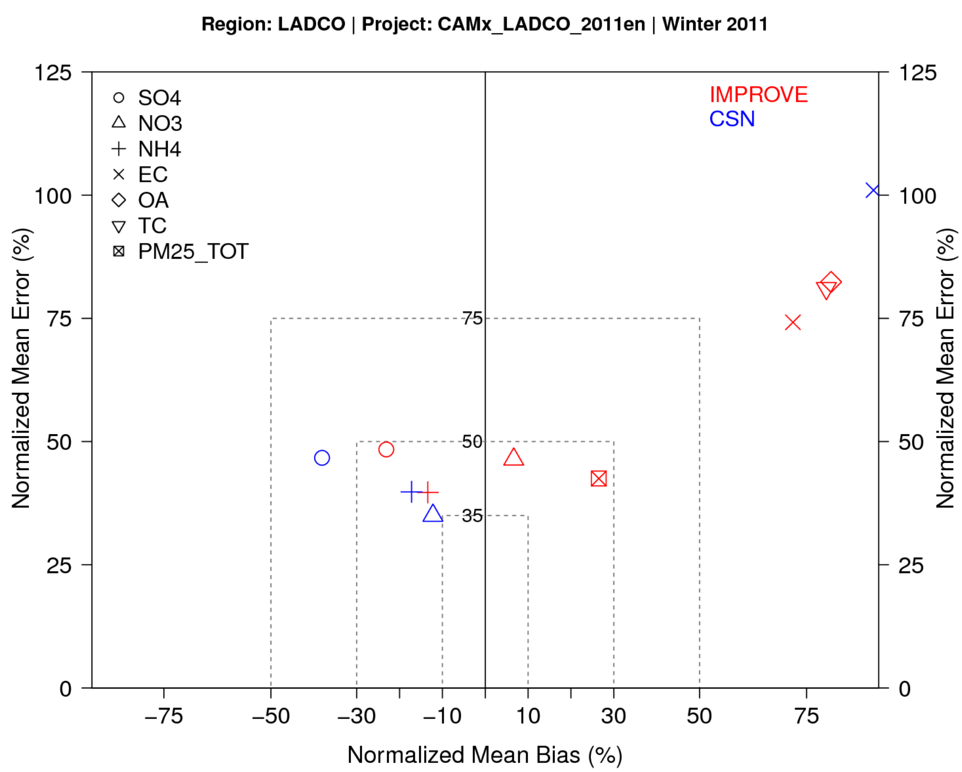


Figure S 5-2. Winter 2011 LADCO region $PM_{2.5}$ performance soccer plot

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.

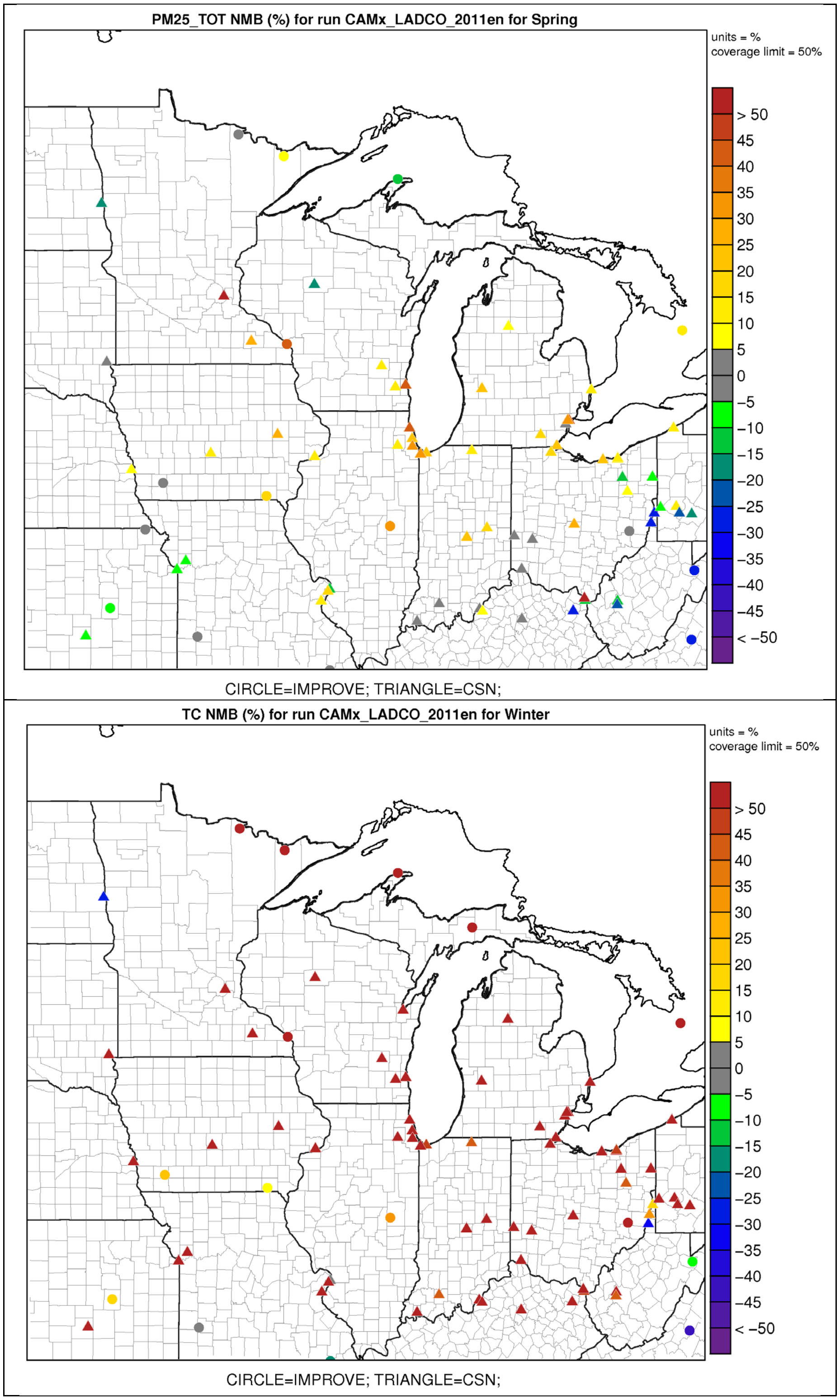


Figure S 5-3. Total $PM_{2.5}$ 2011 seasonal average NMB for the spring (top) and winter (bottom)

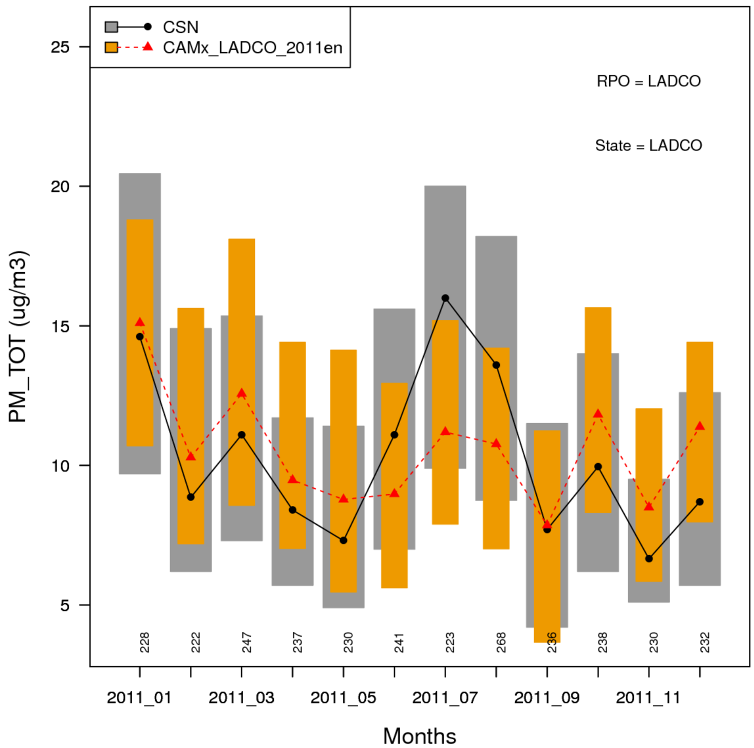


Figure S 5-4. Monthly 2011 $PM_{2.5}$ boxplot of CSN locations in the LADCO region

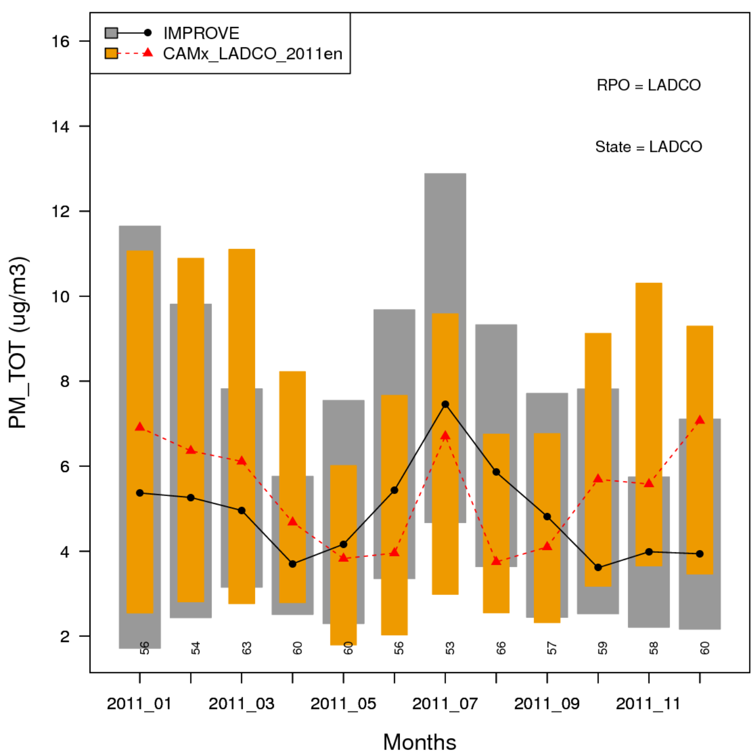


Figure S 5-5. Monthly 2011 $PM_{2.5}$ boxplot of IMPROVE locations in the LADCO region

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%).

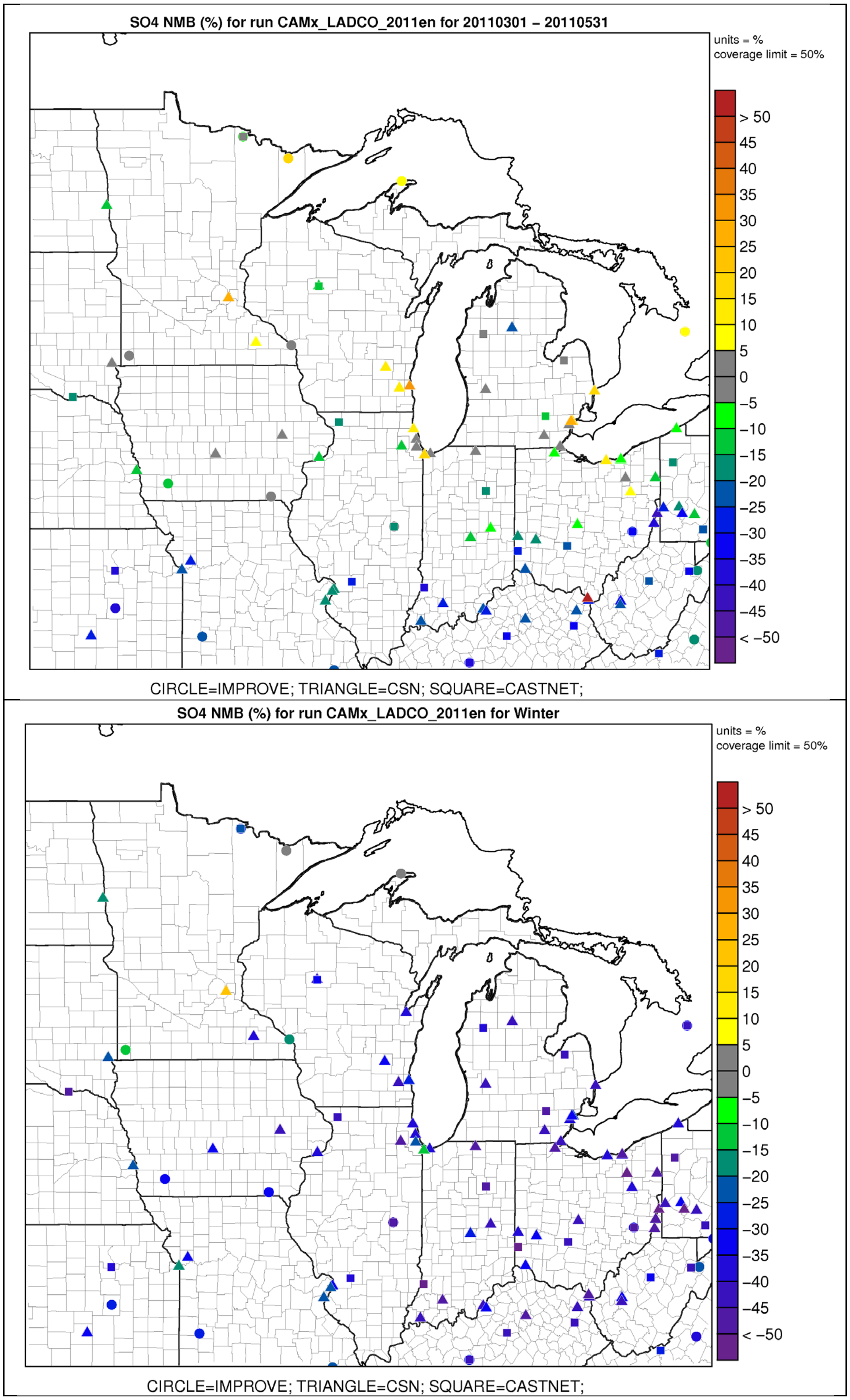


Figure S 5-6. Sulfate 2011 seasonal average NMB for the spring (top) and winter (bottom)

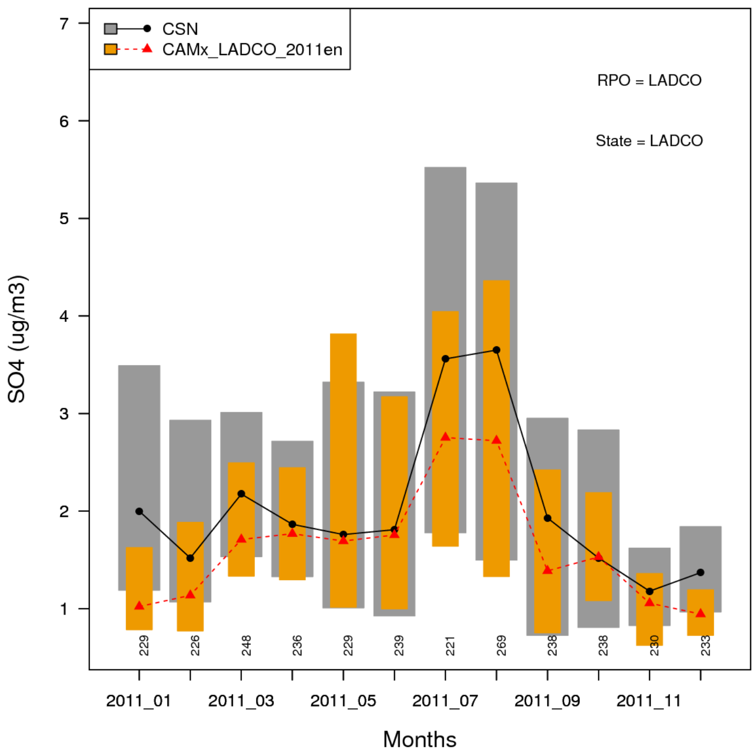


Figure S 5-7. Monthly SO_4 boxplot of CSN locations in the LADCO region

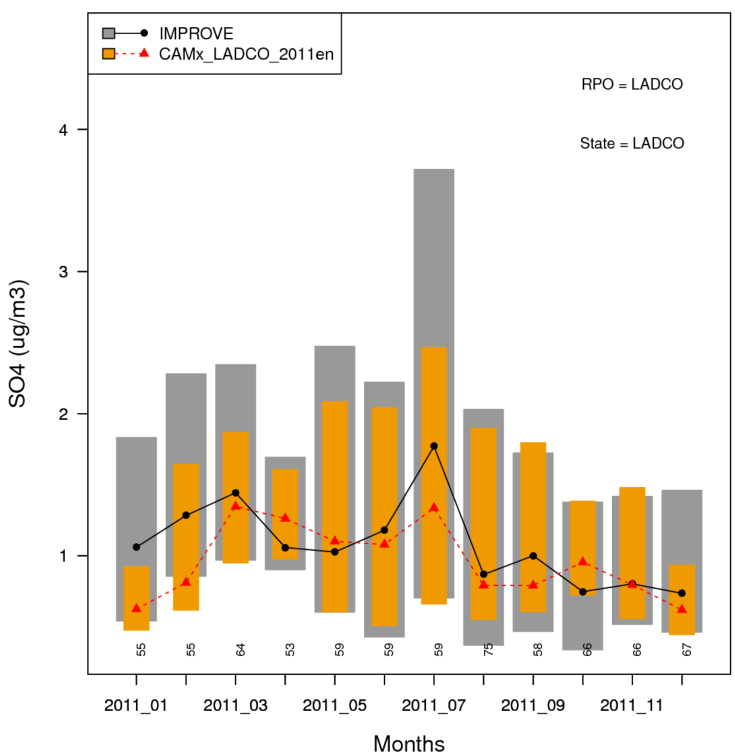


Figure S 5-8. Monthly SO_4 boxplot of IMPROVE locations in the LADCO region

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%).

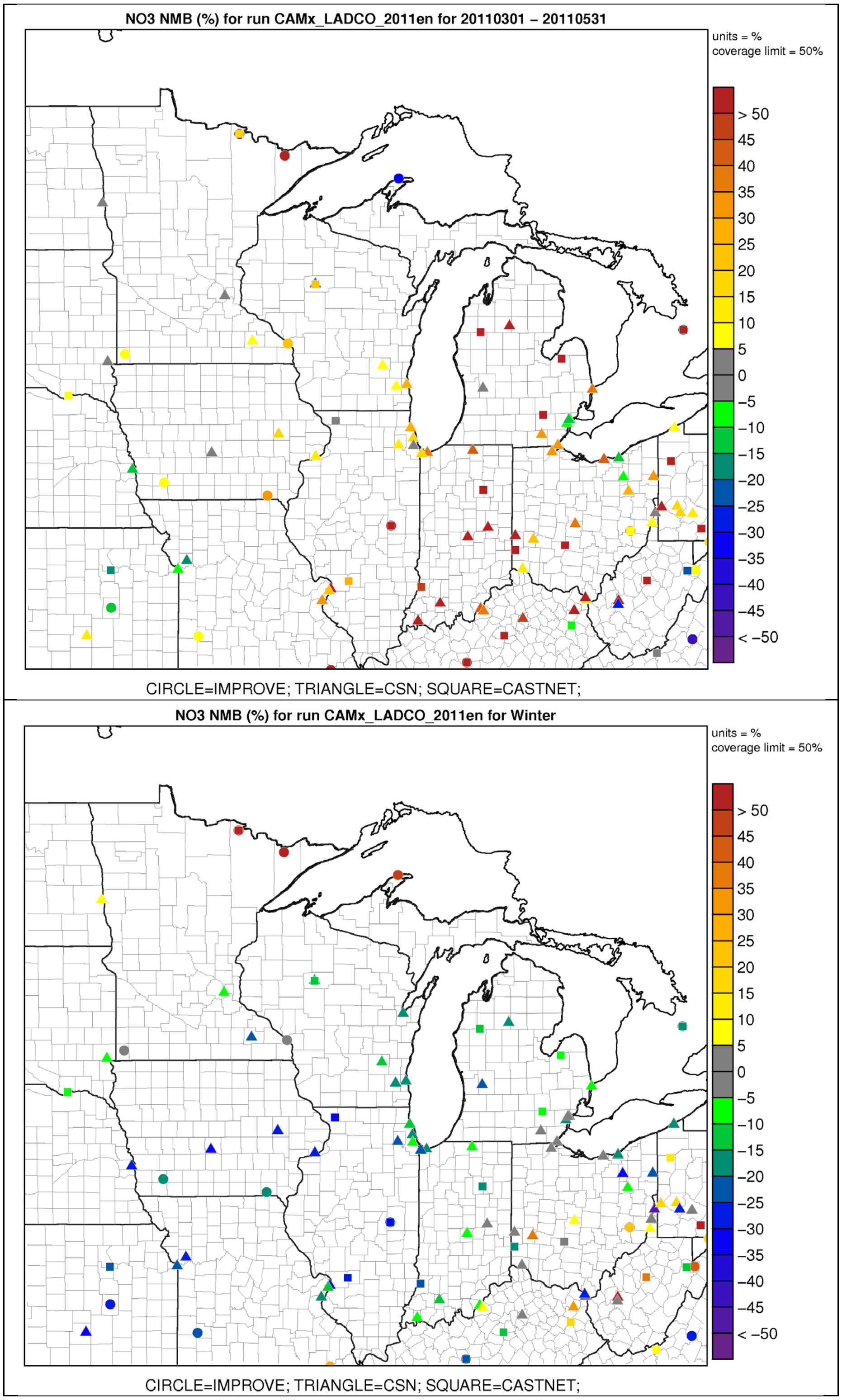


Figure S 5-9. Nitrate 2011 seasonal average NMB for the spring (top) and winter (bottom)

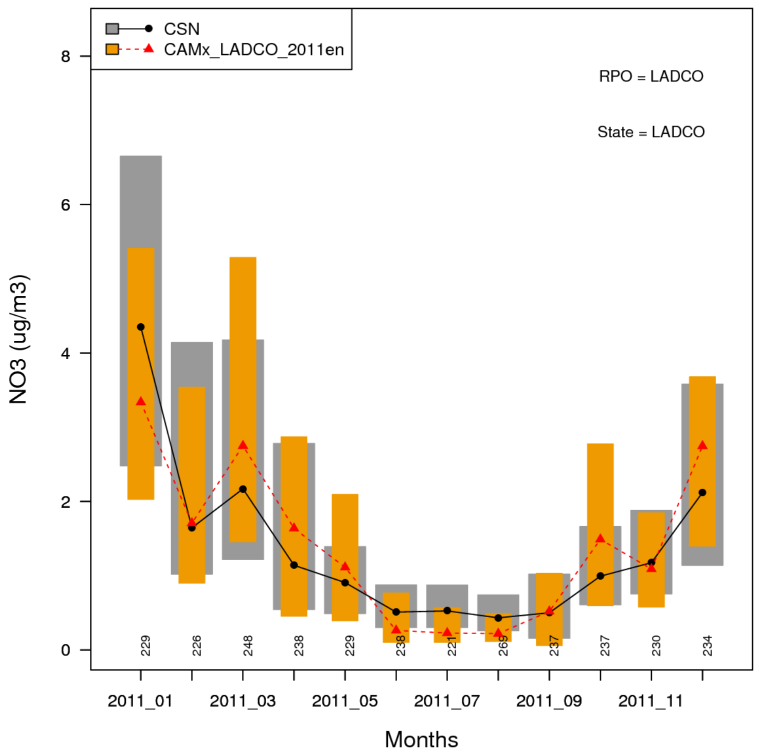


Figure S 5-10. Monthly 2011 NO_3 boxplot of CSN locations in the LADCO region

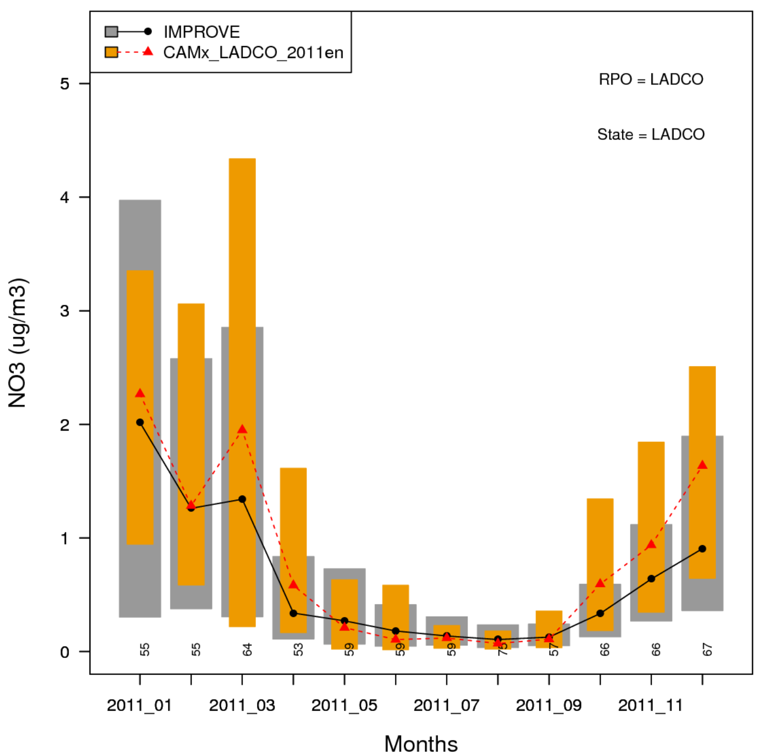


Figure S 5-11. Monthly 2011 NO_3 boxplot of IMPROVE locations in the LADCO region

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.

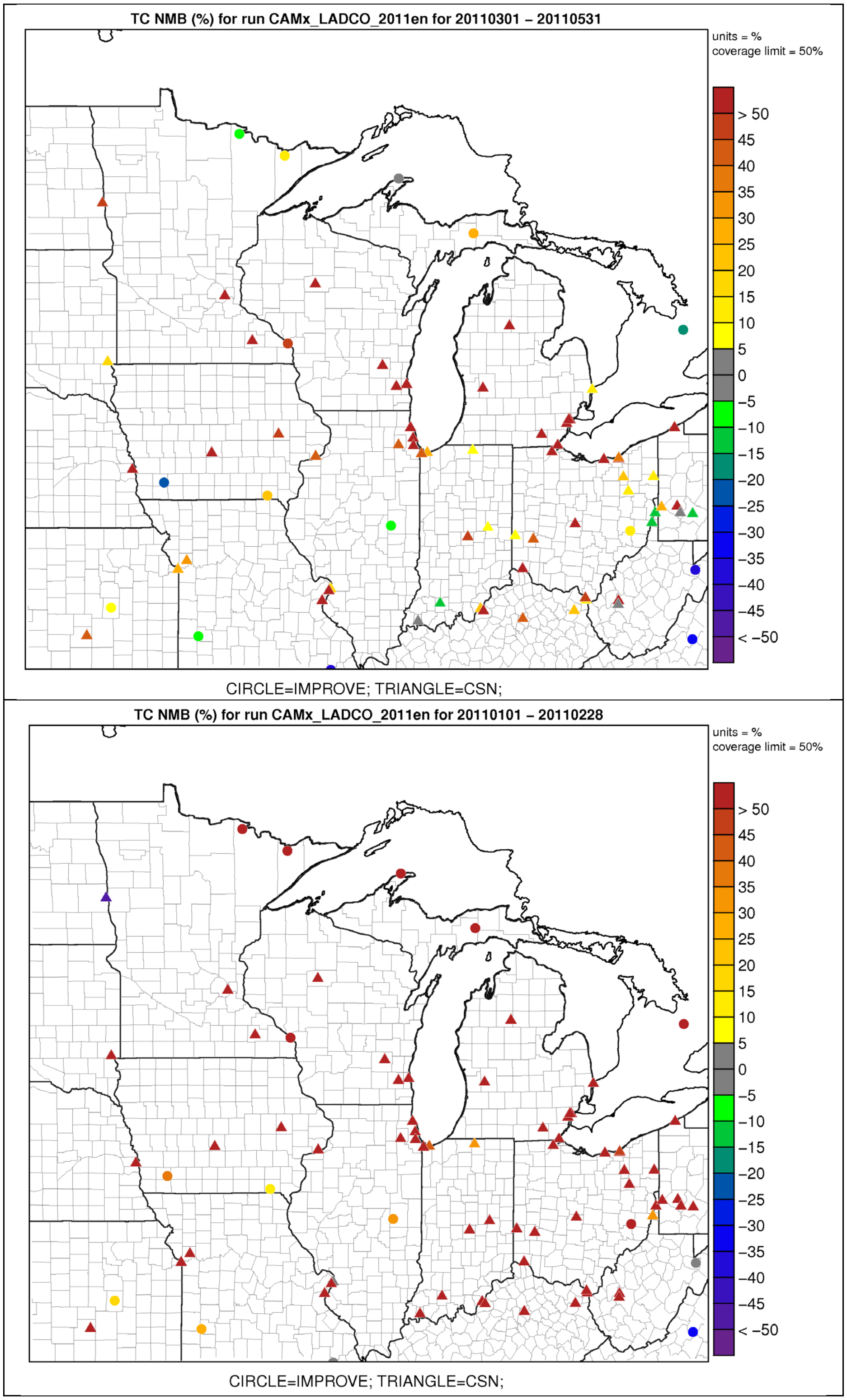


Figure S 5-12. Carbonaceous aerosol 2011 seasonal average NMB for the spring (top) and winter (bottom)

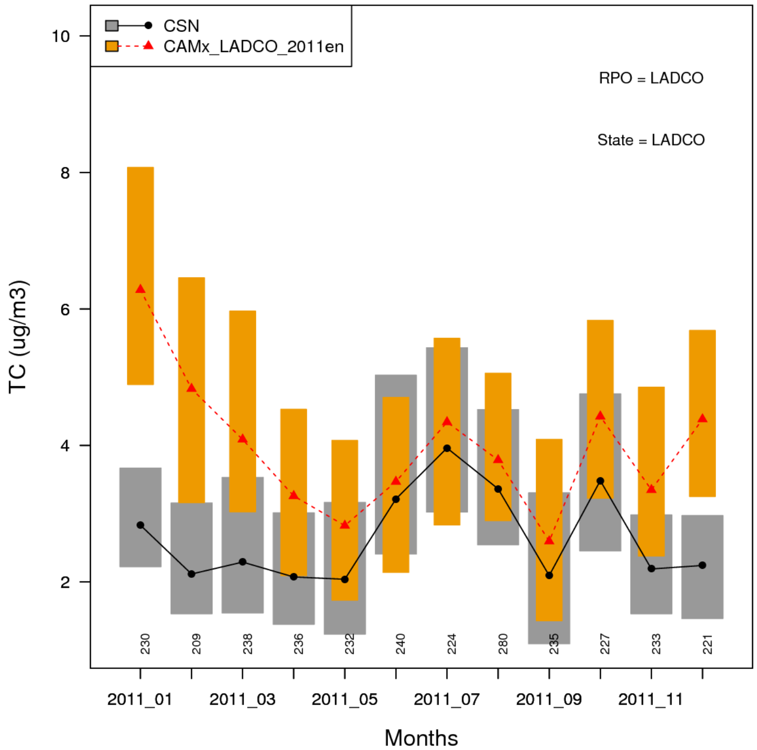


Figure S 5-13. Monthly 2011 TC boxplot of CSN locations in the LADCO region

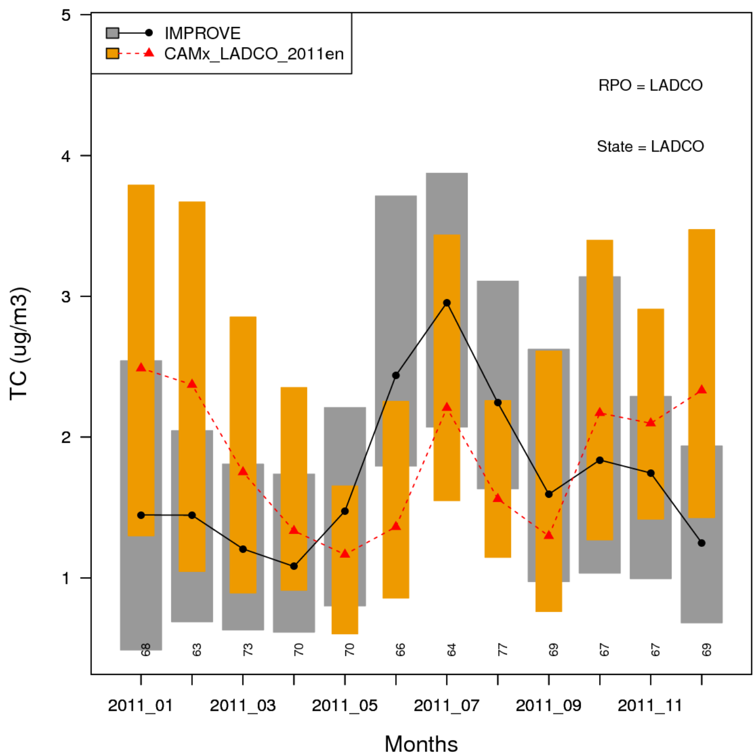


Figure S 5-14. Monthly 2011 TC boxplot of IMPROVE locations in the LADCO region

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/m^3)	CAMx (μg/m^3)	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.

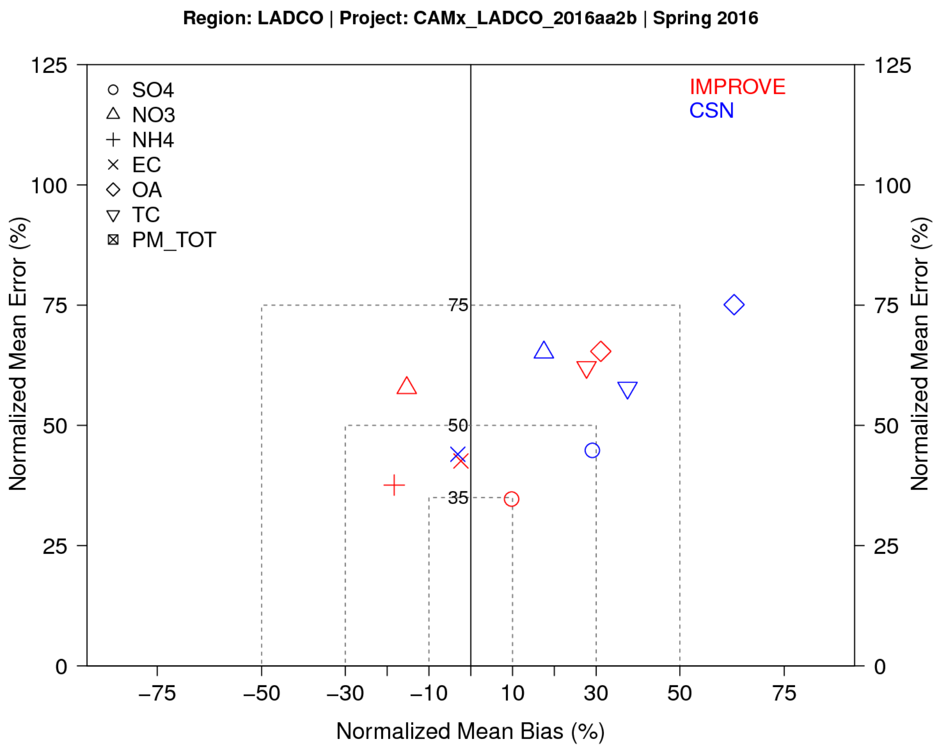


Figure S 5-15. Spring 2016 LADCO region PM performance soccer plot

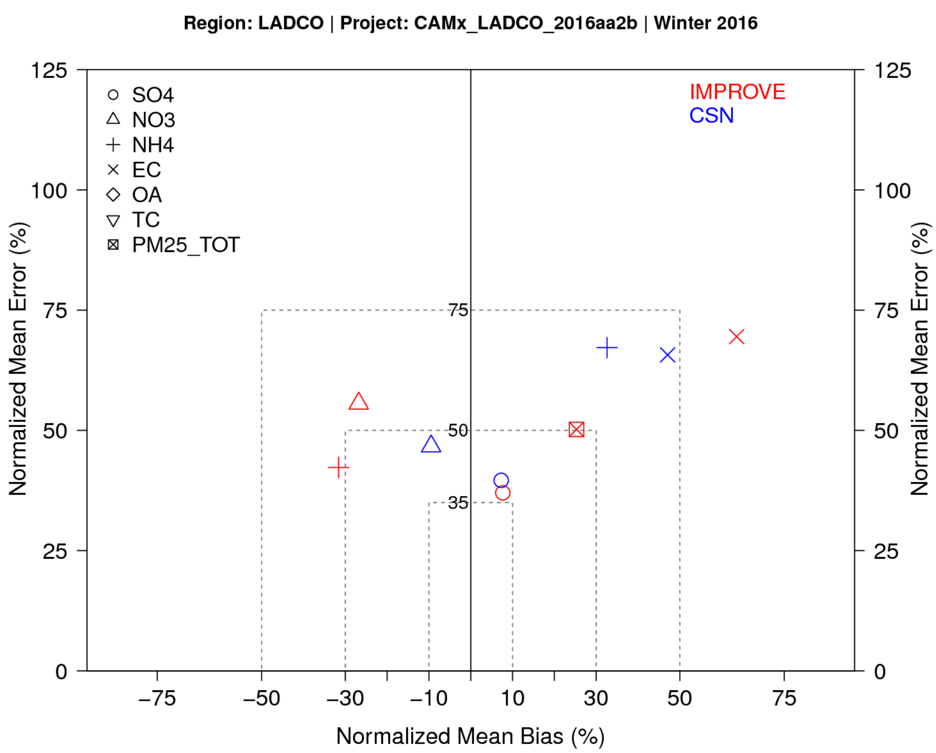


Figure S 5-16. Winter 2016 LADCO region PM performance soccer plot

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 .

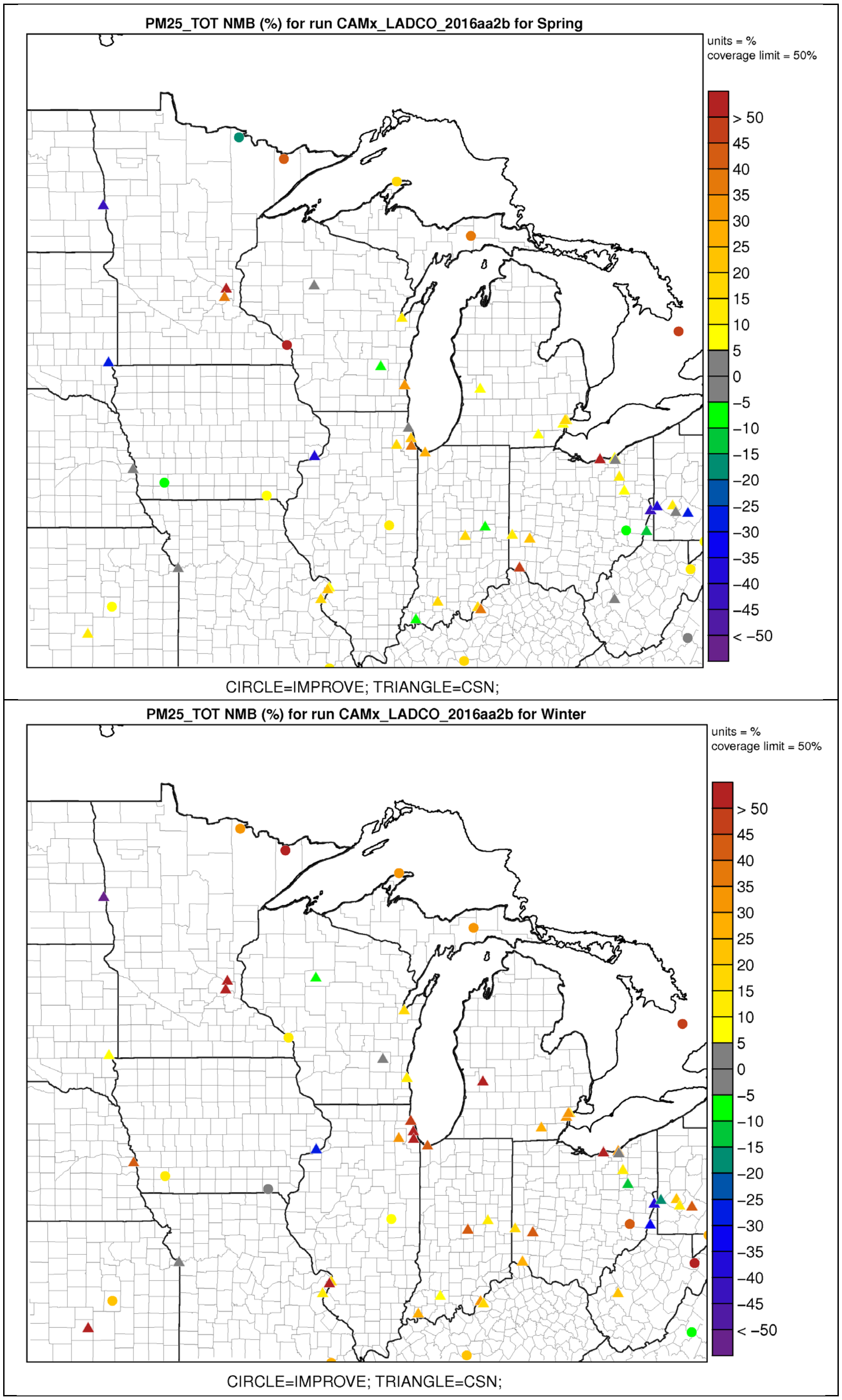


Figure S 5-17. Total $PM_{2.5}$ 2016 seasonal average NMB for the spring (top) and winter (bottom)

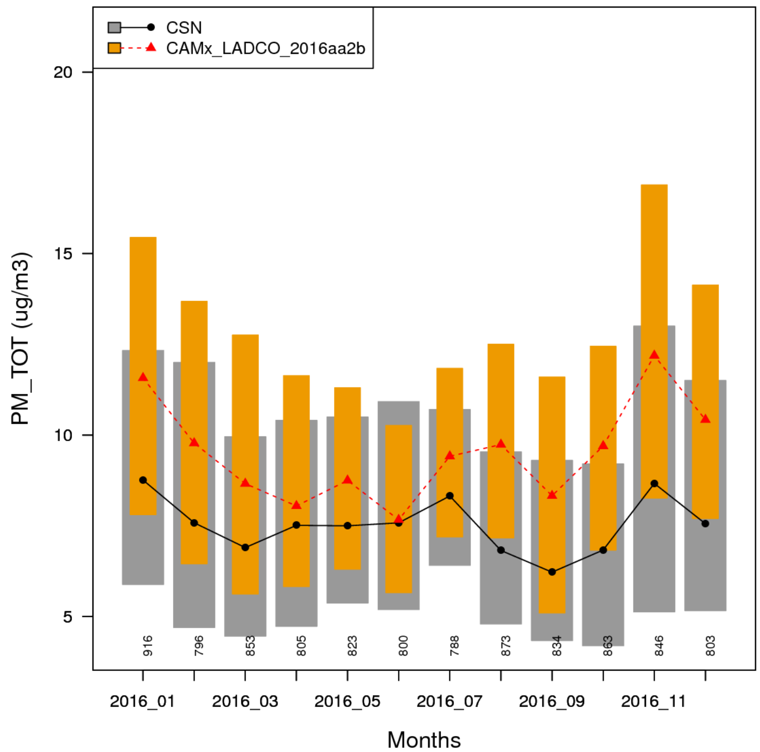


Figure S 5-18. Monthly 2016 $PM_{2.5}$ boxplot of CSN locations in the LADCO region

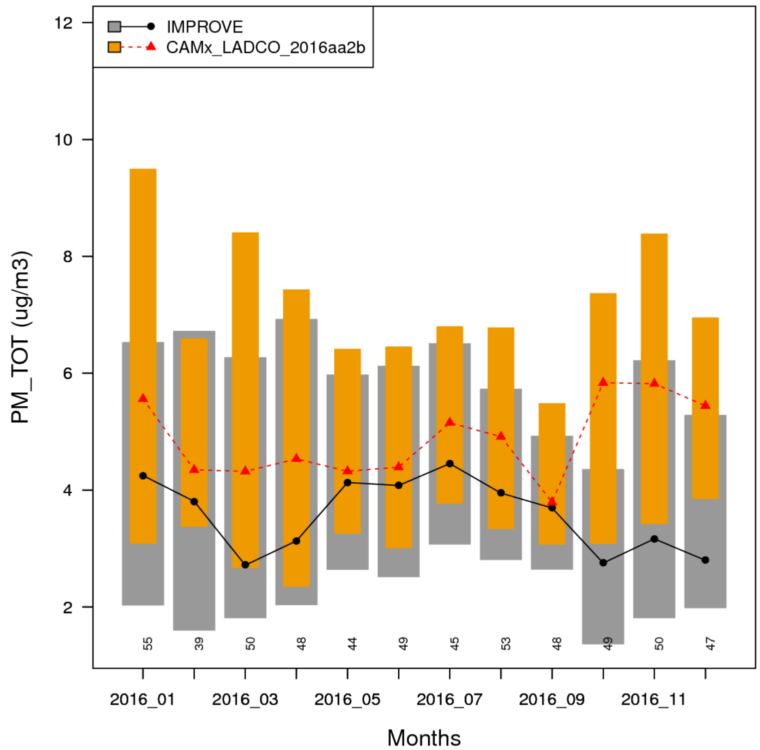


Figure S 5-19. Monthly 2016 $PM_{2.5}$ boxplot of IMPROVE locations in the LADCO region

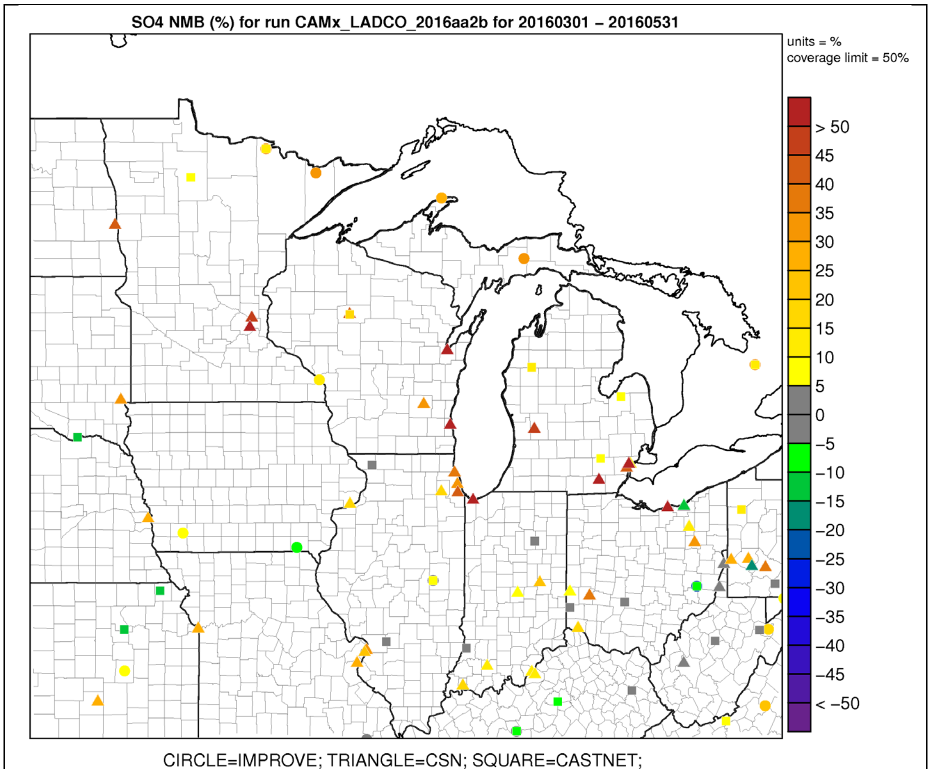
S5.2.2 Sulfate

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%).



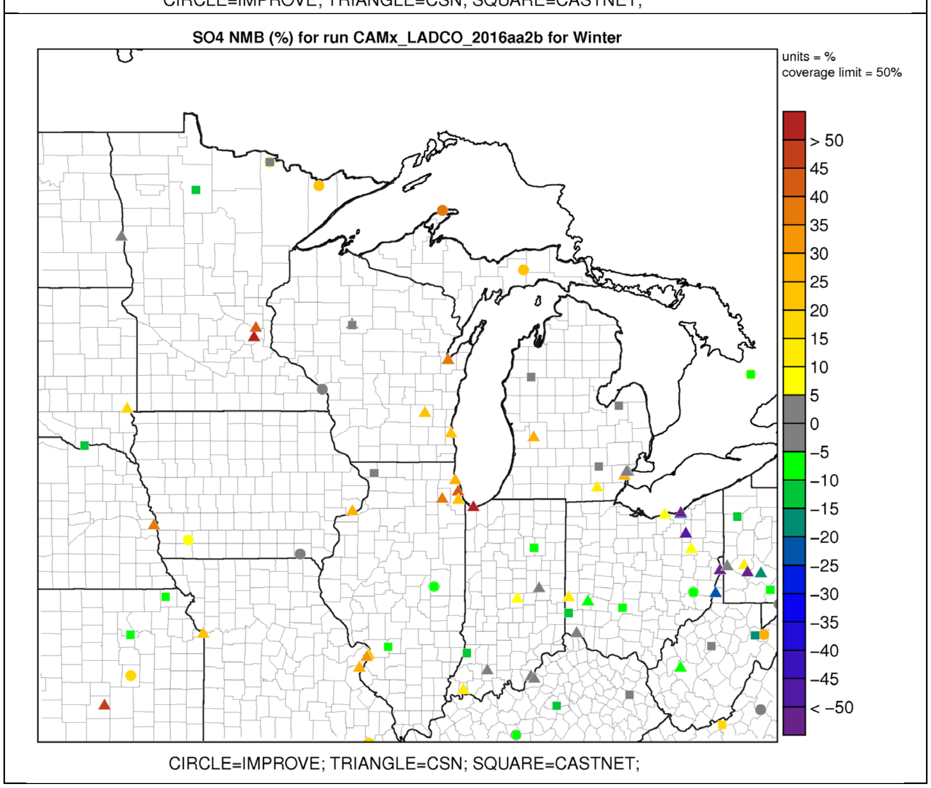


Figure S 5-20. Sulfate 2016 seasonal average NMB for the spring (top) and winter (bottom)

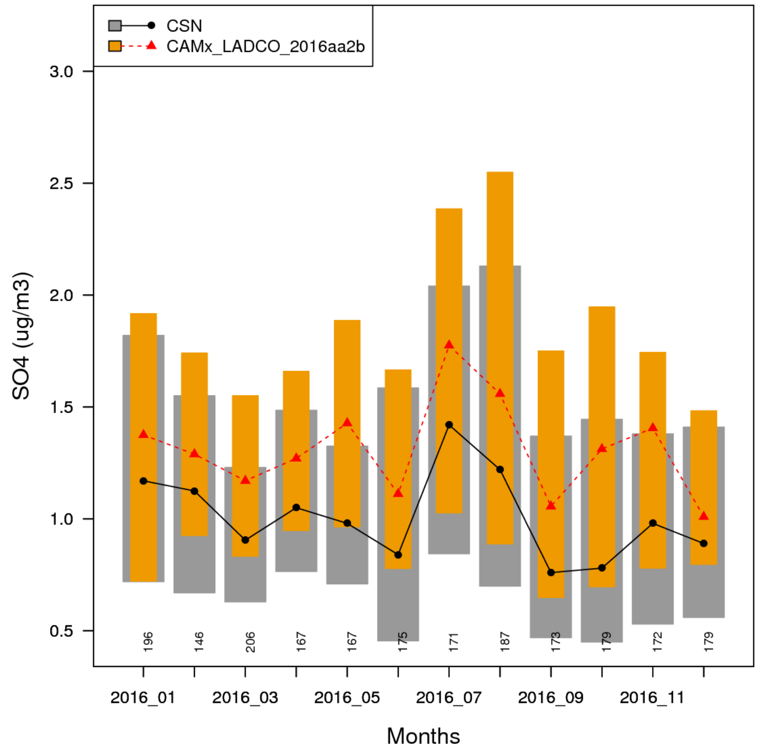


Figure S 5-21. Monthly 2016 SO_4 boxplot of CSN locations in the LADCO region

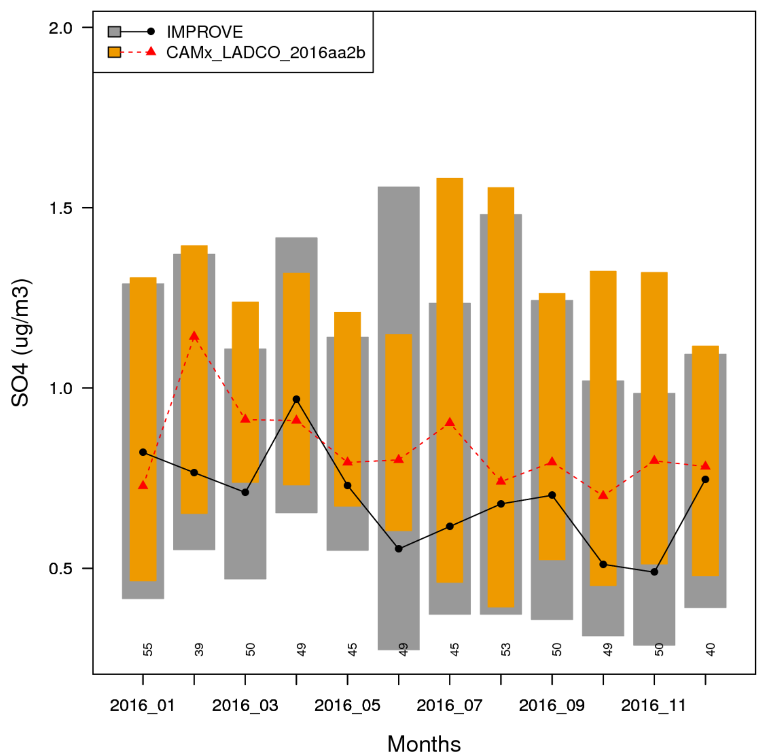


Figure S 5-22. Monthly 2016 SO_4 boxplot of IMPROVE locations in the LADCO region

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.

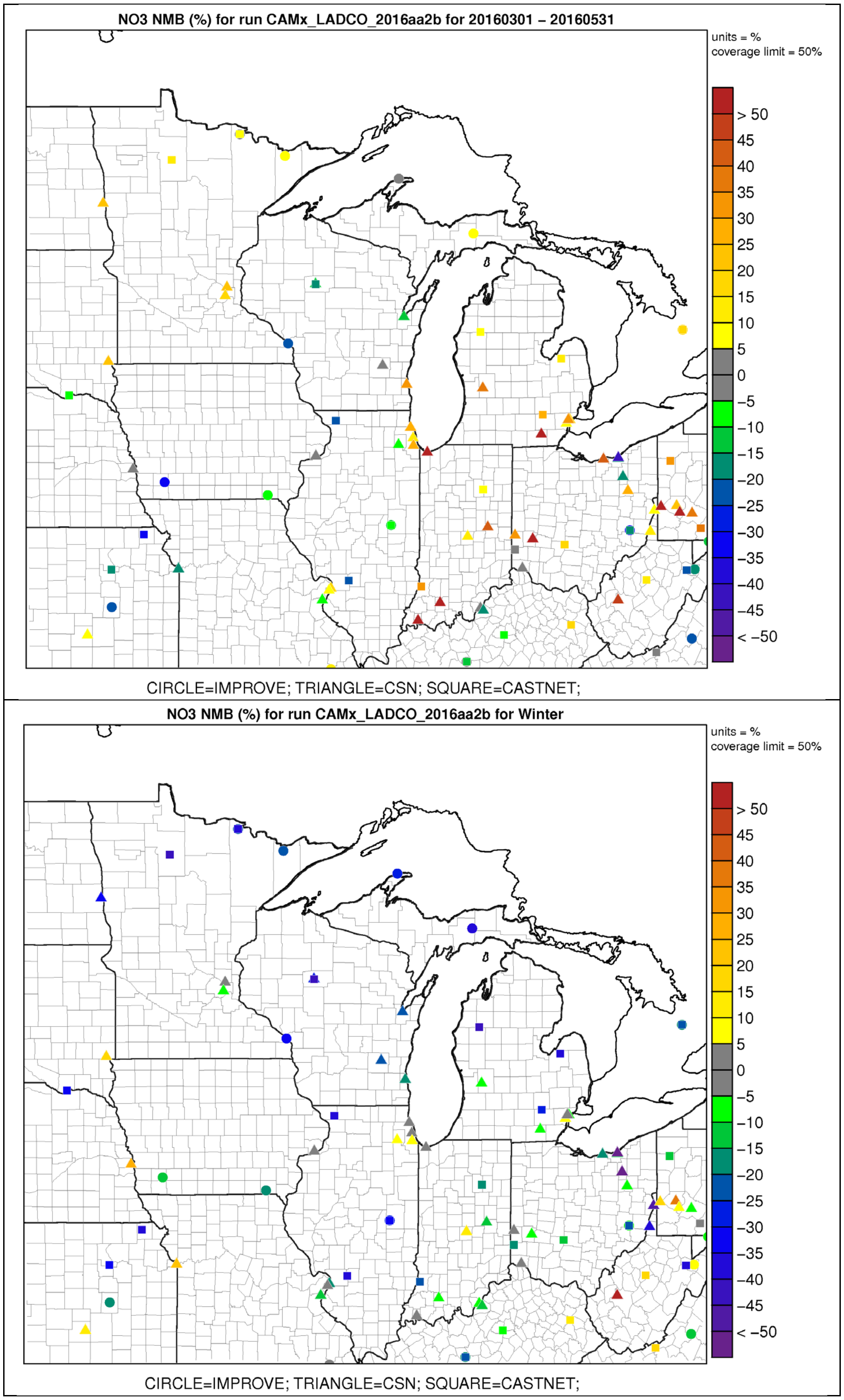


Figure S 5-23. Nitrate 2016 seasonal average NMB for the spring (top) and winter (bottom)

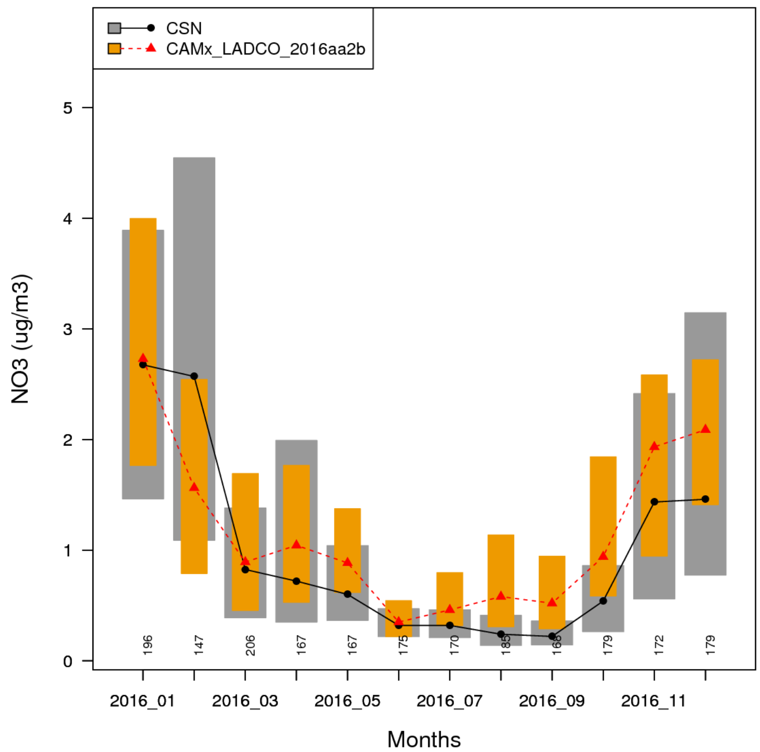


Figure S 5-24. Monthly 2016 NO_3 boxplot of CSN locations in the LADCO region

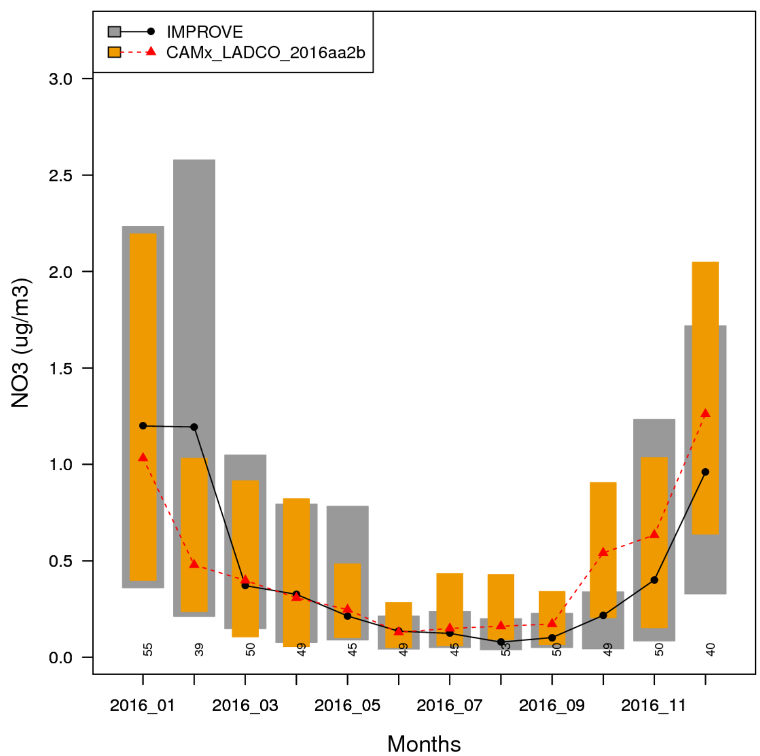


Figure S 5-25. Monthly 2016 NO_3 boxplot of IMPROVE locations in the LADCO region

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.

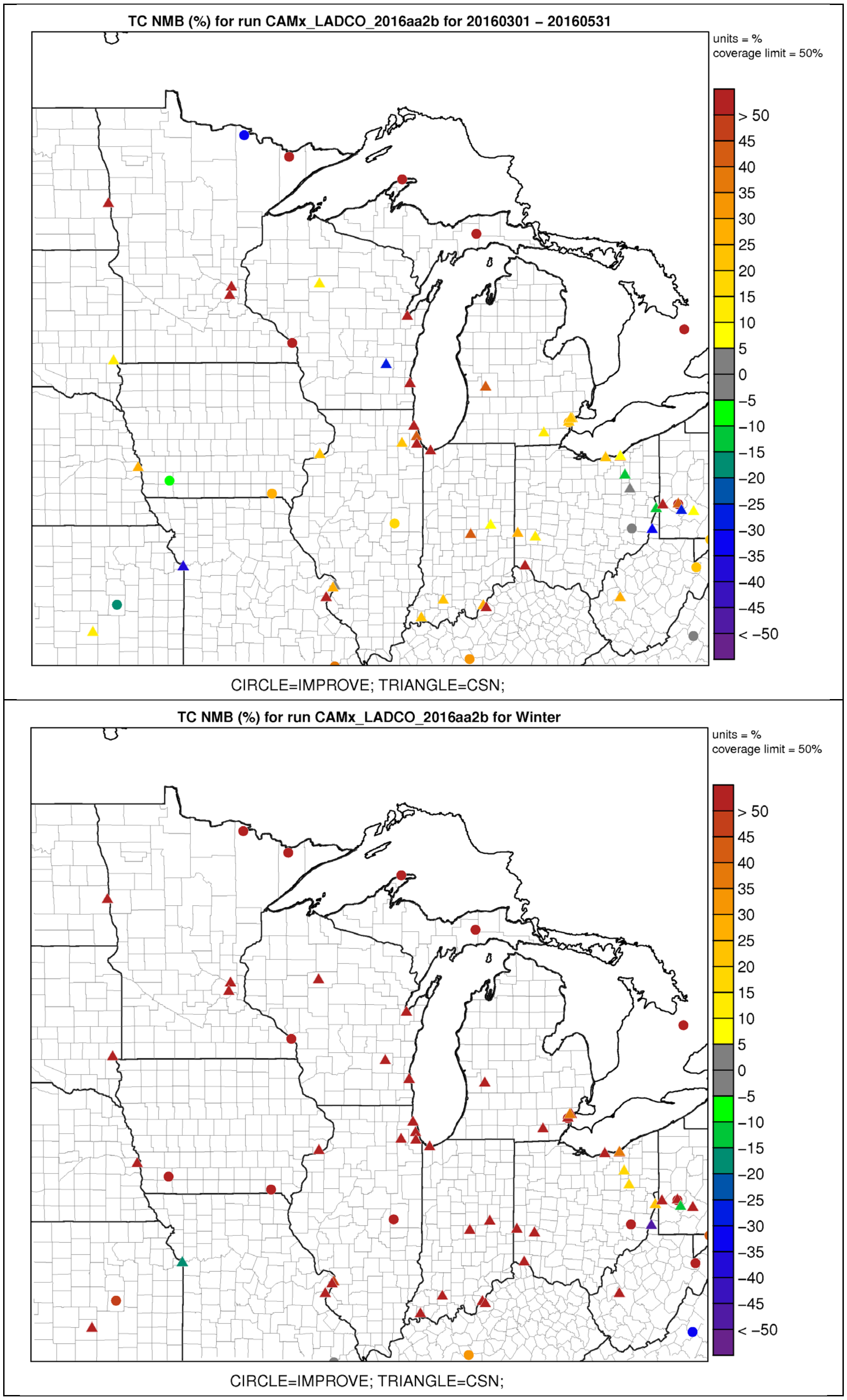


Figure S 5-26. Carbonaceous aerosol 2016 seasonal average NMB for the spring (top) and winter (bottom)

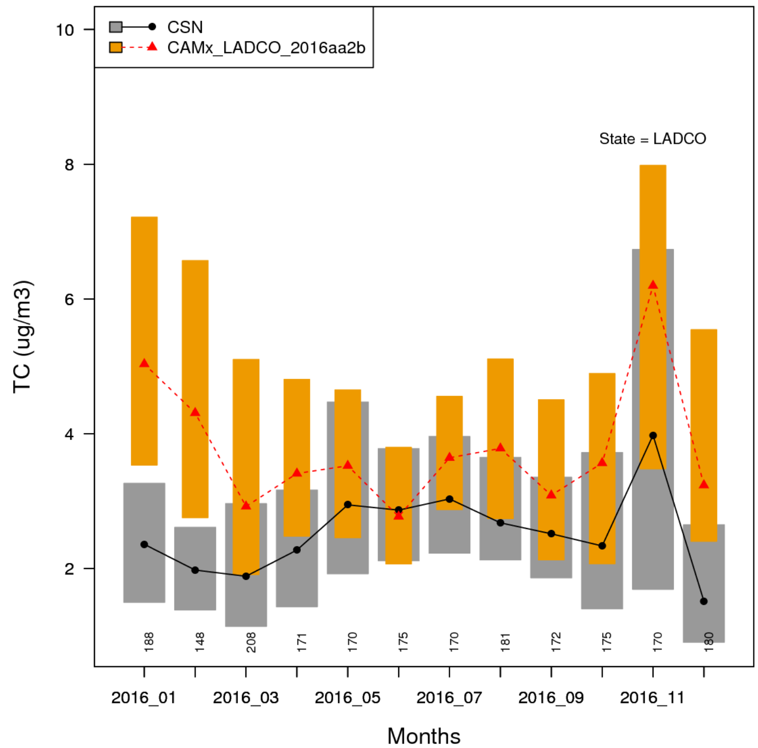


Figure S 5-27. Monthly 2016 TC boxplot of CSN locations in the LADCO region

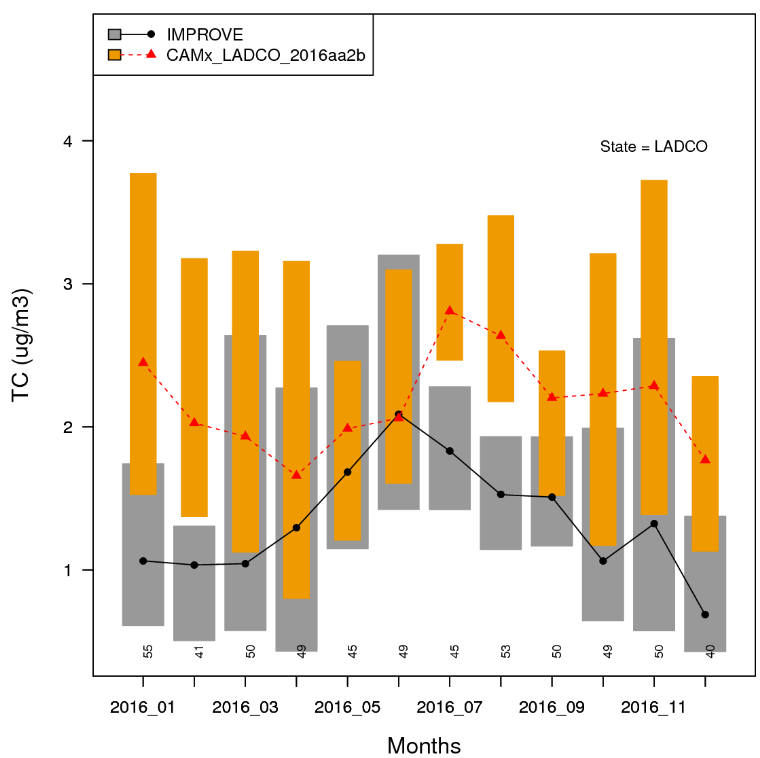


Figure S 5-28. Monthly 2016 TC boxplot of IMPROVE locations in the LADCO region

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 (µg/m³)	CAMx (µg/m³)	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 (µg/m³)	CAMx (µg/m³)	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 ($\mu g/m^3$)	CAMx ($\mu g/m^3$)	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