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

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

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

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

4 Emissions Summaries

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

4.1 2011 Modeling Platform

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

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

4.1.1 2011 Emissions Summary

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

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

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

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

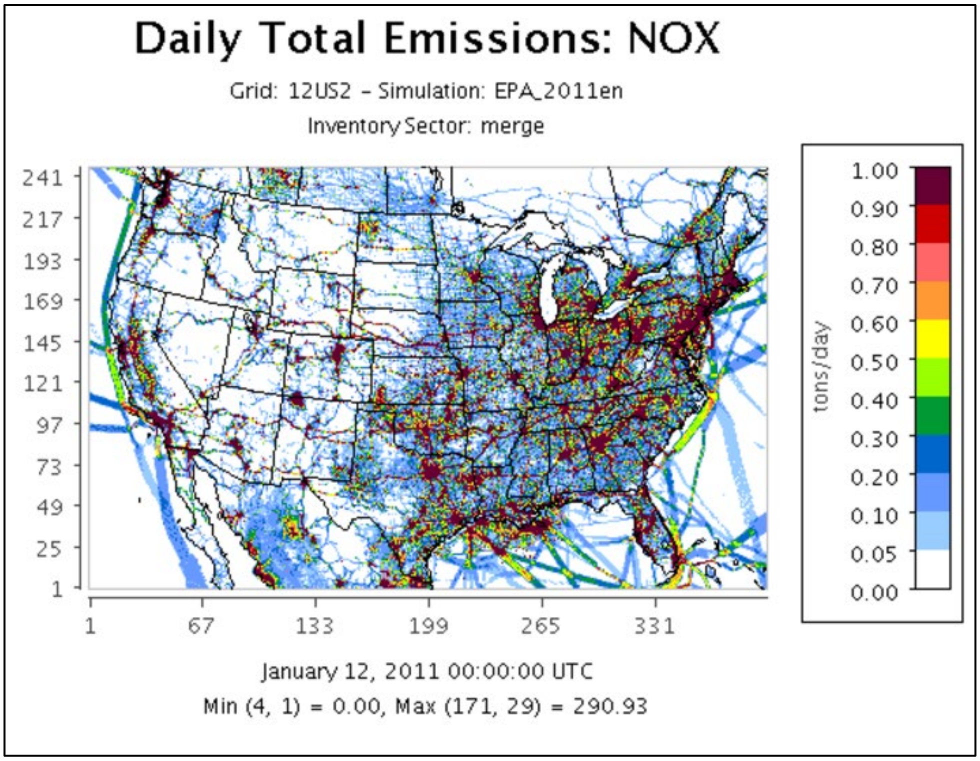

Figure 4-1. Daily total gridded 2011 NOx emissions for an example weekday (tons/day)

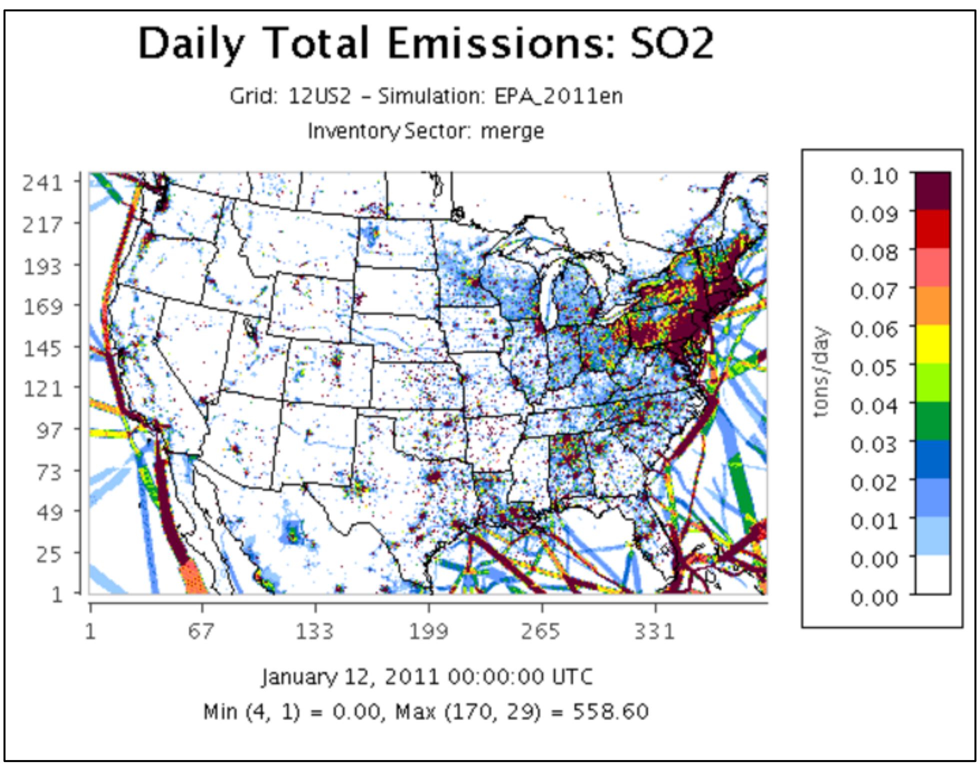

Figure 4-2. Daily total gridded 2011 SO_2 emissions for an example weekday (tons/day)

Table 4-2. 2011 annual emissions totals

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

4.1.2 2028_{2011} Emissions Summary

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

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

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

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

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

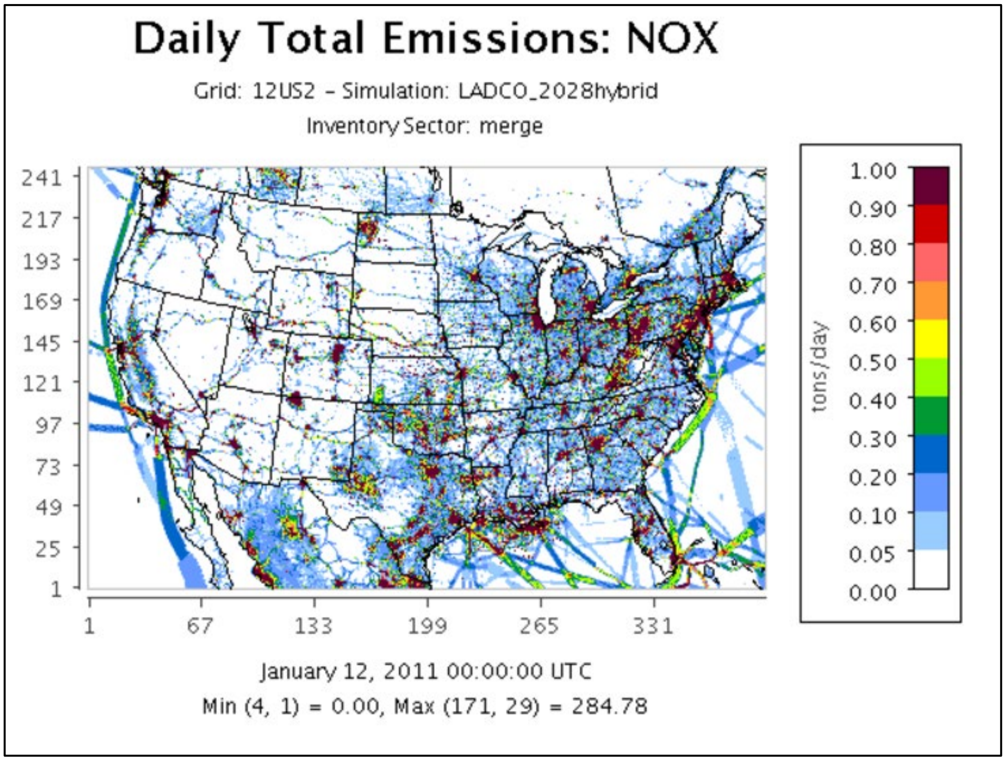

Figure 4-3. Daily total gridded 2028_{2011} NOx emissions for an example weekday (tons/day)

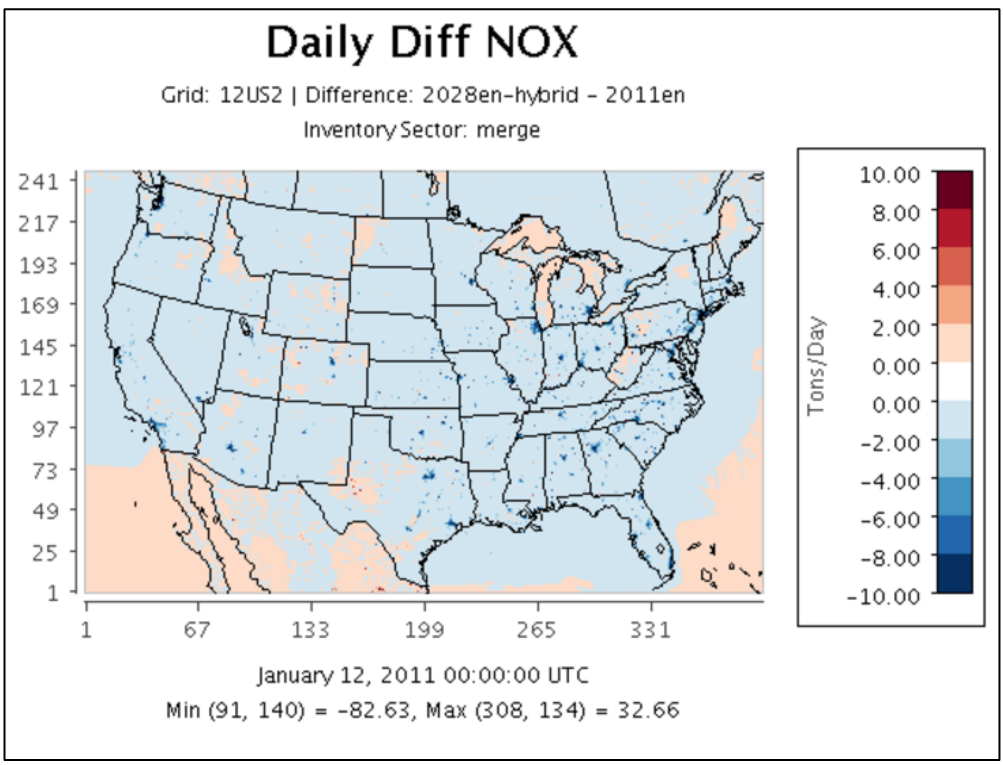

Figure 4-4. Difference (2028-2011) in daily total gridded NOx emissions for an example weekday (tons/day)

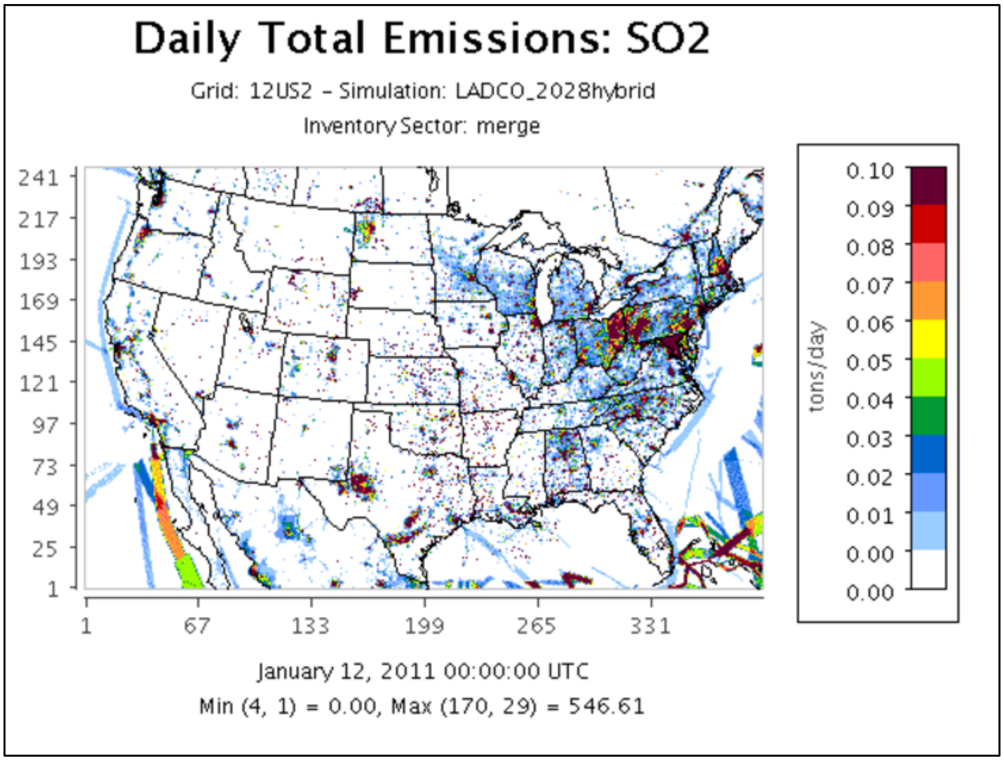

Figure 4-5. Daily total gridded 2028$_{2011}$ SO_2 emissions for an example weekday (tons/day)

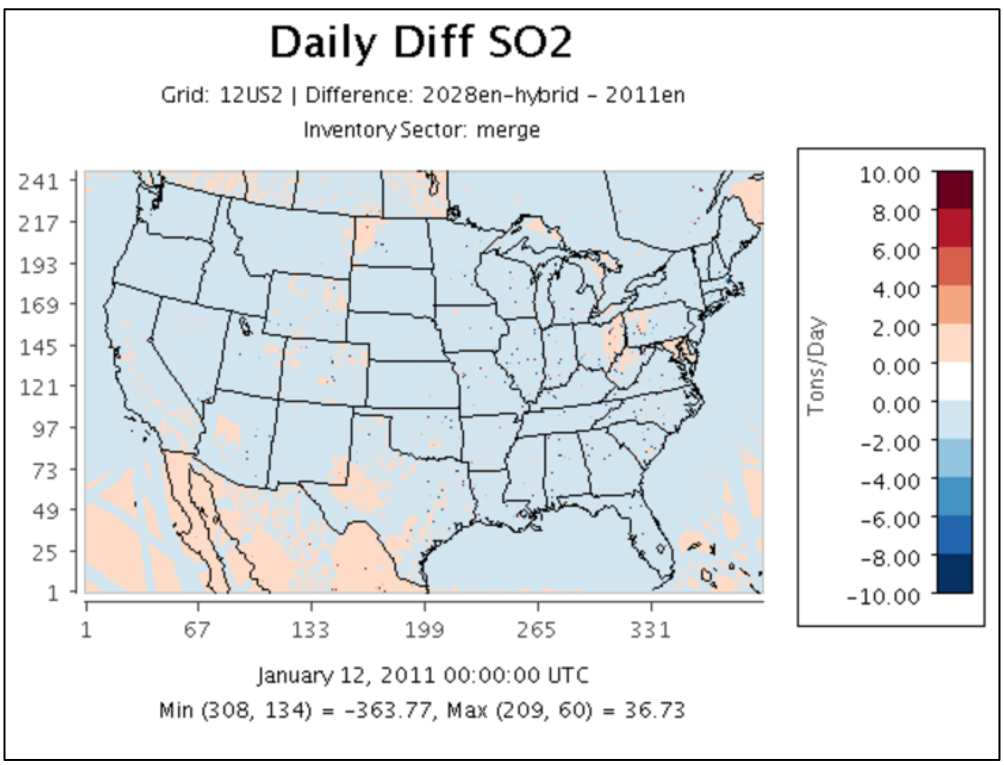

Figure 4-6. Difference (2028-2011) in daily total gridded SO_2 emissions for an example weekday (tons/day)

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

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

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

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

4.2 2016 Modeling Platform

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

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

4.2.1 2016 Emissions Summary

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

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

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

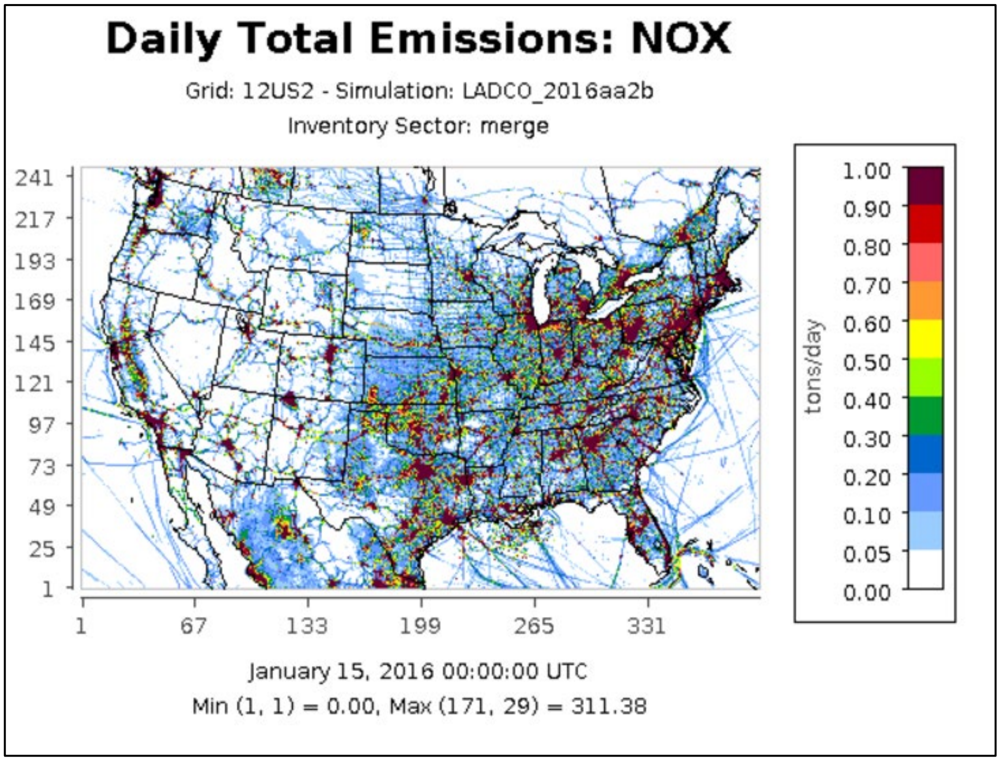

Figure 4-7. Daily total gridded 2016 NOx emissions for an example weekday (tons/day)

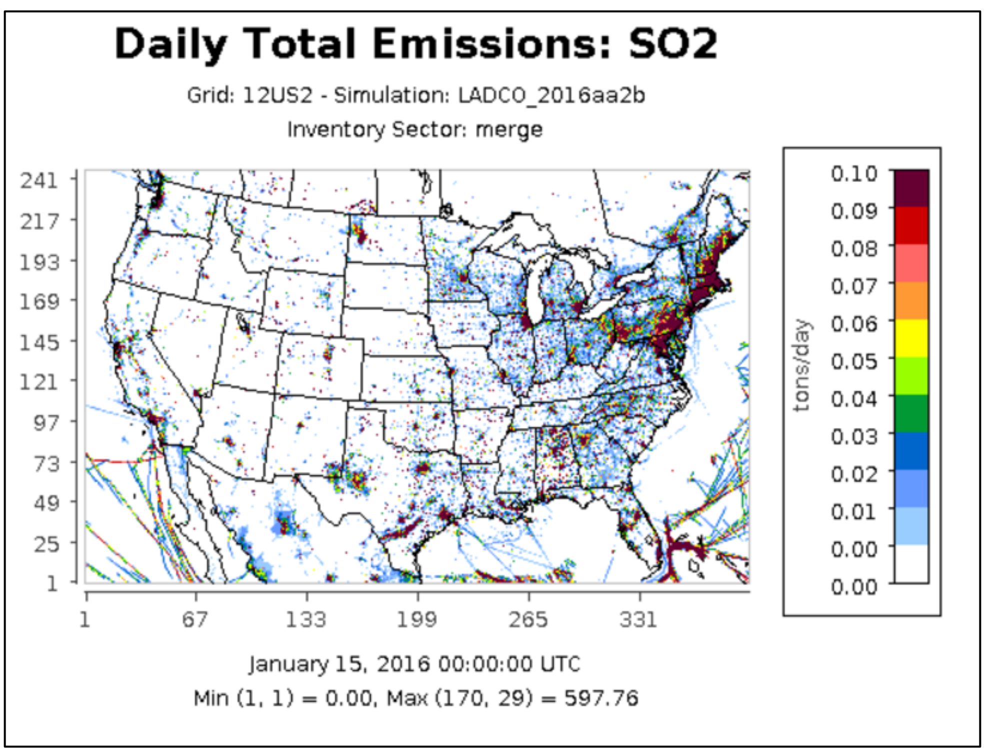

Figure 4-8. Daily total gridded 2016 SO_2 emissions for an example weekday (tons/day)

Table 4-7. 2016 annual emissions totals

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

4.2.2 2028_{2016} Emissions Summary

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

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

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

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

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

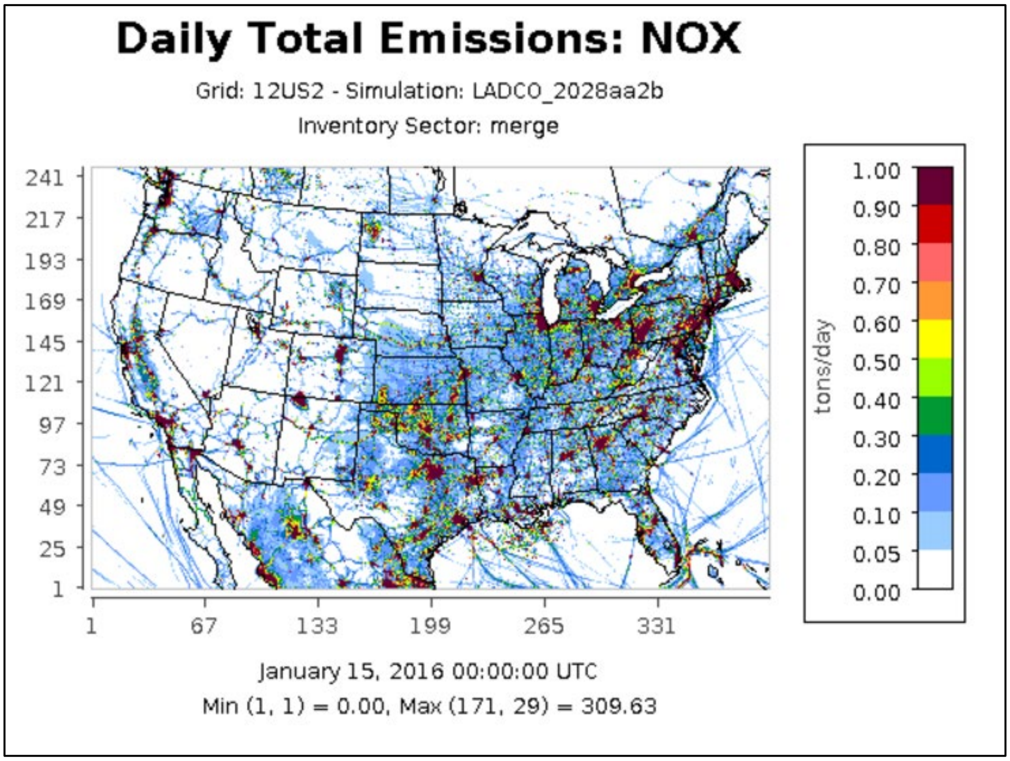

Figure 4-9. Daily total gridded 2028_{2016} NOx emissions for an example weekday (tons/day)

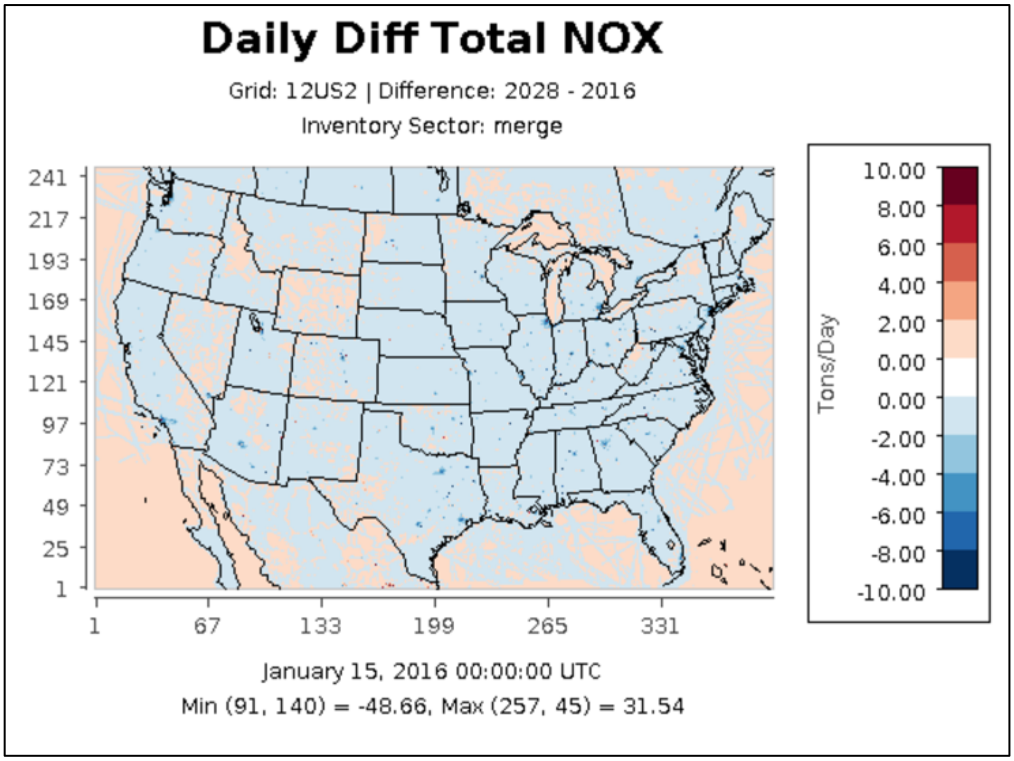

Figure 4-10. Difference (2028-2016) in daily total gridded NOx emissions for an example weekday (tons/day)

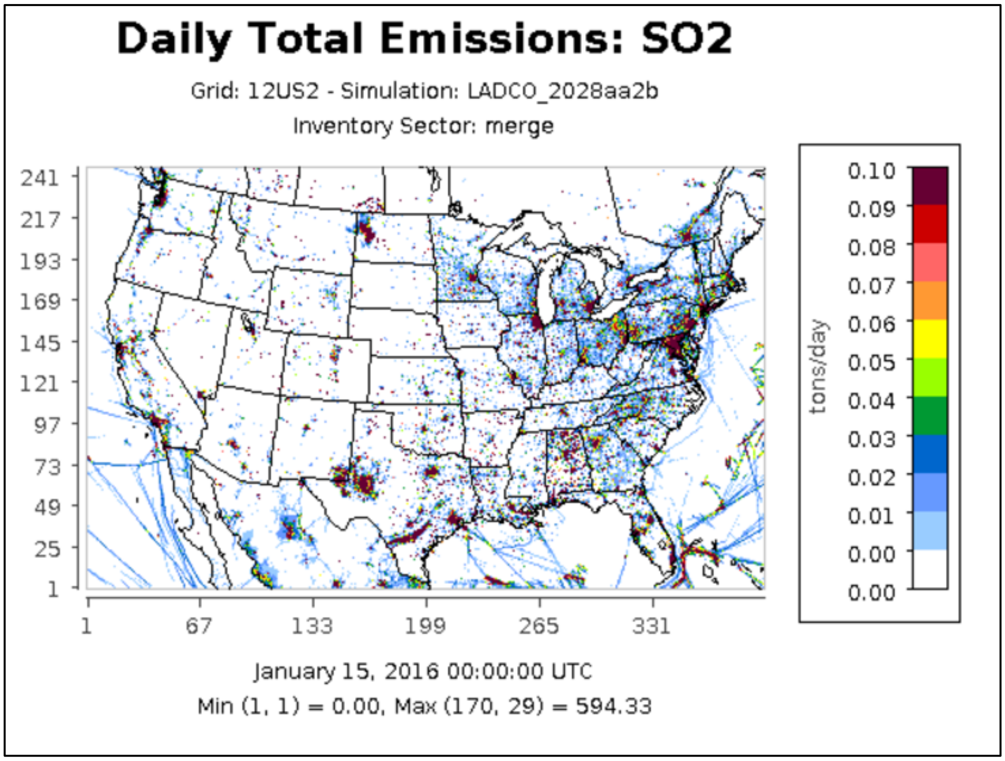

Figure 4-11. Daily total gridded 2028$_{2016}$ SO_2 emissions for an example weekday (tons/day)

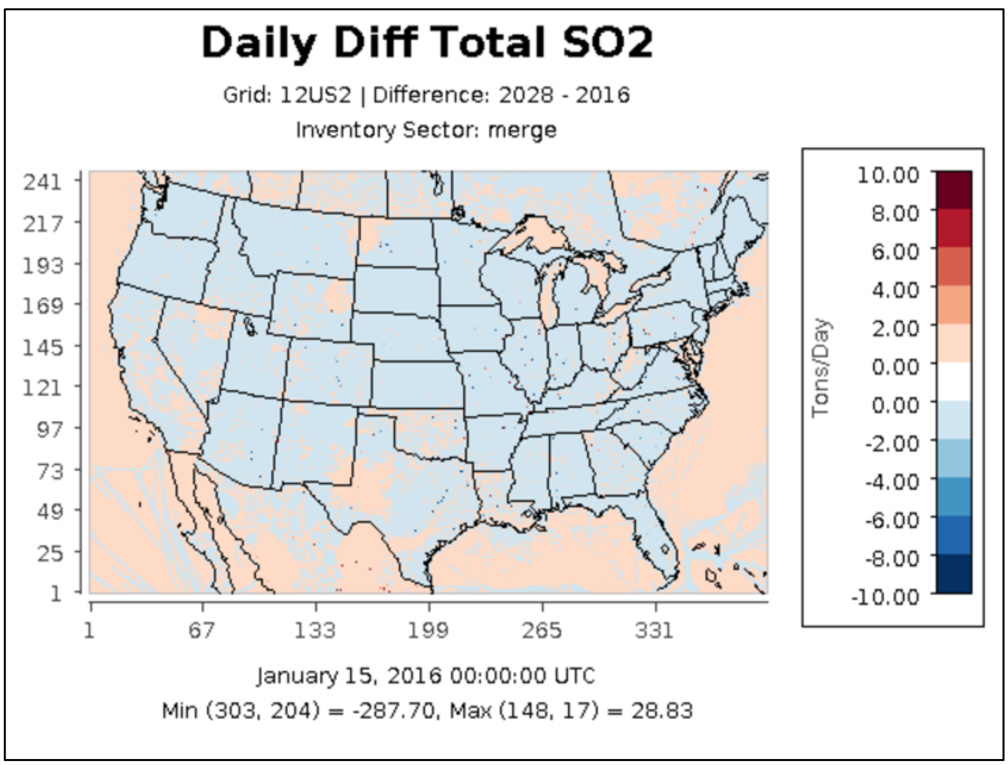

Figure 4-12. Difference (2028-2016) in daily total gridded SO_2 emissions for an example weekday (tons/day)

Table 4-9. 2028_{2016} annual emissions totals

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

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

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

4.2.3 Typical Year Emissions Platform

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

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

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

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

4.3 Comparison of 2011 and 2016 Emissions Platforms

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

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

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

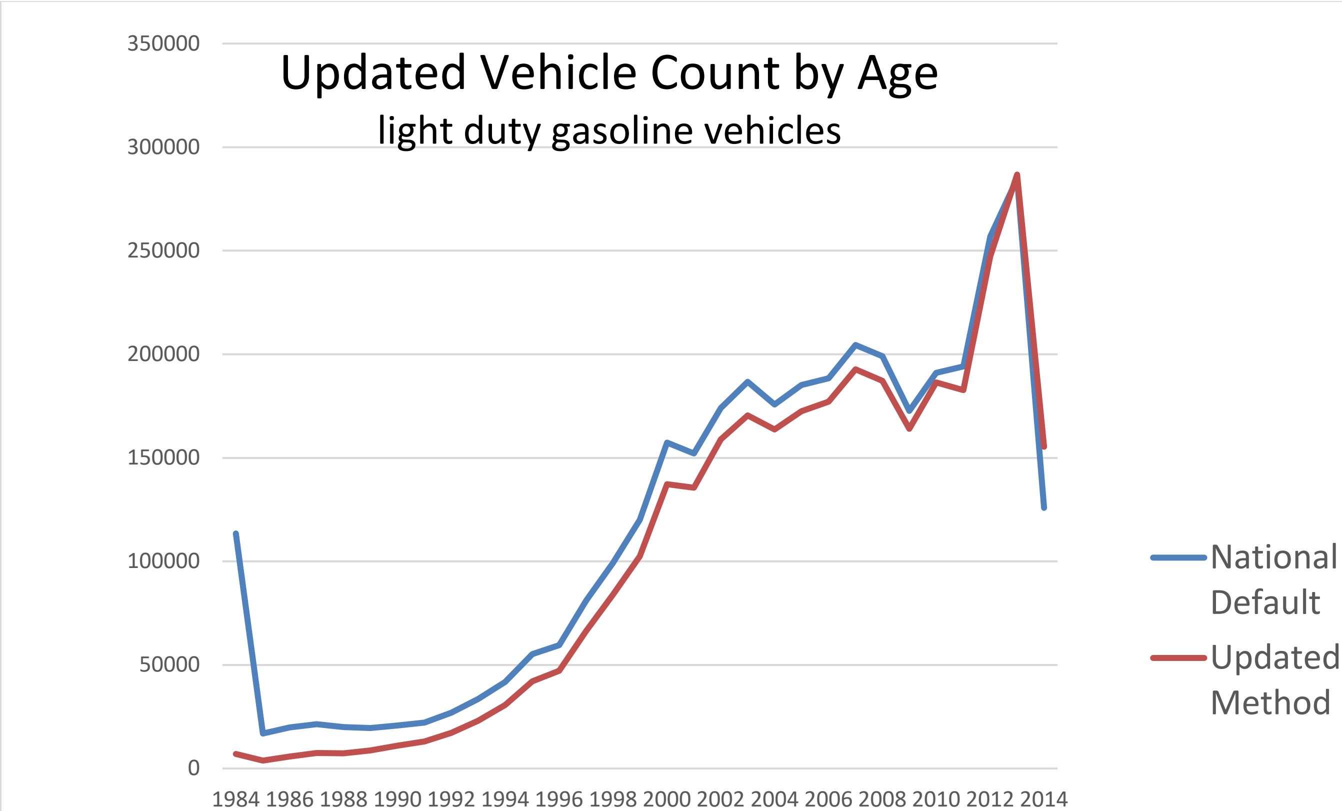

Figure 4-13 Change in vehicle age counts based on updated methodologies to decode VINs.

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

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

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

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

5 Class I Area Q/d Analysis

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

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

5.1 Inventory Sources

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

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

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

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

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

5.2 Q/d Analysis Spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6 CAMx Model Performance Evaluation Results

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

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

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

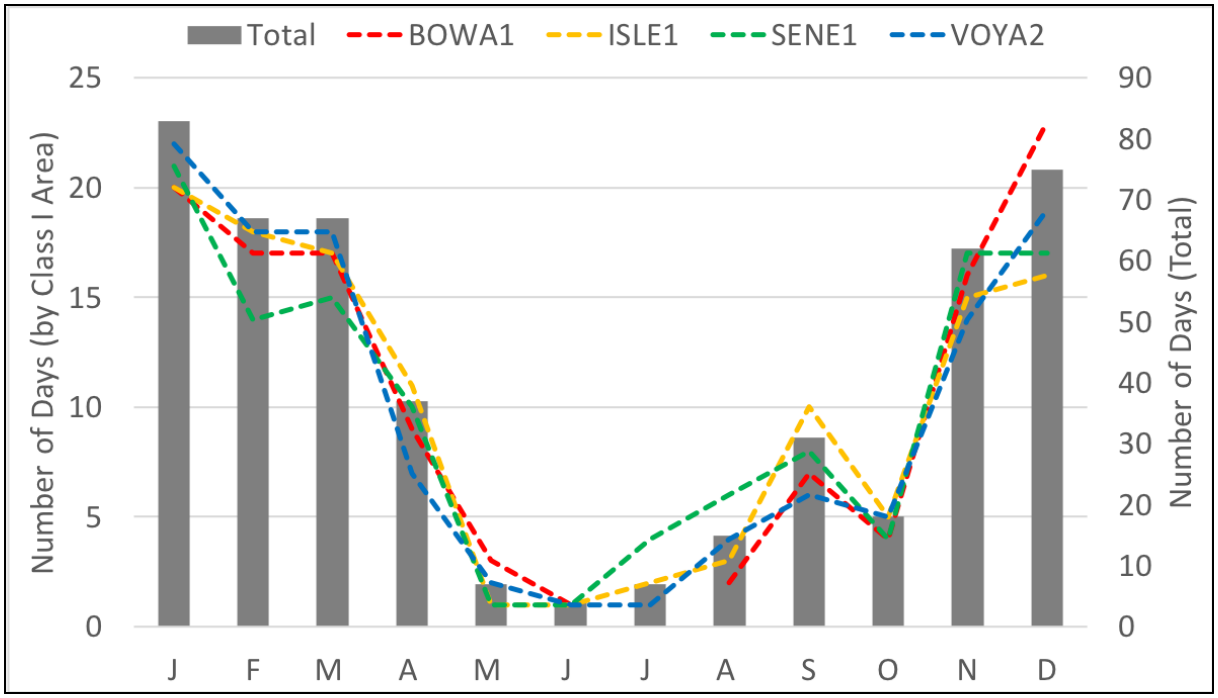

Figure 6-1. Monthly distribution of most impaired days for the LADCO region Class I areas during the period 2014-2018.

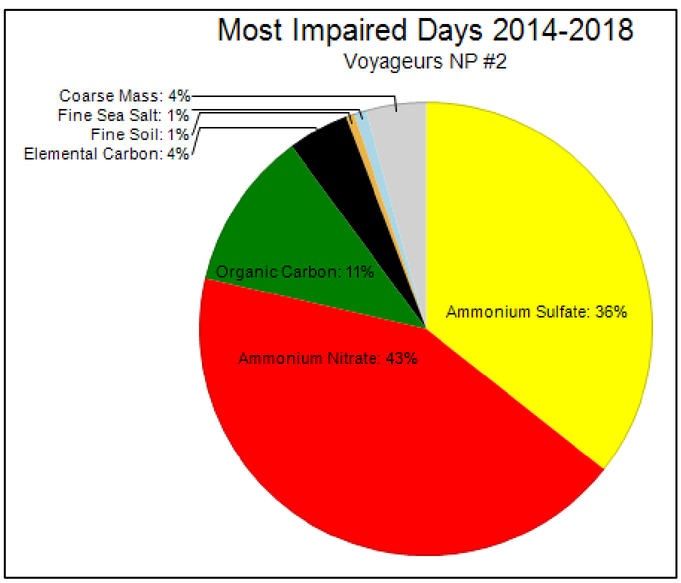

Figure 6-2. Average PM species composition at Voyageurs National Park, MN on the most impaired days during the period 2014-2018.

6.1 2011 CAMx Model Performance Evaluation Results

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

6.1.1 Annual PM Model Performance

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

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

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

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

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

6.1.2 Seasonal PM Model Performance

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

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

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

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

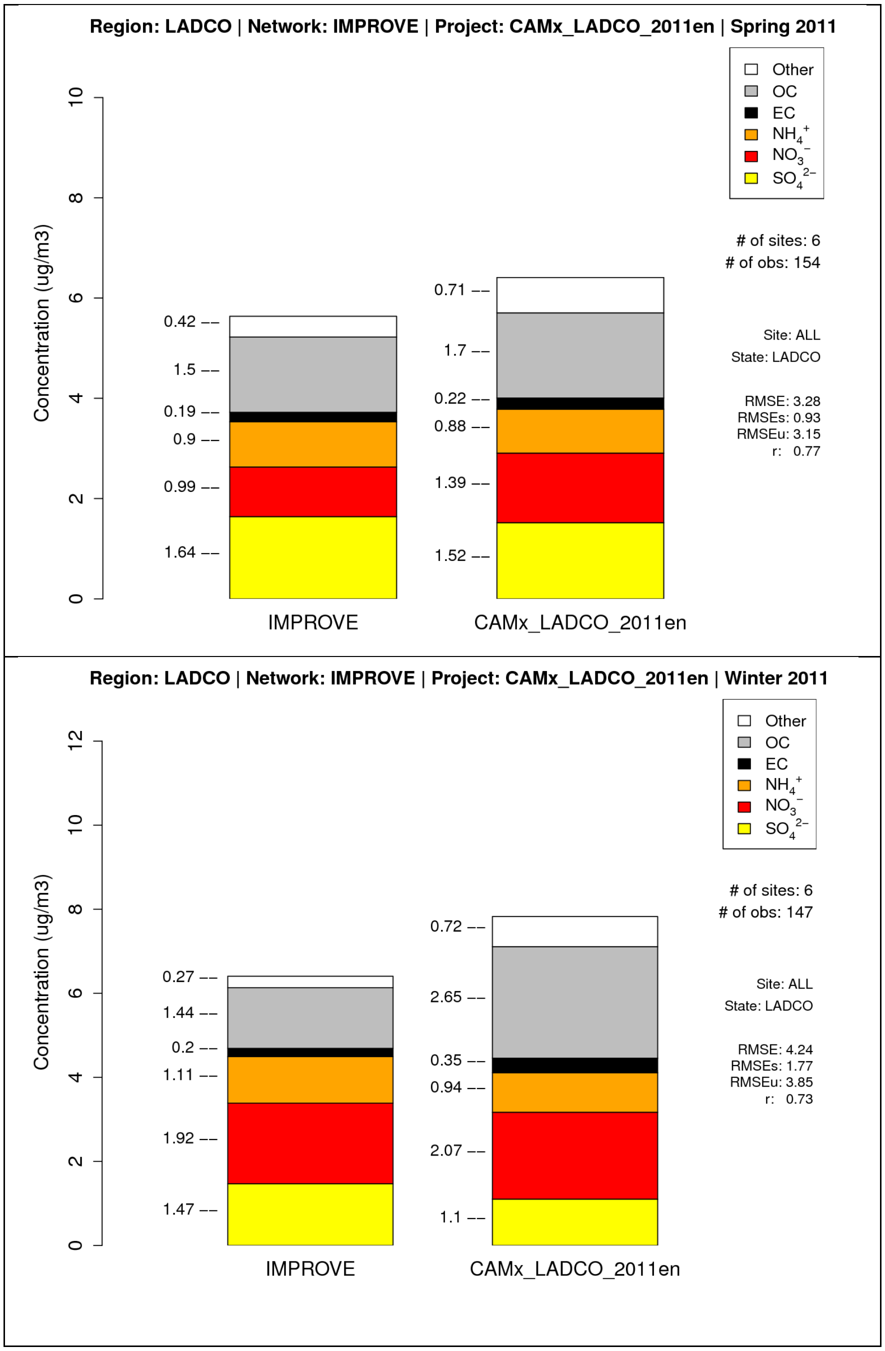

Figure 6-3. Stacked bar plot of spring (top) and winter (bottom) season $PM_{2.5}$ species averaged across all IMPROVE monitors in the LADCO region.

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

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

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

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

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

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

6.2 2016 CAMx Model Performance Evaluation Results

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

6.2.1 Annual PM Model Performance

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

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

Species	Obs (µg/m³)	CAMx (µg/m³)	NMB (%)	NME (%)	r
CSN $PM_{2.5}$	8.19	10.37	30.47	44.68	0.71
IMPROVE $PM_{2.5}$	4.75	5.63	22.82	42.61	0.66
CSN SO_4	1.13	1.42	33.68	48.60	0.70
IMPROVE SO_4	0.99	1.07	16.50	39.53	0.71
CSN NO_3	1.26	1.42	40.19	78.38	0.52
IMPROVE NO_3	0.72	0.64	11.89	75.46	0.50
CSN TC	2.18	4.46	116.93	121.80	0.66
IMPROVE TC	1.89	2.72	56.44	69.95	0.64
Key:	Met MPE Goal		Met MPE Criteria		

6.2.2 Seasonal PM Model Performance

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

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

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

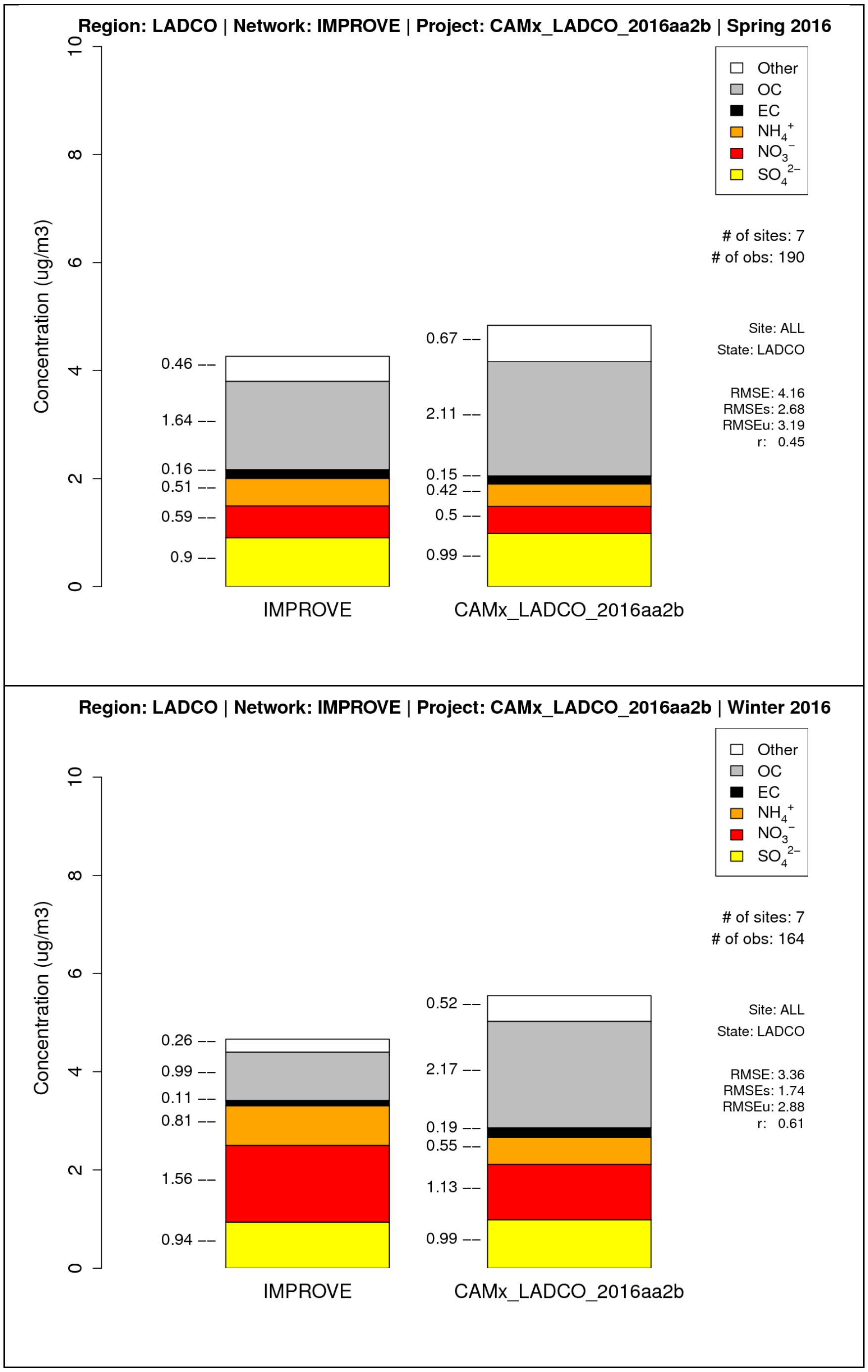

Figure 6-4. Stacked bar plot of 2016 spring (top) and winter (bottom) season $PM_{2.5}$ species averaged across all IMPROVE monitors in the LADCO region.

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

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

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

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

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

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

6.3 Model Performance Discussion

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

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

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

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

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

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

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

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

7 Future Year Haze Projections

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

7.1 Methods

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

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

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

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

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

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

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

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

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

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

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

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

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

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

7.2 LADCO 2028 Haze Projections

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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