
Illustrative Air Quality Analysis for the Light and Medium Duty Vehicle Multipollutant Proposed Rule

Technical Support Document (TSD)

Illustrative Air Quality Analysis for the Light and Medium Duty Vehicle Multipollutant Proposed Rule

Technical Support Document (TSD)

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

Table of Contents

1	Introduction/Overview	1
2	Emissions Inventory Methodology	2
2.1	Emissions Inventory Sector Summary	2
2.2	The Emissions Modeling Process	4
2.3	Emissions Inventory Methodology for 2016v2-Compatible Sectors.....	6
2.4	2055 Emissions Inventory Methodology for the Nonroad Sector	6
2.5	2055 Emissions Inventory Methodology for Fugitive Dust	6
3	Onroad Emissions Inventory Methodology	6
3.1	Emissions Factor Table Development	7
3.2	Activity and Other Data Development	8
3.2.1	2016 Base Year Activity data	9
3.2.2	2055 Projected Activity Data.....	13
3.3	Onroad Emissions Modeling.....	23
3.3.1	Spatial Surrogates	26
3.3.2	Temporal Profiles.....	26
3.3.3	Chemical Speciation	27
3.3.4	Other Ancillary Files.....	27
4	EGU Emissions Inventory Methodology.....	28
4.1	Integrated Planning Model (IPM).....	28
4.2	IPM Inputs	28
4.2.1	IPM Energy Demand Inputs	30
4.3	Air Quality Model-Ready EGU inventory generation.....	34
5	Petroleum Sector Emissions Inventory Methodology	35
5.1	Refinery Emissions	35
5.1.1	Initial Projection of Refinery Emissions to 2050/2055.....	35
5.1.2	Apportioning Total Refinery Emissions to Gasoline and Diesel Fuel Production ...	36
5.1.3	Identifying Refinery Emissions to Adjust for Illustrative Air Quality Analysis	37
5.1.4	Illustrative Air Quality Modeling Scenarios and Associated Refined Fuel Demand	37
5.1.5	Projected Change in U.S. Refinery Activity Related to Decreased Domestic Demand	38
5.1.6	Generation of Adjustment Factors	39
5.2	Crude production well and pipeline emissions	40

5.2.1	Initial Projection of Crude Production Well Site and Pipeline Inventories to 2050/2055	40
5.2.2	Illustrative Air Quality Modeling Scenarios and Associated Crude Demand	40
5.2.3	Generation of Crude Production Well and Pipeline Adjustment Factors	41
5.3	Natural gas production well and pipeline emissions.....	41
5.3.1	Initial Projection of Natural Gas Production Well Site and Pipeline Inventories to 2050/2055	41
5.3.2	Illustrative Air Quality Modeling Scenarios and Associated Natural Gas Demand.	41
5.3.3	Generation of Natural Gas Production Well and Pipeline Adjustment Factors.....	42
6	Inventory Summary Tables.....	43
7	Air Quality Modeling Methodology	46
7.1	Air Quality Model – CMAQ.....	46
7.2	CMAQ Domain and Configuration	46
7.3	CMAQ Inputs.....	48
7.4	CMAQ Model Performance Evaluation	49
7.4.1	Monitoring Networks.....	51
7.4.2	Model Performance Statistics	52
7.4.3	Evaluation for 8-hour Daily Maximum Ozone.....	54
7.4.4	Seasonal Evaluation of PM _{2.5} Component Species.....	60
7.4.5	Seasonal Hazardous Air Pollutants Performance	126
7.4.6	Seasonal Nitrate and Sulfate Deposition Performance	127
7.5	Model Simulation Scenarios	130
8	Additional Results of Illustrative Air Quality Analysis.....	131
8.1	Annual 2055 Reference, LMDV Regulatory, and Onroad-Only Scenario Maps	132
8.2	Seasonal Air Toxics Maps	149
8.3	Projected Visibility in Mandatory Class I Federal Areas	169

1 Introduction/Overview

The Environmental Protection Agency (EPA) is proposing a rule to build on and improve the existing emission control program for on-highway light and medium-duty engines and vehicles by further reducing air pollution from light and medium-duty engines across the United States. This proposed rulemaking is formally titled “Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles,” and is more generally referred to as the "Light Medium Duty Vehicle"(LMDV) proposed rule. The proposed rule would impact emissions of criteria and toxic air pollutants as well as greenhouse gases (GHGs). This document includes information related to the illustrative air quality modeling analysis done in support of the proposed rule and focuses on impacts to ambient concentrations of criteria and toxics pollutants.

EPA conducted an illustrative air quality modeling analysis of a regulatory scenario involving light- and medium-duty "onroad" vehicle emission reductions and corresponding changes in “upstream” emission sources like EGU (electric generating unit) emissions and refinery emissions. Decisions about the emissions and other elements used in the air quality modeling were made early in the analytical process for the proposed rulemaking. Accordingly, the air quality analysis does not represent the proposal's regulatory scenario, nor does it reflect the expected impacts of the Inflation Reduction Act (IRA). Based on updated power sector modeling that incorporated expected generation mix impacts of the IRA, we are projecting the IRA will lead to a significantly cleaner power grid; because the air quality analysis presented here does not account for these impacts on EGU emissions, the location and magnitude of the changes in pollutant concentrations should be considered illustrative and not viewed as Agency projections of what we expect will be the total impact of the proposed standards. Nevertheless, the analysis provides some insights into potential air quality impacts associated with emissions increases and decreases from these multiple sectors.

For this analysis, emission inventories were produced, and air quality modeling was performed, for three scenarios: a 2016 base case, a 2055 reference scenario, and a 2055 light- and medium duty vehicle (LMDV) regulatory case.¹ The illustrative LMDV regulatory case assumes a light- and medium-duty fleet that phased-in to reach 50 percent of new vehicle sales as BEVs in 2030 and remained constant at about 50 percent BEVs for model years 2030-2055, for a total national light-duty vehicle population of 48% BEVs in 2055. The regulatory case also assumes a phase-in of gasoline particulate filters for gasoline vehicles beginning in model year 2027.

An air quality modeling platform consists of all the emissions inventories and ancillary data files used for emissions modeling, as well as the meteorological, initial condition, and boundary condition files needed to run the air quality model. An emissions modeling platform consists of the emissions modeling data and techniques including the emission inventories, the ancillary data files, and the approaches used to transform inventories for use in air quality modeling.

¹ Because the regulatory proposal had not been determined at the time of this analysis, the "regulatory case" described here is not the proposed rule, but a plausible control scenario for illustrative purposes.

This analysis utilizes the 2016v2 emissions modeling platform,² which includes a suite of base year (2016) and projection year (2023, 2026, 2032) inventories, along with ancillary emissions data, and scripts and software for preparing the emissions for air quality modeling. The Technical Support Document (TSD) Preparation of Emissions Inventories for the 2016v2 North American Emissions Modeling Platform describes how the emission inventories for each year of data available in the platform were developed.³

Section 2 of this document gives a summary of the emissions inventory inputs to the air quality modeling. Section 3 of this document describes the methodology for developing onroad mobile emission inventories, Section 4 focuses on the methodology for developing electrical generating unit (EGU) emission inventories, and Section 5 focuses on the methodology for developing petroleum sector emission inventories. Section 6 provides emissions summary tables. Sections 7 and 8 provide an overview of the air quality modeling methodology and results.

2 Emissions Inventory Methodology

This section provides an overview of the emission inventories used in the air quality analysis for the proposed rule. These inventories include point sources, nonpoint sources, onroad and nonroad mobile sources, commercial marine vessels (CMV), locomotive and aircraft emissions, biogenic emissions, and fires for the U.S., Canada, and Mexico. The emissions used for the 2055 control scenarios were the same as those in the 2055 reference scenario for all emissions sectors except for onroad mobile source emissions, EGU emissions, and petroleum sector emissions (specifically refineries, crude oil production well sites and pipelines and natural gas production well sites and pipelines).

For this study, the 2016 emission inventories used were based on those for the 2016v2 platform except for the U.S. onroad and nonroad⁴ mobile sources. For the 2055 cases, the U.S. onroad mobile sources, U.S. nonroad mobile sources were projected to year 2055 levels, while other anthropogenic emissions sources were retained at the 2016v2 platform projected emissions levels for the year 2032. A high-level summary of the emission inventories used is provided in this section, while the development of the U.S. onroad mobile source emissions is described in detail in Section 3, the development of the EGU emissions is described in Section 4, and the development of petroleum sector emissions is described in Section 5.

2.1 Emissions Inventory Sector Summary

For the purposes of preparing the air quality model-ready emissions, emission inventories are split into “sectors”. The significance of a sector is that each sector includes a specific group of emission sources, and those data are run through the emissions modeling system independently

² 2016v2 Emissions Modeling Platform. SMOKE inputs available from <https://gaftp.epa.gov/Air/emismod/2016/v2/>

³ U.S. EPA (2022) Preparation of Emissions Inventories for 2016v2 North American Emissions Modeling Platform Technical Support Document. <https://www.epa.gov/air-emissions-modeling/2016-version-2-technical-support-document>.

⁴ The 2016 U.S. nonroad mobile source emissions inventory in the 2016v2 platform includes emissions for Texas and California which were developed using their own tools. For this study, those state-supplied emissions were replaced with 2016 nonroad emissions computed with an updated version of the Motor Vehicle Emission Simulator, MOVES3.R1.

from the other sectors up to the point of the final merging process. The final merge process combines the sector-specific low-level (of the vertical levels in the AQ model) gridded, speciated, hourly emissions together to create CMAQ-ready emission inputs. While pertinent atmospheric emissions related to the problem being studied are included in each modeling platform, the splitting of inventories into specific sectors for emissions modeling varies by platform. The sectors for the 2016v2 emissions modeling platform used in this study are shown in Table 2-1. Descriptions for each sector are provided. For more detail on the data used to develop the 2016v2 inventories and on the processing of those inventories into air quality model-ready inputs, see the 2016v2 emissions modeling platform TSD.⁵

Table 2-1 Inventory sectors included in the emissions modeling platform

Inventory Sector	Sector Description
Mobile – Nonroad	Mobile sources that do not drive on roads, excluding locomotives, aircraft, and commercial marine vessels (see Section 2.3)
Mobile – Onroad	Onroad mobile source gasoline and diesel vehicles from moving and non-moving vehicles that drive on roads (see Section 3)
Mobile – Category 3 Commercial Marine Vessels	Commercial marine vessels with Category 3 engines within and outside of U.S. waters
Mobile – Category 1 and 2 Commercial Marine Vessels	Commercial marine vessels with Category 1 and 2 engines within and outside of U.S. waters
Mobile – Rail	U.S. Class I line haul, Class II/III line haul, passenger, and commuter locomotives (does not include railyards and switchers)
Nonpoint – Fertilizer	NH ₃ emissions from U.S. fertilizer sources
Nonpoint - Livestock	Primarily NH ₃ and VOC emissions from U.S. livestock sources
Nonpoint – Area Fugitive Dust	PM emissions from paved roads, unpaved roads and airstrips, construction, agriculture production, and mining and quarrying in the U.S.
Nonpoint – Residential Wood Combustion	U.S. residential wood burning emissions from devices such as fireplaces, woodstoves, pellet stoves, indoor furnaces, outdoor burning in fire pits and chimneys
Nonpoint - Oil and Gas	Oil and gas exploration and production, both onshore and offshore
Nonpoint – Solvents	Nonpoint VOC emissions from solvents such as cleaners, personal care products, and adhesives.
Nonpoint - Other	All nonpoint emissions in the U.S. not included in other sectors, including industrial processes, waste disposal, storage and transport of chemicals and petroleum, waste disposal, commercial cooking, and miscellaneous area sources
Point – Airports	Aircraft engines and ground support equipment at U.S. airports
Point – Electrical Generating Units	Electric generating units that provide power to the U.S. electric grid
Point – Oil and Gas	Point sources related to the extraction and distribution of oil and gas in the U.S.
Point – Other	All point sources in the U.S. not included in other sectors. Includes rail yards and refineries.

⁵ U.S. EPA (2022) Preparation of Emissions Inventories for 2016v2 North American Emissions Modeling Platform Technical Support Document. <https://www.epa.gov/air-emissions-modeling/2016-version-2-technical-support-document>.

Point – Fires – Agricultural	Fires due to agricultural burning in the U.S.
Point – Fires – Wild and Prescribed	Wildfires and prescribed burns in the U.S.
Point – Non-U.S. Fires	Fires within the domain but outside of the U.S.
Biogenic (beis)	Emissions from trees, shrubs, grasses, and soils within and outside of the U.S.
Canada – Mobile - Onroad	Onroad mobile sources in Canada (see Section 2.5)
Mexico – Mobile - Onroad	Onroad mobile sources in Mexico (see Section 2.5)
Canada/Mexico - Point	Canadian and Mexican point sources
Canada/Mexico - Nonpoint and Nonroad	Canadian and Mexican nonroad sources and nonpoint sources not included in other sectors
Canada – Agricultural Point	Canadian agricultural ammonia sources
Canada – oil and gas 2D	Canadian low-level point oil and gas sources
Canada – Nonpoint – Area Fugitive Dust	Area source fugitive dust sources in Canada
Canada – Point – Point Fugitive Dust	Point source fugitive dust sources in Canada

2.2 The Emissions Modeling Process

The CMAQ air quality model requires hourly emissions of specific gas and particle species for the horizontal and vertical grid cells contained within the modeled region (i.e., modeling domain). To provide emissions in the form and format required by the model, it is necessary to “pre-process” the emissions inventories for the sectors described above. The process of emissions modeling transforms the emissions inventories from their original temporal, pollutant, and spatial resolution into the hourly, speciated, gridded resolution required by the air quality model. Emissions modeling includes the chemical speciation, temporal allocation, and spatial allocation of emissions along with final formatting of the data that will be input to the air quality model.

Chemical speciation creates the “model species” needed by CMAQ, for a specific chemical mechanism, from the “inventory pollutants” of the input emission inventories. These model species are either individual chemical compounds (i.e., “explicit species”) or groups of species (i.e., “lumped species”). The chemical mechanism used for this platform is the CB6 mechanism.⁶ This platform generates the PM_{2.5} model species associated with the CMAQ Aerosol Module version 7 (AE7). See Section 3.2 of the 2016v2 platform TSD for more information about chemical speciation in the 2016v2 platform.

Temporal allocation is the process of distributing aggregated emissions to a finer temporal resolution, for example converting annual emissions to hourly emissions as is required by CMAQ. While the total annual, monthly, or daily emissions are important, the hourly timing of the occurrence of emissions is also essential for accurately simulating ozone, PM, and other pollutant concentrations in the atmosphere. Many emissions inventories are annual or monthly in nature. Temporal allocation takes these aggregated emissions and distributes the emissions to the hours of each day. This process is typically done by applying temporal profiles to the inventories in this order: monthly, day of the week, and diurnal, with monthly and day-of-week profiles applied only if the inventory is not already at that level of detail. See Section 3.3 of the 2016v2

⁶ Yarwood, G., et al. (2010) Updates to the Carbon Bond Chemical Mechanism for Version 6 (CB6). Presented at the 9th Annual CMAS Conference, Chapel Hill, NC. Available at https://www.cmascenter.org/conference/2010/abstracts/emery_updates_carbon_2010.pdf.

platform TSD for more information about temporal allocation of emissions in the 2016v2 platform.

Spatial allocation is the process of distributing aggregated emissions to a finer spatial resolution, as is required by CMAQ. Over 60 spatial surrogates are used to spatially allocate U.S. county-level emissions to the 12-km grid cells used by the air quality model. See Section 3.4 of the 2016v2 platform TSD for a description of the spatial surrogates used for allocating county-level emissions in the 2016v2 platform.

The primary tool used to perform the emissions modeling to create the air quality model-ready emissions was the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system, version 4.9 (SMOKE 4.9). When preparing emissions for CMAQ, emissions for each sector are processed separately through SMOKE. The elevated point source emissions are passed to CMAQ directly so the model can perform plume rise based on hourly meteorological conditions, while the low-level emissions are combined to create model-ready 2-D gridded emissions. Gridded emissions files were created for a 36-km national grid named 36US3 and for a 12-km national grid named 12US2, both of which include the contiguous states and parts of Canada and Mexico as shown in Figure 2-1. This figure also shows the region covered by other grids that are relevant to the development of emissions for this and related studies.

Figure 2-1 Air quality modeling domains



2.3 Emissions Inventory Methodology for 2016v2-Compatible Sectors

Except for the onroad mobile source emissions, the emissions used for the 2016 air quality case are consistent with those developed through the 2016v2 Platform. For the 2055 cases, emissions for sectors other than U.S. onroad and nonroad mobile sources and emissions for onroad mobile sources for Canada and Mexico, were developed to be consistent with the 2032 emissions developed by the Inventory Collaborative and are described in the 2016v2 Platform TSD. Development of the 2055 nonroad emissions is described in Section 2.4. The development of the U.S. onroad mobile source emissions for each of the cases is described below in Section 3. Additionally, for CMV, the 2016v3 inventories, which have improved state and county apportionment compared to 2016v2, were used. Nonpoint-solvents also used the new 2016v3 inventory as of May 2022 (not final 2016v3) and associated speciation/gridding/temporal xrefs and profiles. For the point (non-egu) sector 2016v2 was used with the difference being that point solvents were included. Another update that was made for this modeling included using the corrected BEIS 3.7 (processed in April/May 2022), with CMAQ run using inline biogenics.

2.4 2055 Emissions Inventory Methodology for the Nonroad Sector

To prepare the nonroad mobile source emissions, an updated version of the Motor Vehicle Emission Simulator (MOVES), MOVES3.R1, was run using inputs compatible with the 2016v2 platform for all states. The nonroad component of MOVES was configured to create a national nonroad inventory for 2055. The 2055 MOVES nonroad inventory was used in all states.

2.5 2055 Emissions Inventory Methodology for Fugitive Dust

The inventory for road dust is generated using VMT⁷, and the total projected VMT in 2055 did not change between the reference and LMDV regulatory scenario (only the fraction of EVs changed). Road dust inventories for 2055 were projected using 2055 VMT (see Section 3.2.2) and are presented in Table 6-7.

3 Onroad Emissions Inventory Methodology

This section focuses on the approach and data sources used to develop gridded, hourly emissions for the onroad mobile sector that are suitable for input to an air quality model in terms of the format, grid resolution, and chemical species. While the emission factors used to develop emissions for the reference and control scenarios differed, the approach and all other data sources used to calculate emissions for both scenarios were identical.

Onroad mobile source emissions result from motorized vehicles operating on public roadways. These include passenger cars, motorcycles, minivans, sport-utility vehicles, light-duty trucks, heavy-duty trucks, and buses. The sources are further divided by the fuel they use, including diesel, gasoline, E-85, electricity, and compressed natural gas (CNG) vehicles. The sector accounts for emissions from parked vehicle processes (e.g., starts, hot soak, and extended idle) as well as from on-network processes (i.e., from vehicles as they move along the roads). The onroad emissions are generated using SMOKE programs that leverage MOVES-generated

⁷ See Section 4.2.3.1 of the 2016v2 TSD for more detail on how fugitive dust is projected.

emission factors with county, fuel type, source type, and road type-specific activity data, along with hourly meteorological data.

The MOVES-generated onroad emission factors were combined with activity data (e.g., vehicle miles traveled, vehicle population) to produce emissions within the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system. The collection of programs that compute the onroad mobile source emissions are known as SMOKE-MOVES. SMOKE-MOVES uses a combination of vehicle activity data, emission factors from MOVES, meteorology data, and temporal allocation information needed to estimate hourly onroad emissions. Additional types of ancillary data are used for the emissions processing, such as spatial surrogates which spatially allocate emissions to the grid used for air quality modeling.

More details on the generation of the emission factors, activity data, and on the modeling of the emissions are in the following subsections. National onroad emission summaries for key pollutants are provided in Section 4.

3.1 Emissions Factor Table Development

Onroad mobile source emission factors were generated for the modeled cases by running an updated version of MOVES3⁸ (MOVES3.R1) which incorporates the latest vehicle activity data, newer emission rules, and changes that reflect improvements in EPA's understanding of vehicle emissions and add features to better model electric vehicles. More information on these updates is available in a memo to the docket.⁹

In addition to the updates incorporated in MOVES3.R1 that were used in all three modeling cases, we also developed case-specific inputs. The LMDV regulatory case assumes light-duty and medium-duty BEV sales of about 50 percent for model years 2030 and beyond, plus some improvements to particulate matter emissions for light-duty and medium-duty vehicles as detailed in the DRIA. Thus, case-specific BEV fractions were incorporated into each county's fuel mix described in Section 3.2.2.5 below. Also, for the LMDV regulatory case, we reduced the gasoline light- and medium-duty PM exhaust emission rates to account for GPF control and changed the adjustment weight in EVPopICEAdjustLD to zero for HC and NO_x to indicate no averaging with electric vehicles. This effectively caps the light- and medium-duty internal combustion NO_x and HC emissions at the model year 2026 rate. We did not change the adjustment weights for energy consumption since this case assumed that CO₂ averaging with electric vehicles would continue.

The emission factor tables input to SMOKE-MOVES are generated by running MOVES. These tables differentiate emissions by process (i.e., running, start, vapor venting, etc.), fuel type, vehicle type, road type, temperature, speed bin for rate per distance processes, hour of day, and day of week. To generate the MOVES emission factors across the U.S., MOVES was run to produce emission factors for a series of temperatures and speeds for a set of "representative

⁸ USEPA (2020) Motor Vehicle Emission Simulator: MOVES3. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. <https://www.epa.gov/moves>.

⁹ USEPA (2023). *Updates to MOVES for the Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles*, Memo to Docket, February 2023. Memorandum to Docket EPA-HQ-OAR-2022-0829. February 2023

counties,” to which every other county in the country is mapped. The representative counties for which emission factors are generated are selected according to their state, elevation, fuels used in the region, vehicle age distribution, and inspection and maintenance programs. Every county in the country is mapped to a representative county based on its similarity to the representative county with respect to those attributes. The representative counties selected for the 2016v2 platform were retained for this analysis. More details on the methodology behind choosing representative counties is available in the 2016v2 TSD.

Emission factors were generated by running MOVES for each representative county for two “fuel months” – January to represent winter months and July to represent summer months – because in some parts of the country different types of fuels are used in each season. MOVES was run for the range of temperatures that occur in each representative county for each season. The calculations of the temperature ranges needed for each fuel month were based on meteorology for every county and grid cell in the continental U.S. for each hour of the year. The SMOKE interface accounts for the sensitivity of the on-road emissions to temperature and humidity by using the gridded hourly temperature information available from the meteorological model outputs used for air quality modeling.

MOVES3.R1 was run using the above approach to create emission factors for each of the three modeling cases: 2016 base year, 2055 reference, and a 2055 regulatory case. A new set of emission factor tables were developed for this study using the same representative counties as were used the 2016v2 platform. The county databases (CDBs) input to MOVES for 2016 were equivalent to those used for the 2016v2 platform. To prepare the 2055 CDBs used to generate year 2055 emissions factors, the vehicle age distributions were projected to reflect the year 2055 as were the tables representing the inspection and maintenance programs. The fuels used were also representative of year 2055. The CDBs for each of the 2055 modeling cases incorporated the case-specific fuel mix as detailed in Section 3.2.2.5 below.

3.2 Activity and Other Data Development

To compute onroad mobile source emissions, SMOKE selects the appropriate MOVES emission rates for each county, hourly temperature, speed bin, and SCC (which includes the fuel type, source type and road type), then multiplies the emission rate by the appropriate activity data such as VMT (vehicle miles travelled), VPOP (vehicle population), SPEED/SPDIST (speed distributions and averages), HOTELING (hours of extended idle), ONI (hours of off-network idling), or STARTS (engine starts), to produce emissions. For each of these activity datasets, first a national dataset was developed; this national dataset is called the “EPA default” dataset. Data submitted by state agencies were incorporated into the activity data sets used for the study where they were available and passed quality assurance checks.

The activity data for the 2016 base year were consistent with the activity data used in the 2016v2. Additional details on the development of activity data are available in the 2016v2 TSD.

In addition to activity data, this section also describes inputs for fuel parameters and county-specific vehicle inspection and maintenance programs.

3.2.1 2016 Base Year Activity data

3.2.1.1 *Vehicle Miles Traveled (VMT)*

EPA calculated default 2016 VMT by backcasting the 2017 NEI VMT to 2016. The 2017 NEI Technical Support Document¹⁰ contains details on the development of the 2017 VMT. The data backcast to 2016 were used for states that did not submit 2016 VMT data. The factors to adjust VMT from 2017 to 2016 were based on VMT data from the FHWA county-level VM-2 reports.. For most states, EPA calculated county-road type factors based on FHWA VM-2 County data for 2017 and 2016. Separate factors were calculated by vehicle type for each MOVES road type. Some states have a very different distribution of urban activity versus rural activity between 2017 NEI and the FHWA data, due to inconsistencies in the definition of urban versus rural. For those states, a single county-wide projection factor based on total FHWA VMT across all road types was applied to all VMT, independent of road type. County-total-based (instead of county+road type) factors were used for all counties in IN, MS, MO, NM, TN, TX, and UT because many counties had large increases in one particular road type and decreases in another road type.

For the 2016v1 platform, VMT data submitted by state and local agencies were incorporated and used in place of EPA defaults. Note that VMT data need to be provided to SMOKE for each county and SCC. The onroad SCCs characterize vehicles by MOVES fuel type, vehicle (aka source) type, emissions process, and road type. Any VMT provided at a different resolution than this were converted to a full county-SCC resolution to prepare the data for processing by SMOKE.

A final step was performed on all state-submitted VMT. The distinction between a “passenger car” (MOVES source type 21) versus a “passenger truck” (MOVES source type 31) versus a “light commercial truck” (MOVES source type 32) is not always consistent between different datasets. This distinction can have a noticeable effect on the resulting emissions, since MOVES emission factors for passenger cars are quite different than those for passenger trucks and light commercial trucks.

To ensure consistency in the 21/31/32 splits across the country, all state-submitted VMT for MOVES vehicle types 21, 31, and 32 (all of which are part of HPMS vehicle type 25) was summed, and then re-split using the 21/31/32 splits from the EPA 2016v2 default VMT. VMT for each source type as a percentage of total 21/31/32 VMT was calculated by county from the EPA default VMT. Then, state-submitted VMT for 21/31/32 was summed and re-split according to those percentages.

3.2.1.2 *Vehicle Population (VPOP)*

The EPA default VPOP dataset was based on the EPA default VMT dataset described above. In the areas where EPA backcasted 2017 NEI VMT:

¹⁰ U.S. EPA (2021) 2017 National Emissions Inventory: January 2021 Updated Release, Technical Support Document. <https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-technical-support-document-tsd>

$$2016v2 \text{ VPOP} = 2016v2 \text{ VMT} * (\text{VPOP/VMT ratio by county-SCC6}).$$

where the ratio by county-SCC is based on 2017NEI with MOVES3.R1 fuel splits and SCC6 means the first six digits of the SCC code that include fuel type and source type but exclude the road type and process. In the areas where we used 2016v1 VMT resplit to MOVES3.R1 fuels, 2016v2 VPOP = 2016v1 VPOP with two resplits: first, source types 21/31/32 were resplit according to 2017 NEI EPA default 21/31/32 splits so that the whole country has consistent 21/31/32 splits. Next, fuels were resplit to MOVES3.R1 fuels. There are some areas where 2016 VMT was submitted but 2016 VPOP was not; those areas are using 2016v1 VPOP (with resplits). The same method was applied to the 2016 EPA default VMT to produce an EPA default VPOP data set.

3.2.1.3 Speed Activity (*SPEED/SPDIST*)

In the version of SMOKE used for this analysis (SMOKE 4.7), SMOKE-MOVES was updated to use speed distributions similarly to how they are used when running MOVES in inventory mode. This new speed distribution file, called SPDIST, specifies the amount of time spent in each MOVES speed bin for each county, vehicle (aka source) type, road type, weekday/weekend, and hour of day. This file contains the same information at the same resolution as the Speed Distribution table used by MOVES but is reformatted for SMOKE. Using the SPDIST file results in a SMOKE emissions calculation that is more consistent with MOVES than the previous hourly speed profile (SPDPRO) approach, because emission factors from all speed bins can be used, rather than interpolating between the two bins surrounding the single average speed value for each hour as is done with the SPDPRO approach.

As was the case with the previous SPDPRO approach, the SPEED inventory that includes a single overall average speed for each county, SCC, and month, must still be read in by the SMOKE program Smkinven. SMOKE requires the SPEED dataset to exist even when speed distribution data are available, even though only the speed distribution data affects the selection of emission factors. The SPEED and SPDIST datasets are carried over from 2017 NEI and are based on a combination of the Coordinating Research Council (CRC) A-100 data and 2017 NEI MOVES CDBs.

3.2.1.4 Hoteling Hours (*HOTELING*)

Hoteling hours activity is used to calculate emissions from extended idling and auxiliary power units (APUs) for heavy duty diesel vehicles. For the 2016v2 platform, hoteling hours were computed using a new factor identified by EPA's Office of Transportation and Air Quality as more appropriate based on recent studies.

The method used in 2016v2 is the following:

- 1 Start with 2016 VMT for combination long haul trucks (i.e., MOVES source type 62) on restricted roads, by county.

- 2 Multiply the VMT by 0.007248 hours/mile.¹¹
- 3 Apply parking space reductions to keep hoteling within the estimated maximum hours by county, except for states that requested EPA do not do that (CO, ME, NJ, NY).

Hoteling hours were adjusted down in counties for which there were more hoteling hours assigned to the county than could be supported by the known parking spaces. To compute the adjustment, the hoteling hours for the county were computed using the above method, and reductions were applied directly to the 2016 hoteling hours based on known parking space availability so that there were not more hours assigned to the county than the available parking spaces could support if they were full every hour of every day.

A dataset of truck stop parking space availability with the total number of parking spaces per county was used in the computation of the adjustment factors.¹² This same dataset is used to develop the spatial surrogate for hoteling emissions. Since there are 8,784 hours in the year 2016; the maximum number of possible hoteling hours in a particular county is equal to 8,784 * the number of parking spaces in that county. Hoteling hours for each county were capped at that theoretical maximum value for 2016 in that county unless the number of parking spaces listed was less than 12, in which case the hours were not reduced.

For 2016v2, hoteling was calculated as:

$$2016v2 \text{ HOTELING} = 2017\text{NEI HOTELING} * 2016v2 \text{ VMT}/2017\text{NEI VMT}$$

This is effectively consistent with applying the 0.007248 factor directly to the 2016v2 VMT. Then, for counties that provided 2017 hoteling but did not have vehicle type 62 restricted VMT in 2016 – that is, counties that should have hoteling, but do not have any VMT from which to calculate it - EPA backcast 2017 hoteling to 2016 using the FHWA-based county total 2017 to 2016 trend. Finally, the annual parking-space-based caps for hoteling hours were applied. The same caps were used as for 2017 NEI, except recalculated for a leap year (multiplied by 366/365).

3.2.1.5 Off-Network Idling Hours (ONI)

After creating VMT inputs for SMOKE-MOVES, Off-network idle (ONI) activity data were also needed. ONI is defined in MOVES as time during which a vehicle engine is running idle and the vehicle is somewhere other than on the road, such as in a parking lot, a driveway, or at the side of the road. This engine activity contributes to total mobile source emissions but does not take place on the road network.

¹¹ USEPA (2020). *Population and Activity of Onroad Vehicles in MOVES3*. EPA-420-R-20-023. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. <https://www.epa.gov/moves/moves-technical-reports>.

¹² From *2016 version 1 hoteling workbook.xlsx* developed based on the input dataset for the hoteling spatial surrogate in the 2016v1 platform.

Examples of ONI activity include:

- light duty passenger vehicles idling while waiting to pick up children at school or to pick up passengers at the airport or train station,
- single unit and combination trucks idling while loading or unloading cargo or making deliveries, and
- vehicles idling at drive-through restaurants.

Note that ONI does not include idling that occurs on the road, such as idling at traffic signals, stop signs, and in traffic—these emissions are included as part of the running and crankcase running exhaust processes on the other road types. ONI also does not include long-duration idling by long-haul combination trucks (hoteling/extended idle), as that type of long duration idling is accounted for in other MOVES processes.

ONI activity hours were calculated based on VMT. For each representative county, the ratio of ONI hours to onroad VMT (on all road types) was calculated using the MOVES ONI Tool by source type, fuel type, and month. These ratios were then multiplied by each county's total VMT (aggregated by source type, fuel type, and month) to get hours of ONI activity.

3.2.1.6 Engine Starts (STARTS)

Onroad “start” emissions are the instantaneous exhaust emissions that occur at the engine start (e.g., due to the fuel rich conditions in the cylinder to initiate combustion) as well as the additional running exhaust emissions that occur because the engine and emission control systems have not yet stabilized at the running operating temperature. Operationally, start emissions are defined as the difference in emissions between an exhaust emissions test with an ambient temperature start and the same test with the engine and emission control systems already at operating temperature. As such, the units for start emission rates are instantaneous grams/start.

MOVES3.R1 uses vehicle population information to sort the vehicle population into source bins defined by vehicle source type, fuel type (gas, diesel, etc.), regulatory class, model year and age. The model uses default data from instrumented vehicles (or user-provided values) to estimate the number of starts for each source bin and to allocate them among eight operating mode bins defined by the amount of time parked (“soak time”) prior to the start. Thus, MOVES3.R1 accounts for different amounts of cooling of the engine and emission control systems. Each source bin and operating mode has an associated g/start emission rate. Start emissions are also adjusted to account for fuel characteristics, LD inspection and maintenance programs, and ambient temperatures.

$$2016v2 \text{ STARTS} = 2016v2 \text{ VMT} * (2017 \text{ STARTS} / 2017 \text{ VMT by county \& SCC6})$$

3.2.1.7 Fuels

The 2016 scenario used MOVES3.R1 default fuels. These fuels are the same as the fuels in MOVES3.0.1.¹³

3.2.2 2055 Projected Activity Data

The projected 2055 activity data are primarily based on the 2016v2 platform's projected 2032 data, updated to be consistent with the default data and algorithms in MOVES3.R1, as well as to estimate geographic differences in fuel and age distributions. To accomplish this analysis, the following steps were taken:

1. Calendar year 2055 CDBs were developed for each representative county, as described in more detail later in this section. Each scenario (the reference case and the two control cases) had its own set of CDBs.
2. MOVES3.R1 was run with each CDB to calculate detailed activity data for each representative county.
3. The MOVES activity results for each representative county were allocated to the individual counties represented by each representative county using the 2016v2 platform allocations.

The following sections describe how the 2055 CDBs were developed to calculate the 2055 projected activity data.

3.2.2.1 Data Used As-is from the 2016v2 Platform

The starting point for developing the 2055 CDBs was the 2016v2 platform for calendar year 2032. The following data were used as-is from the 2016v2 platform data in the 2055 CDBs:

- Geography tables: State, County, Zone, and ZoneMonthHour
- VMT distribution tables: MonthFraction, DayFraction, and HourFraction
- Speed distribution table: AvgSpeedDistribution
- Road distribution tables: RoadTypeDistribution and ZoneRoadType
- Retrofit table: OnroadRetrofit

3.2.2.2 Default Data Used As-is from MOVES3.R1

National default data and algorithms in MOVES3.R1 were used for the following tables:

- Some (but not all) fuels tables: FuelFormulation, FuelSupply, and FuelUsageFraction

¹³U.S. EPA (2021) Fuel Supply Defaults: Regional Fuels and the Fuel Wizard in MOVES3, EPA-420-R-21-006. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. March 2021.

- Starts tables: StartsPerDayPerVehicle, StartsMonthAdjust, StartsHourFraction, StartsAgeAdjustment, and StartsOpModeDistribution
- Hotelling tables: HotellingHoursPerDay, HotellingMonthAdjust, HotellingHourFraction, HotellingAgeFraction, and HotellingActivityDistribution
- Off-Network Idle tables: TotalIdleFraction, IdleModelYearGrouping, IdleMonthAdjust, and IdleDayAdjust
- I/M table: IMCoverage

Note that in MOVES3.R1, starts, hotelling, and off-network idle tables are optional tables, and therefore can be empty in a CDB if the intention is to use default data. Therefore, these tables are empty in the 2055 CDBs. However, the fuels tables and I/M table are required inputs. Since the default database contains county (or region) specific data, the 2055 CDBs contain the relevant subset of the default database's data. See the MOVES3.R1 technical reports^{14,15,16,17,18,19} for more information about how these default data were derived.

3.2.2.3 *Default Data from MOVES3.R1 Allocated Using 2016v2 Platform*

National default data in MOVES3.R1 were allocated to representative counties for the following tables:

- VMT table: HPMSVTypeYear
- VPOP table: SourceTypeYear

VMT fractions by HPMSVTypeID and county were calculated from the 2032 VMT projections in the 2016v2 platform and used to allocate the national default VMT projections for 2055 to the county level. Similarly, VMT fractions by sourceTypeID and county were calculated from the 2016v2 platform to allocate the national default VPOP projections for 2055. See the MOVES3.R1 technical report for more information about how the national default data were derived.¹⁸

3.2.2.4 *2055 Age Distributions*

Each CDB has a sourceTypeAgeDistribution table. The 2055 age distributions by representing county were primarily derived using July 1, 2020, vehicle registration data

¹⁴ U.S. EPA (2023) Exhaust Emission Rates for Light Duty Onroad Vehicles in MOVES3.R1. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. February 2023.

¹⁵ U.S. EPA (2023) Exhaust Emission Rates for Heavy Duty Onroad Vehicles in MOVES3.R1. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. February 2023.

¹⁶ U.S. EPA (2023) Emission Adjustments for Onroad Vehicles in MOVES3.R1. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. February 2023.

¹⁷ U.S. EPA (2023) Evaporative Emissions from Onroad Vehicles in MOVES3.R1. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. February 2023.

¹⁸ U.S. EPA (2023) Population and Activity of Onroad Vehicles in MOVES3.R1. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. February 2023.

¹⁹ U.S. EPA (2023) Greenhouse Gas and Energy Consumption Rates for Onroad Vehicles in MOVES3.R1. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. February 2023.

purchased from IHS Markit, vehicle stock and sales projections from the Annual Energy Outlook (AEO) 2021²⁰, and vehicle scrappage rates presented in the Transportation Energy Data Book (TEDB).²¹ The age distributions were calculated using a modified version of the age distribution projection algorithm described in Appendix C of the Population and Activity of Onroad Vehicles in MOVES3.R1 technical report.¹⁸ The algorithm was modified to maintain differences between counties, such that counties that had newer-than-average fleets in 2020 continue to have newer-than-average fleets in 2055 and, similarly, counties with older fleets now have older fleets in the future. The fundamental approach to solving this problem was to define how age distributions in a local area are different from the national average, and then apply that difference to future years.

The following algorithm was implemented for calculating a representative county's base age distribution:

1. Subset the 2020 registration data to get vehicle counts by source type and model year for all counties represented by the representative county.
2. Group all model years 1990 and older together, because MOVES groups all vehicles ages 30 and older together.
3. Calculate age fractions by source type.
4. Replace age 0 (model year 2020) fractions with the ratio of vehicle sales to stock from AEO. This is because the July 1 registration data pull represents an incomplete year.
5. Renormalize the age distributions, retaining the age 0 fractions.

The following equations were used to project a representative county's base age distribution one year into the future:

- Population distribution for the next calendar year = Population distribution for the current calendar year, minus vehicles scrapped in the current calendar year, plus locally adjusted new vehicle sales in the next year
- Vehicles scrapped in the current calendar year = Scrappage factor times the base scrappage rate times the population distribution for the current calendar year
- Scrappage factor = (Total number of vehicles in the current year, minus total number of vehicles in the next year, plus locally adjusted new vehicle sales in the next year) divided by the sum of the base scrappage rate times the current year's population distribution. The purpose of the scrappage factor is to scale the base scrappage rate to balance the equation accounting for the total number of vehicles in each calendar year. For example, if the total number of vehicles remains constant from one year to the next and vehicle sales are high, then the scrappage factor would be high as well, as

²⁰ US Energy Information Administration (EIA), Annual Energy Outlook 2021, Washington, DC: February 2021. <https://www.eia.gov/outlooks/archive/aeo21/>

²¹ Davis, S. and R Boundy (2022), Transportation Energy Data Book, Ed. 40, Oak Ridge National Laboratory, ORNL/TM-2022/2376, https://tedb.ornl.gov/wp-content/uploads/2022/03/TEDB_Ed_40.pdf

more vehicles would be scrapped to balance out the higher sales while maintaining constant number of total vehicles.

The population distribution of the current calendar year is known; thus, the algorithm starts with the base age distribution and then the algorithm iterates, so the output of the algorithm is the input for the next year. The total number of vehicles in the next year and the vehicle sales in the next year are also known, based on AEO. The base scrappage curve is also known, based on data presented in TEDB.

The differences between local areas were accounted for by applying a local sales scaling factor to the number of new vehicles sold in the next year in the equations above. This scaling factor was defined as the difference between the local and the national population fractions summed over an age range $[1, j]$, divided by the national population fraction over the same age range. Essentially, this is using the fraction of newer vehicles in a local fleet compared to the national average as a surrogate for what future sales in a local area might be.

The precise age range $[1, j]$ used was determined for each source type, chosen so that the difference between the local average age and the projected national average age in 2055 was as close as possible to the difference between the local and national average ages in 2020. That is, the chosen age ranges tried to maintain the same delta in average age between the local and the national case in the future. The chosen age ranges by source type were:

- Motorcycles: $[1, 7]$
- Passenger cars: $[1, 10]$
- Passenger trucks: $[1, 5]$
- Light commercial trucks: $[1, 5]$
- Other buses: $[1, 10]$
- Transit buses: $[1, 10]$
- School buses: $[1, 8]$
- Refuse trucks: $[1, 10]$
- Single unit trucks: $[1, 7]$
- Motor homes: $[1, 10]$
- Combination short-haul trucks: $[1, 10]$

Note that for some counties, some source types were not present in the IHS data. In these rare cases, the national default age distributions were assumed. Additionally, combination long-haul trucks were assumed to have the same age distribution nationally.

The algorithm and data described above were used to calculate SourceTypeAgeDistribution tables for each representing county in 2055. The same age distributions were used for all scenarios. The following figures show the resulting projected average age in 2055 by county for the light-duty source types.

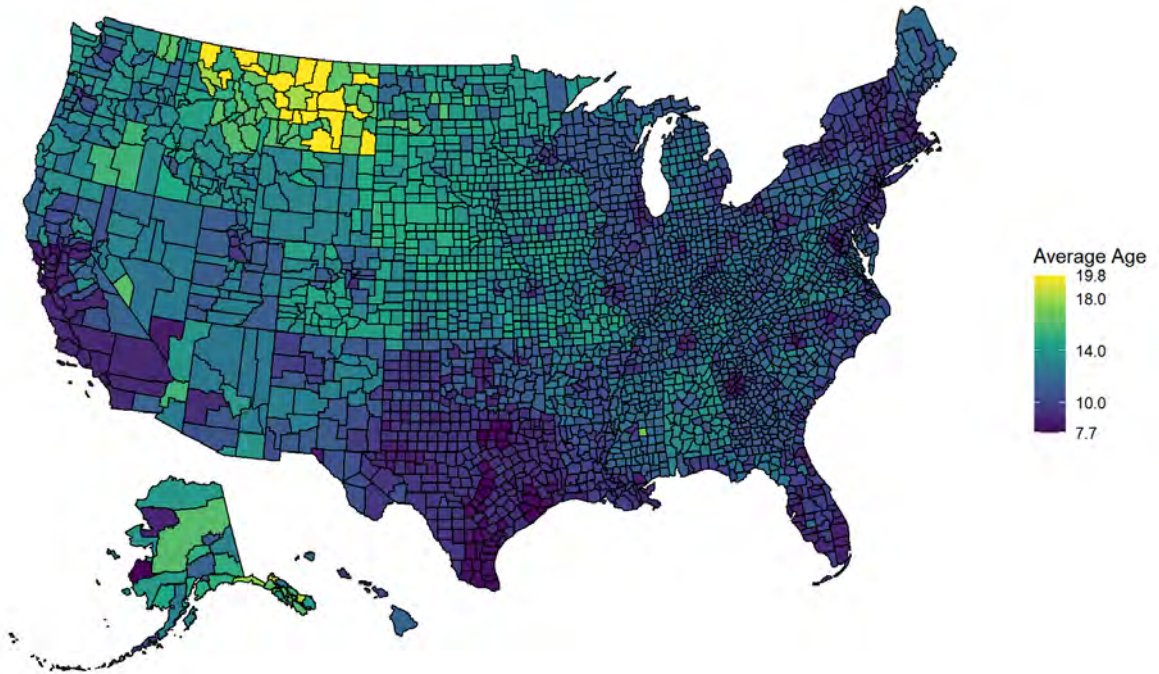


Figure 3-1 Projected average age of passenger cars in 2055

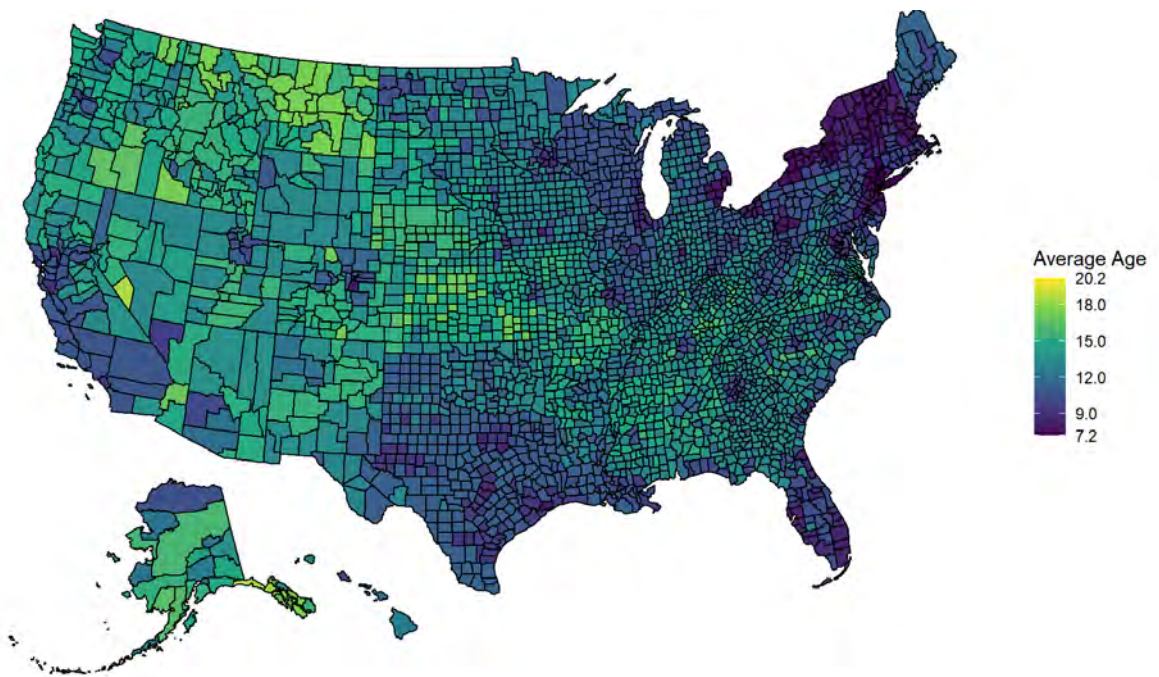


Figure 3-2 Projected average age of passenger trucks in 2055

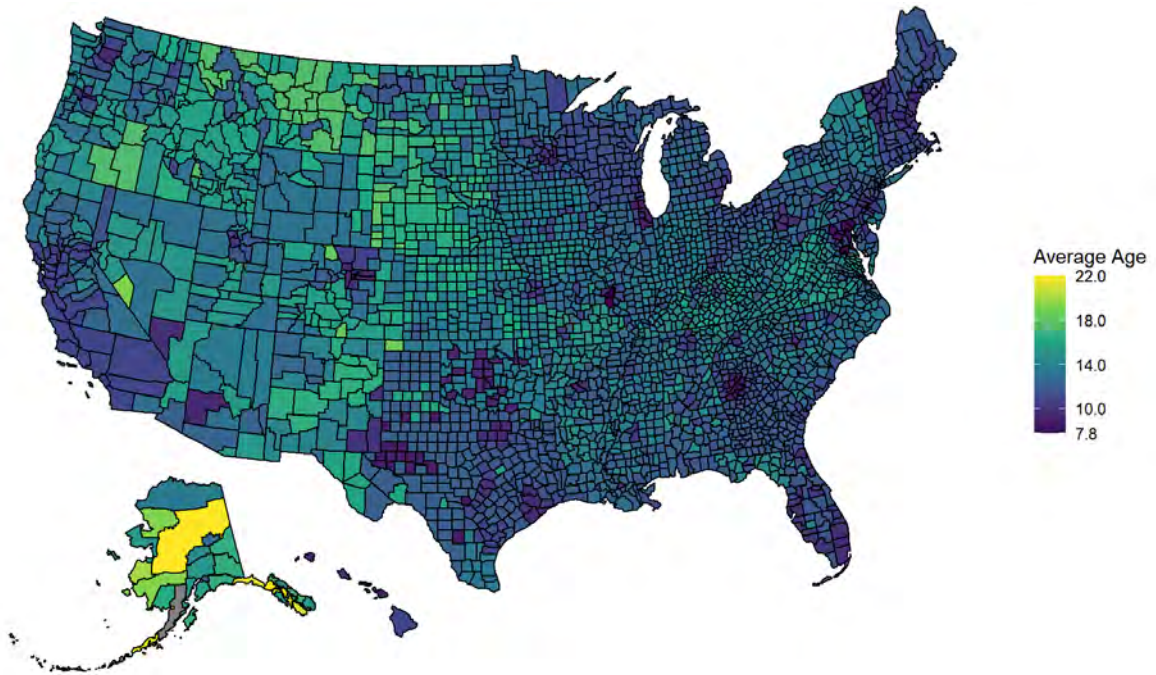


Figure 3-3 Projected average age of light commercial trucks in 2055

3.2.2.5 2055 Fuel Mix

The mix of the fuel types used in vehicles (or “fuel distributions”) for 2055 rely on national projections, which vary by scenario. The national projected fuel distributions for the reference case rely on July 1, 2020, vehicle registration data purchased from IHS Markit, vehicle sales projections from AEO2021,²⁰ EPA’s Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards,²² and CARB’s Advanced Clean Trucks regulation. More information about the national projected fuel distributions for the reference case can be found in the MOVES3.R1 technical report.¹⁸

Fuel distributions for the regulatory case assume a shift to more electric vehicles, with the market share for electric vehicles reaching about 50 percent of light and medium-duty sales. Additional details are available in the Draft RIA.

The goal of the representative county fuel distribution projection was to maintain differences between counties, while simultaneously maintaining the projected national average electric vehicle (EV) penetration rates. That is, counties with higher-than-average fractions of EVs in 2020 are assumed to have higher-than-average fractions of EVs in the future reference and regulatory scenario. The fundamental approach to solving this problem was to define how a

²² U.S. EPA (2021). Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards (86 FR 74434, December 30, 2021)

local area is different from the national average, and then apply that difference with the appropriate weighting to future years.

The 2020 vehicle registration data were subset for all counties represented by a representative county, and the local EV fraction for model year 2019 (the most recent complete model year in the registration data) was calculated by dividing the number of EVs by the total number of vehicles for each light-duty source type. The local EV fraction was divided by the national EV fraction to obtain the local to national ratio for each representative county.

Since EVs are not randomly distributed throughout the country (they are more likely to appear in areas that incentivize EVs), these ratios were weighted based on the vehicle populations in the local area, so that the national average EV fraction was maintained. Specifically, a national average ratio was calculated for each source type and model year, weighted by the source type and model year VPOP in each local area; the local ratios were then divided by this national average ratio, so that the effective national average ratio was 1.

Additionally, EPA assumes that as EVs become more prevalent, they will be less concentrated geographically. Therefore, a maximum ratio value of 2.0 was chosen, representing that in the future, no county will have more than 2 times the EV penetration as the national average. In the algorithm description below, the "uncapped ratio" represents the local ratio as described above, and the "capped ratio" is the lesser of the uncapped ratio or 2.0.

To calculate light-duty fuel distributions in each representative county, the following algorithm was implemented for each source type and model year:

1. Calculate the local vehicle population (based on the SourceTypeYear and SourceTypeAgeDistribution tables in the CDB).
2. Calculate the uncapped EV fraction by multiplying the uncapped ratio by the national EV fraction.
3. Calculate the capped EV fraction by multiplying the capped ratio by the national EV fraction.
4. If the uncapped fraction is greater than the capped fraction, the number of excess EVs in this county is calculated by multiplying the vehicle population by the difference between the uncapped and capped fractions.
5. If the capped fraction is greater than 1.0 (this is possible when the national average EV fraction is greater than 50%), additional excess EVs are calculated by multiplying the vehicle population by the difference between the capped fraction and 1.0.
6. The number of EVs in the county is calculated by multiplying the vehicle population by the capped fraction or 1.0, whichever is less.
7. The internal combustion engine (ICE) fraction is 1 minus the EV fraction. Gasoline counts are calculated by multiplying the ICE fraction by AEO gasoline sales divided

by AEO (gasoline + diesel + FFV sales). Diesel and FFV counts are calculated similarly.

8. Steps 1-7 are performed for each representative county.
9. Excess EVs are reallocated to all representative counties that have not reached their EV penetration cap. This is done proportionally across representative counties, weighted by the number of remaining ICE vehicles in each county. Within a representative county, the excess EVs proportionally reduce the number of ICE vehicles. If this reallocation would bring a county to over 100% EVs, the reallocation step is repeated until all excess EVs have been placed in a county.

Once all excess EVs were reallocated, the light-duty fuel distributions were formatted for use in the MOVES AVFT table and were stored in the CDBs.

Note that the heavy-duty fuel distributions were not assumed to vary geographically. The national average fuel distributions for all heavy-duty source types were used uniformly across all representative counties. The following figures compare the projected EV penetration rates by county in 2055 between the reference case and the regulatory case for each light-duty source type.

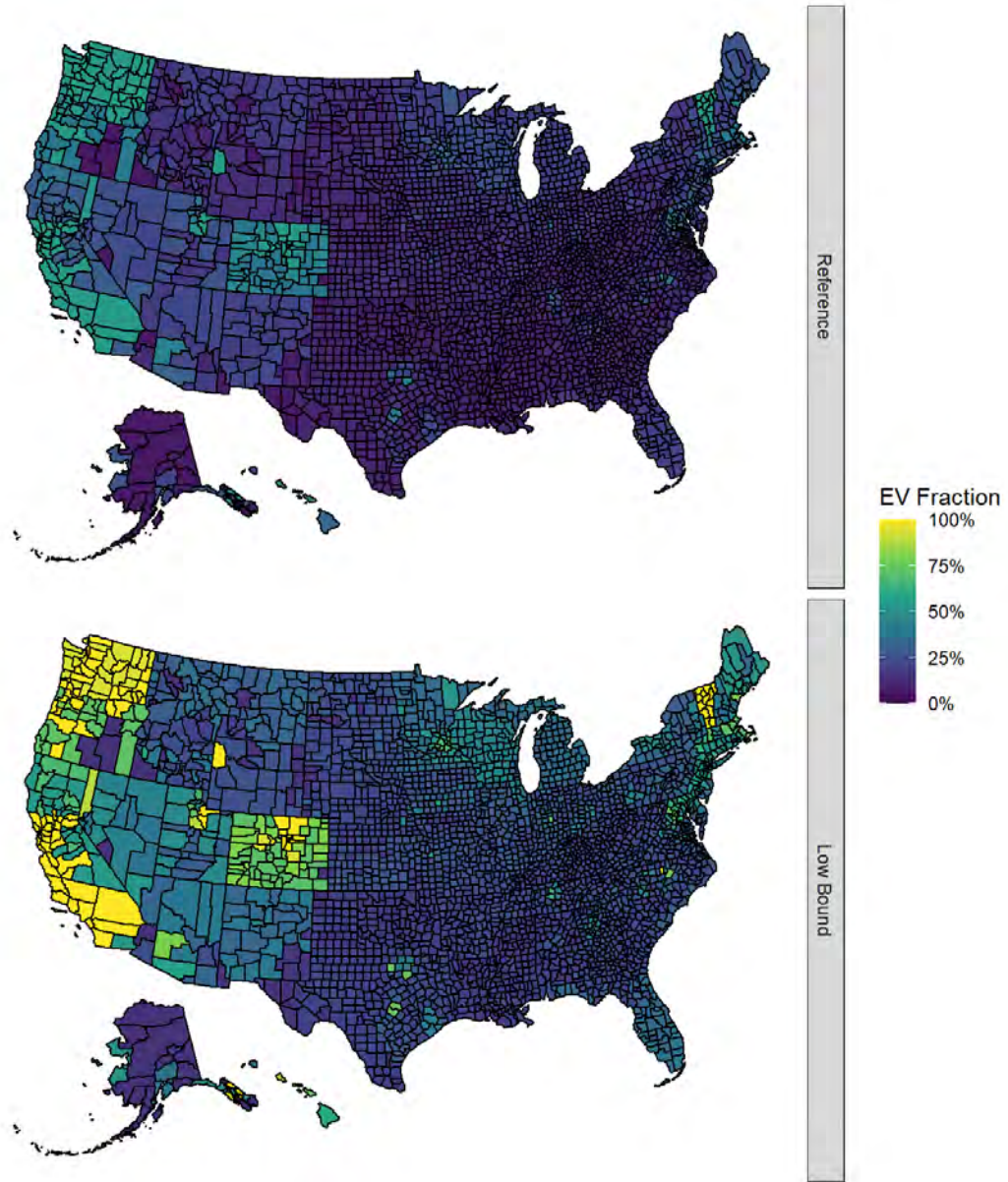


Figure 3-4 Comparing passenger car EV penetrations in 2055

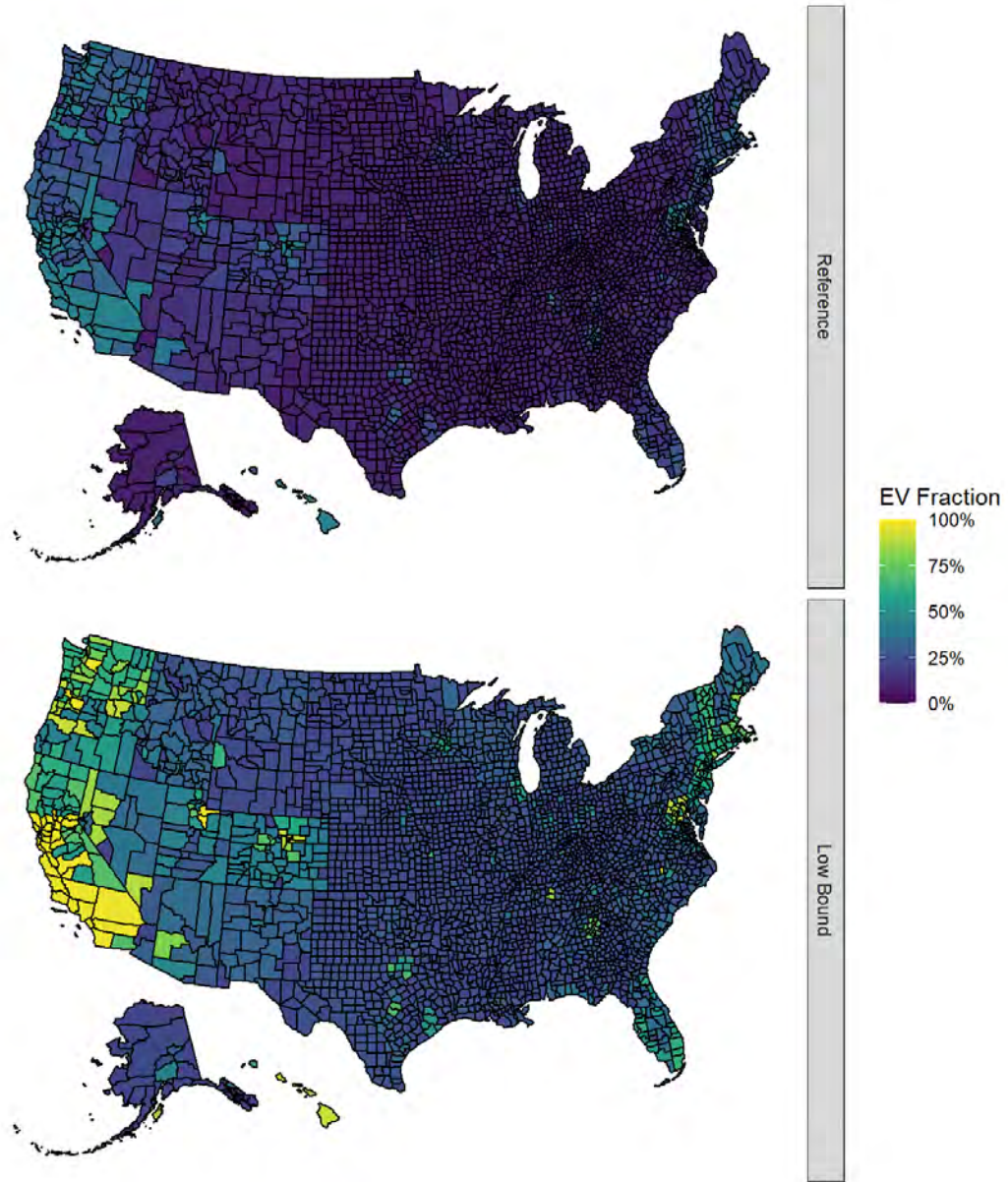


Figure 3-5 Comparing passenger truck EV penetrations in 2055

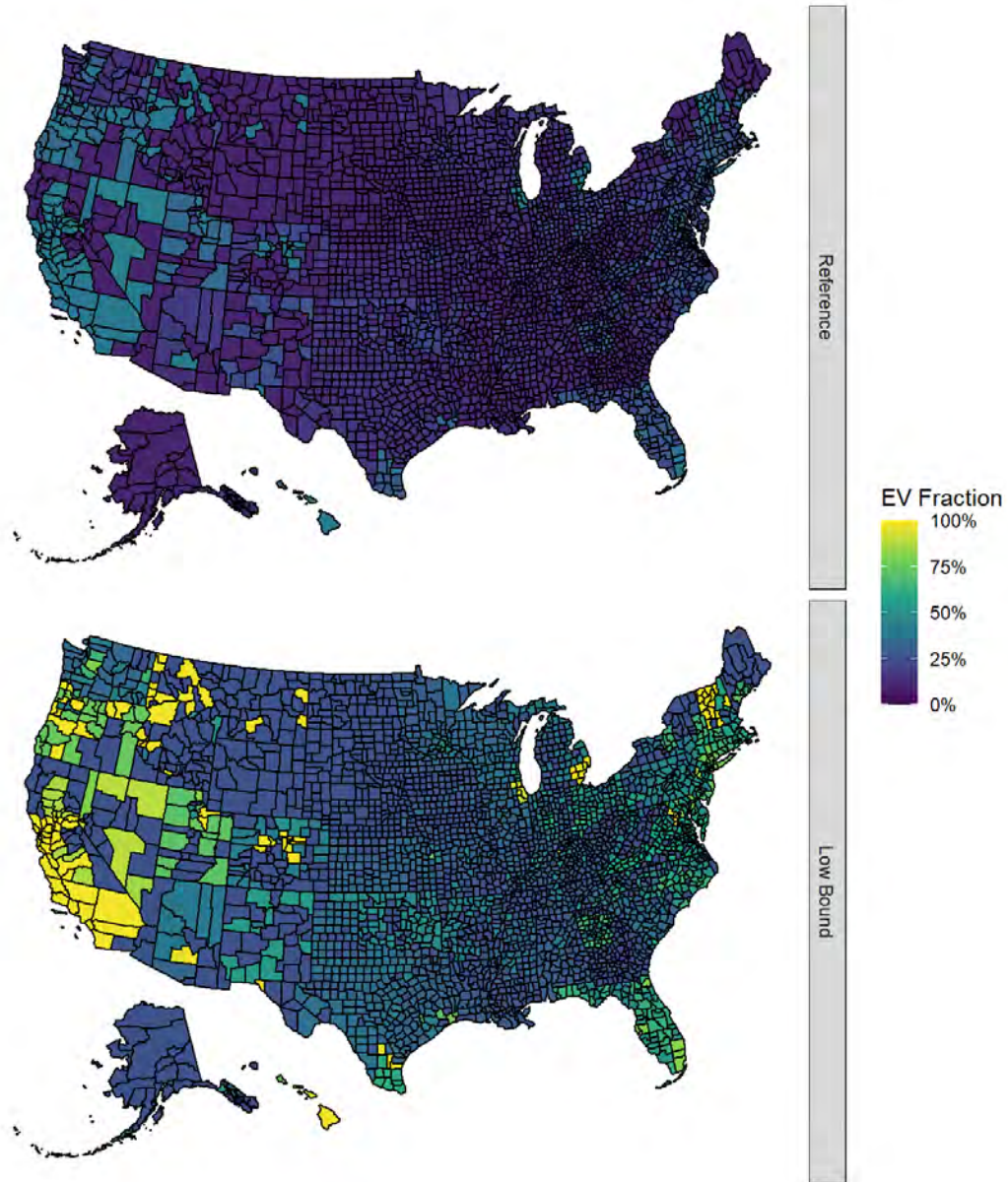


Figure 3-6 Comparing light commercial truck EV penetrations in 2055

3.3 Onroad Emissions Modeling

The SMOKE-MOVES process for creating the air quality model-ready onroad mobile emissions consists of the following steps:

- 1) Select the representative counties to use in the MOVES runs.
- 2) Determine which months will be used to represent other month's fuel characteristics.

- 3) Create inputs needed only by MOVES. MOVES requires county-specific information on vehicle populations, age distributions, speed distribution, road type distributions, temporal profiles, inspection-maintenance programs, and presence of Low Emission Vehicle (LEV) program for each of the representative counties.
- 4) Create inputs needed both by MOVES and by SMOKE, including temperatures and activity data.
- 5) Run MOVES to create emission factor tables for the temperatures and speeds that exist in each county during the modeled period.
- 6) Run SMOKE to apply the emission factors to activity data (VMT, VPOP, HOTELING, STARTS, ONI) to calculate emissions based on the gridded hourly temperatures in the meteorological data.
- 7) Aggregate the results to the county-SCC level for summaries and quality assurance.

The onroad emissions are processed as five components that are merged into the final onroad sector emissions:

- rate-per-distance (RPD) uses VMT as the activity data plus speed and speed profile information to compute on-network emissions from exhaust, evaporative, permeation, refueling, and brake and tire wear processes;
- rate-per-vehicle (RPV) uses VPOP activity data to compute off-network emissions from exhaust, evaporative, and permeation processes;
- rate-per-profile (RPP) uses VPOP activity data to compute off-network emissions from evaporative fuel vapor venting, including hot soak (immediately after a trip) and diurnal (vehicle parked for a long period) emissions;
- rate-per-start (RPS) uses START activity data to compute off-network emissions from vehicle starts;
- rate-per-hour (RPH) uses hoteling hours activity data to compute off-network emissions for idling of long-haul trucks from extended idling and auxiliary power unit process; and
- rate-per-hour-ONI (RPHO) uses off-network idling hours activity data to compute emissions for vehicles while idling off-network, (e.g., idling in a parking lot or unloading freight). This is a new emission calculation which was added to the CTI version of MOVES.

As described above, MOVES3.R1 was run for three scenarios: 2016, a 2055 reference case, and a 2055 regulatory case. Scenario specific EV fractions were developed for each representative county. MOVES was used to compute onroad emissions in California.

SCC descriptions for onroad emissions

SCCs in the onroad sector follow the pattern 220FVV0RPP, where:

- F = MOVES fuel type (1 for gasoline, 2 for diesel, 3 for CNG, 5 for E-85, and 9 for electric)
- VV = MOVES vehicle (aka source) type, see Table 3-1
- R = MOVES road type (1 for off-network, 2 for rural restricted, 3 for rural unrestricted, 4 for urban restricted, 5 for urban unrestricted)
- PP = SMOKE aggregate process. In the activity data, the last two digits of the SCC are always 00, because activity data is process independent. MOVES separately tracks over a dozen processes, but for computational reasons it is not practical to model all of these processes separately within SMOKE-MOVES. Instead, “aggregate” processes are used in SMOKE. To support this, the MOVES processes are mapped to SMOKE aggregate processes according to Table 3-2. The MOVES3.R1 model includes a process, 92 that corresponds to emissions from off-network idling (ONI).

Table 3-1 MOVES vehicle types

MOVES Vehicle Type	Description
11	Motorcycle
21	Passenger Car
31	Passenger Truck
32	Light Commercial Truck
41	Intercity Bus
42	Transit Bus
43	School Bus
51	Refuse Truck
52	Single Unit Short-haul Truck
53	Single Unit Long-haul Truck
54	Motor Home
61	Combination Short-haul Truck
62	Combination Long-haul Truck

Table 3-2 SMOKE-MOVES aggregate processes

MOVES Process ID	Process description	SMOKE aggregate process
01	Running Exhaust	72
02	Start Exhaust	72
09	Brakewear	40
10	Tirewear	40
11	Evap Permeation	72
12	Evap Fuel Vapor Venting	72
13	Evap Fuel Leaks	72
15	Crankcase Running Exhaust	72
16	Crankcase Start Exhaust	72
17	Crankcase Extended Idle Exhaust	53
18	Refueling Displacement Vapor Loss	62
19	Refueling Spillage Loss	62
90	Extended Idle Exhaust	53
91	Auxiliary Power Exhaust	91
92	Off-network Idle Exhaust	92

3.3.1 Spatial Surrogates

Onroad county activity data were allocated to a national 12 km grid for air quality modeling using spatial surrogates. For all processes other than the ONI process present in the MOVES3.R1 model, the spatial surrogates used to allocate onroad activity to the national 12km grid are the same as in the 2016v2 platform and are described in the 2016v2 platform TSD. ONI and other off-network activity data including VPOP and STARTS were spatially allocated using the surrogates listed in Table 3-3.

Table 3-3 Spatial surrogates for on-network idling (ONI)

Source Type	Description	Spatial Surrogate	Description
11	Motorcycle	307	NLCD All Development
21	Passenger Car	307	NLCD All Development
31	Passenger Truck	307	NLCD All Development
32	Light Commercial Truck	308	NLCD Low + Med + High
41	Other Bus (non-transit, non-school)	258	Other Bus Terminals
42	Transit Bus	259	Transit Bus Terminals
43	School Bus	506	Education
51	Refuse Truck	306	NLCD Med + High
52	Single Unit Short-haul Truck	306	NLCD Med + High
53	Single Unit Long-haul Truck	306	NLCD Med + High
54	Motor Home	304	NLCD Open + Low
61	Combination Short-haul Truck	306	NLCD Med + High
62	Combination Long-haul Truck	306	NLCD Med + High

3.3.2 Temporal Profiles

For on-network and hoteling emissions, VMT and hoteling activity were temporally allocated from annual or monthly values to hourly and SMOKE was run for every day of the year. The temporal profiles for VMT and hoteling activity are the same as in the 2016v1 platform and are

described in more detail in the 2016v1 platform TSD. ONI monthly activity data were temporally allocated to hourly values using a subset of the temporal profiles that are used to temporally allocate VMT. VMT data were temporally allocated using temporal profiles which vary by region (e.g., county, MSA), source type, and road type. ONI activity was developed for each county and source type, but not road type. This means ONI cannot be temporalized in exactly the same way as VMT. Instead, a subset of the VMT temporal profiles was selected to be applied to ONI. Only temporal profiles for unrestricted road types were chosen to be used for ONI, since off-network idling activity is assumed to better match the temporal pattern of unrestricted road type driving, rather than on freeways. There are also different VMT temporal profiles for urban road types and rural road types. ONI activity has no urban or rural designation, and so within each county, we can only apply either a rural temporal profile or an urban temporal profile. Therefore, we used the MOVES3.R1 county classification as either an urban county or a rural county for the purposes of choosing appropriate temporal profiles for ONI in each county.²³ In urban counties, ONI activity was temporally allocated using VMT profiles for urban unrestricted roads, and in rural counties, For rural unrestricted roads, ONI activity was temporally allocate using VMT profiles.

3.3.3 Chemical Speciation

Chemical speciation of onroad emissions is internal to MOVES except for brake and tire-wear particulate matter (PM) speciation, which occurs in SMOKE. The emission factor tables from MOVES include both unspciated emissions totals in grams for criteria air pollutants (CAPs) and hazardous air pollutants (HAPs), and speciated emissions totals for CB6 model species in moles (or grams for PM). The speciation cross reference (GSREF) and speciation profile (GSPRO) input files used by SMOKE-MOVES do not do any actual speciation. The GSREF file has no function and only exists to prevent a SMOKE error. The GSPRO and mobile emissions process and pollutant (MEPROC) files in SMOKE work in tandem to select which species and pollutants to include in SMOKE outputs. The MEPROC includes all unspciated pollutants, and the GSPRO maps unspciated pollutants to individual model species (e.g., brake wear PM2_5 to all individual PM species). Model-ready emissions files will include all species in the GSPRO that are mapped to one or more pollutants present in the MEPROC. Movesmrg reports include all of those model species, plus all of the pollutants listed in the MEPROC.

3.3.4 Other Ancillary Files

SMOKE-MOVES requires several other types of ancillary files to prepare emissions for air quality modeling:

- Mobile county cross reference (MCXREF): Maps individual counties to representative counties.
- Mobile fuel month cross reference (MFMREF): Maps actual months to fuel months for each representative county. May through September are mapped to the July fuel month, and all other months to the January fuel month.

²³ USEPA (2020). *Population and Activity of On-road Vehicles in MOVES CTI NPRM*. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI.

- MOVES lookup table list (MRCLIST): Lists emission factor table filenames for each representative county.
- Mobile emissions processes and pollutants (MEPROC): Lists which pollutants to include in the SMOKE run.
- Meteorological data for MOVES (METMOVES): Gridded daily minimum and maximum temperature data. This file is created by the SMOKE program Met4moves and is used for RatePerProfile (RPP) processing.

4 EGU Emissions Inventory Methodology

This section focuses on the approach and data sources used to develop gridded, hourly emissions for the electrical generating unit (EGU) or “power plant” sector that are suitable for input to an air quality model in terms of the format, grid resolution, and chemical species.

4.1 Integrated Planning Model (IPM)

The 2055 EGU emissions inventories were developed from the output of the Pre-IRA 2022 Reference Case run of the Integrated Planning Model (IPM). This version of IPM included EGU fleet information, and rules and regulations that were final at the time the IPM version was finalized, but not impacts due to the Inflation Reduction Act (IRA).²⁴ IPM is a linear programming model that accounts for variables and information such as energy demand, planned unit retirements, and planned rules to project unit-level energy production and configurations.

4.2 IPM Inputs

The following specific rules and regulations are included in the IPM run:

- The Revised Cross-State Air Pollution Rule (CSAPR) Update, a federal regulatory measure affecting EGU emissions from 12 states to address transport under the 2008 National Ambient Air Quality Standards (NAAQS) for ozone.
- The Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units through rate limits.
- The Mercury and Air Toxics Rule (MATS) finalized in 2011. MATS establishes National Emissions Standards for Hazardous Air Pollutants (NESHAP) for the “electric utility steam generating unit” source category.
- Current and existing state regulations, including current and existing Renewable Portfolio Standards and Clean Energy Standards as of the summer of 2021.

²⁴ <https://www.epa.gov/power-sector-modeling/pre-ira-2022-reference-case>

- The latest actions EPA has taken to implement the Regional Haze Regulations and Guidelines for Best Available Retrofit Technology (BART) Determinations Final Rule. The regulation requires states to submit revised State Implementation Plans (SIPs) that include (1) goals for improving visibility in Class I areas on the 20% worst days and allowing no degradation on the 20% best days and (2) assessments and plans for achieving Best Available Retrofit Technology (BART) emission targets for sources placed in operation between 1962 and 1977. Since 2010, EPA has approved SIPs or, in a few cases, put in place regional haze Federal Implementation Plans for several states. The BART limits approved in these plans (as of summer 2020) that will be in place for EGUs are represented in the Summer 2021 Reference Case.
- California AB 32 CO2 allowance price projections and the Regional Greenhouse Gas Initiative (RGGI) rule.
- Three non-air federal rules affecting EGUs: National Pollutant Discharge Elimination System Final Regulations to Establish Requirements for Cooling Water Intake Structures at Existing Facilities and Amend Requirements at Phase I Facilities, Hazardous, and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities; and the Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category.

IPM is run for a set of years, including 2050 and 2055. 2055 was the furthest out year in this set of runs so in order to avoid end of timeframe issues we used the 2050 outputs and assumed they are constant through 2055. All inputs, outputs and full documentation of EPA's IPM Pre-IRA 2022 Reference Case and the associated NEEDS version is available on the power sector modeling website (<https://www.epa.gov/power-sector-modeling/pre-ira-2022-reference-case>).

Some of the key parameters used in the IPM run are:

- Demand: AEO 2021
- Gas and Coal Market assumptions: updated as of December 2021
- Cost and performance of fossil generation technologies: AEO 2021
- Cost and performance of renewable energy generation technologies: NREL ATBG 2021 (mid-case)
- Nuclear unit operational costs: AEO 2020 with some adjustments
- Environmental rules and regulations (on-the-books): Revised CSAPR, MATS, BART, CA AB 32, RGGI, various RPS and CES, non-air rules (Cooling Water Intake, ELC, CCR), State Rules. This version does not include IRA
- Financial assumptions: 2016-2020 data, reflects tax credit extensions from Consolidated Appropriations Act of 2021
- Transmission: updated data with build options

- Retrofits: carbon capture and sequestration option for CCs
- Operating reserves (in select runs): Greater detail in representing interaction of load, wind, and solar, ensuring availability of quick response of resources at higher levels of RE penetration
- Fleet: Summer 2021 reference case NEEDS

4.2.1 IPM Energy Demand Inputs

4.2.1.1 LMDV Reference Case

IPM requires an electricity demand, and the default electricity demand for the version of IPM used in this analysis is based on AEO2021, which does not include the full forecasted zero emission vehicle (ZEV) adoption in its reference case. Relative to AEO2021, the LMDV reference case has increased HD ZEV adoption and LD BEV adoption (to account for EPA’s Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards (LD GHG 2023–2026) final rule (86 FR 74434, December 30, 2021)).²⁵ Therefore, we developed IPM input files specific to the demand of electric vehicles not captured by IPM’s defaults, which we call incremental demand input files.

We used the output of national MOVES3.R1 runs to develop the set of IPM incremental demand input files for the LMDV reference scenario.²⁶ Electricity demand was calculated using the MOVES national modeling domain, with output by each type of day (i.e., for an average weekday and weekend). IPM requires grid demand to be specified by day type, by each of IPM’s geographic regions, and by each hour of the day.

IPM requires grid demand to be geographically allocated by IPM region. We developed regional allocation factors based on county-level CO₂ emissions in the 2016v2 emissions modeling platform.^{27,28} We used CO₂ emissions as our basis for regional allocation because CO₂ scales well with VMT while capturing differing fleet characteristics in different counties. IPM includes a mapping of each county to an IPM region, which we used to aggregate county allocation factors by IPM region.

Inputs to the IPM model include not only the anticipated electricity demand from plug-in electric vehicles (PEVs), but also how that demand is distributed by time of day. This will depend on when PEVs charge. We develop and apply charging profiles to reflect the share of demand from PEV charging that we assume occurs each hour on weekdays and weekends.

²⁵ Beardsley, Megan. 2023. “Updates to MOVES for the Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles.” Memorandum to the Docket EPA-HQ-OAR-2022-0829.

²⁶ US EPA, 2023. “Incremental Demand Input Files for the Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles.” Memorandum to the Docket EPA-HQ-OAR-2022-0829.

²⁷ The emissions modeling platform is a product of the National Emissions Inventory Collaborative consistent of more than 245 employees of state and regional air agencies, EPA, and Federal Land Management agencies. It includes a full suite of base year (2016) and projection year (2023 and 2028) emission inventories modeled using EPA’s full suite of emissions modeling tools, including MOVES, SMOKE, and CMAQ.

²⁸ U.S. EPA. “2016v2 Platform”. January 23, 2023. Available online: <https://www.epa.gov/air-emissions-modeling/2016v2-platform>

We source charging profiles for light-duty PEVs from the Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite developed by the National Renewable Energy Laboratory in collaboration with others.²⁹ EVI-Pro Lite allows users to generate charging profiles³⁰ for different scenarios based on the number³¹ and mix of vehicles, daily vehicle miles traveled, ambient temperature, and availability and preference for certain charging types and charging strategies. While full customization isn't possible in the tool, we generally tried to make selections among the available options most consistent with our reference case where applicable, using default selections for other variables.³² The resulting weekday and weekend charging profiles³³ are shown in Figure 4-1.

²⁹ U.S. Department of Energy, Alternative Fuels Data Center. 2023. "Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite." Available at: <https://afdc.energy.gov/evi-pro-lite/load-profile>.

³⁰ The tool asks users to select a city or urban area, which changes default selections for average ambient temperature and vehicle miles traveled. Since we use the resulting profiles nationwide, we made selections (e.g., 50°F) intended to reflect that.

³¹ We selected 30,000 PEVs (the highest default option available in the tool). However, it is important to note that we do not use the charging profiles from EVI-Pro Lite to estimate the amount of PEV demand. Rather, we use the profiles only to distribute our estimate of PEV demand for the Reference and Regulatory cases by hour of day.

³² We made the following selections: average daily miles traveled per vehicle: 35 miles; average ambient temperature: 50°F; PEVs that are all-electric: 75% (highest available option); PEVs that are sedans: 50%; mix of workplace charging: 20% Level 1 and 80% Level 2; access to home charging: 75%; mix of home charging: 50% Level 1 and 50% Level 2; preference for home charging: 100%; home charging strategy: immediate - as fast as possible; work charging strategy: immediate - as fast as possible.

³³ Profiles from the EVI-Pro Lite tool are generated in 15-minute increments. Here we have aggregated to hourly shares for use in IPM. We also normalized profiles such that the sum of hourly demand shares totals 100%.

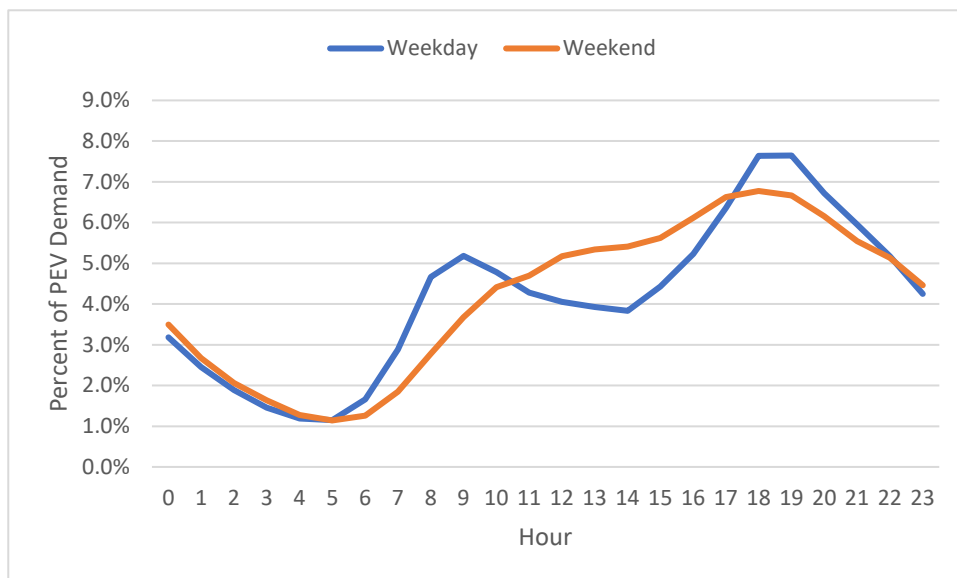


Figure 4-1: Charging profiles for light-duty PEV demand in the reference Case³⁴

Heavy-duty vehicles comprise a broad spectrum of vehicle types and applications, and we would expect charging patterns to vary accordingly. For this reason, we develop individual charging profiles for seven vehicle categories: transit buses, school buses, other buses, refuse trucks, single unit short-haul trucks, combination short-haul trucks, and motorhomes. We start from data on vehicle soaks (or times when vehicles are not operating) in MOVES3.R1 for each of the above categories. For our analysis, we considered only soak lengths that were greater than or equal to 12 hours, using this as a proxy for when vehicles may be parked at a depot, warehouse, or other off-shift location and may have an opportunity to charge. How long a particular vehicle will take to charge will depend on a variety of factors including the vehicle’s daily electricity consumption and the power level of the charging equipment. The time that charging occurs will also depend on the charging preferences of BEV owners or operators. Some may choose to start charging as soon as the vehicle is parked, while others may delay charging to accommodate other vehicles in a fleet, take advantage of time-of-use electricity rates, or for other reasons. In developing national, fleetwide profiles, we made the simplifying assumption that charging demand would be evenly distributed across the 12 hours before vehicles start daily operation, i.e. when the soak periods end.³⁵

As a final step, we weight the seven individual charging profiles by the relative share of electricity demand for each vehicle category in MOVES3.R1 under the reference case. The resulting aggregate weekday and weekend profiles are shown in Figure 4-2.

³⁴ We use light-duty charging profiles to distribute PEV demand for cars, passenger trucks, and light commercial trucks (MOVES vehicle types 21, 31, and 32, see Table 3-1).

³⁵ See “Heavy-duty BEV Charging Profiles.xlsx,” available in the docket.

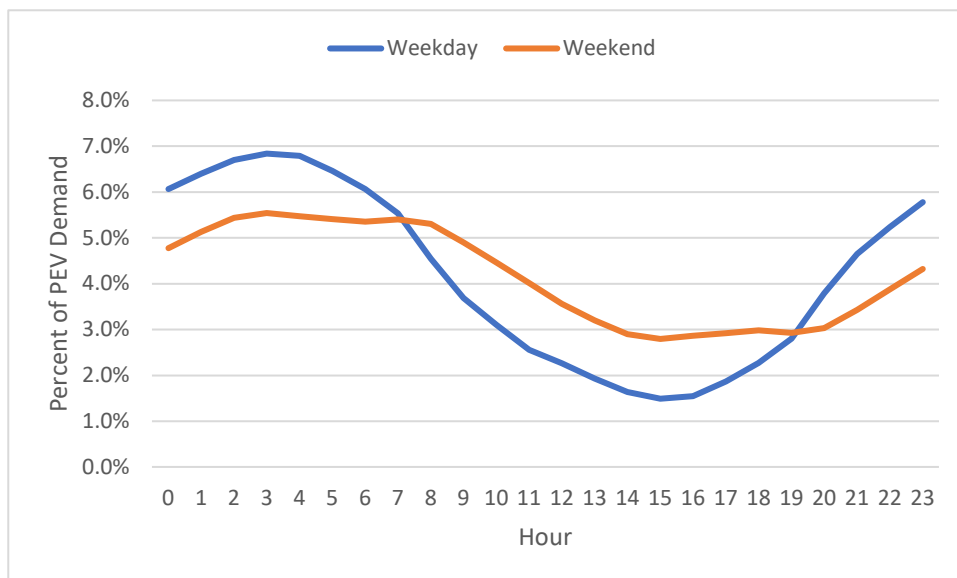


Figure 4-2: Charging profiles for heavy-duty PEV demand in the reference case³⁶

Finally, upstream emissions that would be incurred for fuel cell electric vehicles (FCEVs) due to the production of hydrogen are not captured by MOVES. We made a simplifying assumption that all hydrogen used to fuel FCEVs is produced via the electrolysis of water, and thus in this analysis, all hydrogen production is represented as additional demand to EGUs and the emissions are modeled using IPM. Hydrogen in the U.S. today is primarily produced via steam methane reforming (SMR) largely in support of petroleum refining and ammonia production. New transportation demand and economic incentives may shift how hydrogen is produced, and electrolysis is a key mature technology for hydrogen production. The relative emissions impact of hydrogen production via SMR versus electrolysis depends on the source of electricity generation, and this varies significantly by region across the country. Electrolysis powered by electricity from the grid on average in the U.S. may overestimate the upstream emissions impacts that are attributable to HD FCEVs in the near-term.

We developed yearly scalar multipliers which were applied to MOVES FCEV energy consumption to represent total grid demand from the hydrogen production necessary to support the projected levels of FCEVs. First, we assumed hydrogen is produced by a series of decentralized, grid-powered polymer electrolyte membrane (PEM) electrolyzer systems, each with a hydrogen production capacity around 1,500 kilograms per day.^{37,38} Next, we assumed the gaseous hydrogen is compressed and pre-cooled for delivery to vehicles using grid-powered electrical equipment. Finally, we assumed a linear improvement between our estimated current and future efficiency for hydrogen production. The linear interpolation is between current values

³⁶ We use heavy-duty charging profiles to distribute demand for PEVs of MOVES vehicle type 41 and higher (see Table 3-1).

³⁷ This is based on assumptions from the Hydrogen Analysis Production (H2A) Model from the National Renewable Energy Laboratory (NREL).

³⁸ National Renewable Energy Laboratory (NREL). “H2A: Hydrogen Analysis Production Model: Version 3.2018”. Available online: <https://www.nrel.gov/hydrogen/h2a-production-archive.html>

that start in 2025 and future values represented for 2055, assuming a period of diffusion for more efficient electrolysis technology improvements to spread. The final scaling factors range from 1.748 in 2025 to 1.616 in 2055.

4.2.1.2 LMDV Regulatory Case

Similar to the LMDV reference case incremental demand input files described in Chapter 4.2.1.1, we used output from a national MOVES 3R.1 run to develop the set of IPM incremental demand input files for the LMDV regulatory scenario.³⁹

We use the same charging profiles for light-duty PEV demand in our regulatory case as in the Reference case (see Figure 4-1). For heavy-duty charging profiles, we start from the same charging profiles developed for each of the seven vehicle types, but apply weightings from MOVES 3.R1 for the regulatory case. The resulting profiles are show in Figure 4-3.

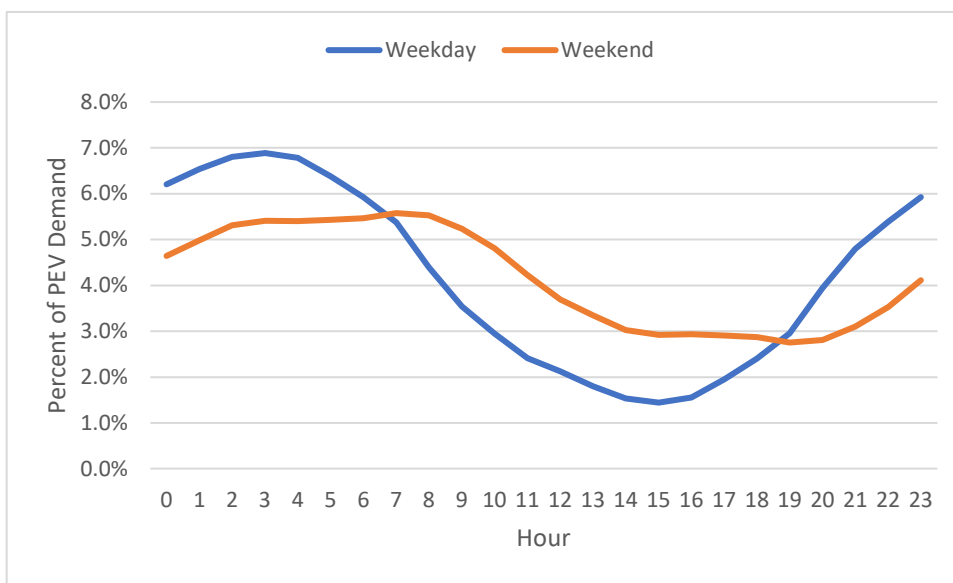


Figure 4-3: Charging profiles for heavy-duty PEV demand in the regulatory case

4.3 Air Quality Model-Ready EGU inventory generation

The EGU emissions are calculated for the inventory using the output of the IPM model for the forecast year. Units that are identified to have a primary fuel of landfill gas, fossil waste, non-fossil waste, residual fuel oil, or distillate fuel oil may be missing emissions values for certain pollutants in the generated inventory flat file. Units with missing emissions values are gapfilled using projected base year values.

The projections are calculated using the ratio of the future year seasonal generation in the IPM parsed file and the base year seasonal generation at each unit for each fuel type in the unit as derived from the 2018 EIA923 tables and the 2018 NEI. New controls identified at a unit in the IPM parsed file are accounted for with appropriate emissions reductions in the gapfill projection values. When base year unit-level generation data cannot be obtained no gapfill value is

³⁹ US EPA, 2023. “Incremental Demand Input Files for the Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles.” Memorandum to the Docket EPA-HQ-OAR-2022-0829.

calculated for that unit. Additionally, some units, such as landfill gas, may not be assigned a valid SCC in the initial flat file. The SCCs for these units are updated based on the base year SCC for the unit-fuel type. Combined cycle units produce some of their energy from process steam that turns a steam turbine. The IPM model assigns a fraction of the total combined cycle production to the steam turbine. When the emissions are calculated these steam units are assigned emissions values that come from the combustion portion of the process. In the base year NEI steam turbines are usually implicit to the total combined cycle unit. To achieve the proper plume rise for the total combined cycle emissions, the stack parameters for the steam turbine units are updated with the parameters from the combustion release point. Large EGUs in the IPM-derived flat file inventory are associated with hourly CEMS data for NO_x and SO₂ emissions values in the base year. To maintain a temporal pattern consistent with the 2016 base year, the NO_x and SO₂ values in the hourly CEMS inventories are projected to match the total seasonal emissions values in the future years.

5 Petroleum Sector Emissions Inventory Methodology

This section focuses on the approach and data sources used to develop adjusted gridded, hourly emissions for some of the sectors related to producing petroleum liquid fuels for mobile sources. While the emission factors used to develop emissions for the reference and control scenarios differed, the approach and data sources used to calculate emissions for both scenarios were consistent.

Emission sources related to producing petroleum liquid fuels for mobile sources include extracting, transporting, and storing crude oil, extracting, transporting, and storing natural gas, and refining and transporting and storing finished fuels like gasoline and diesel. These sources are described in the emissions modeling platform TSD in Section 2.1.2 (point oil and gas) and 2.2.4 (nonpoint oil and gas).⁴⁰

More details on the modeling of the petroleum sector emissions are in the following subsections and national emission summaries for key pollutants are provided in Section 6. The docketed spreadsheet “2055 LMDV AQM petroleum adjustment factors final.xlsx” presents the calculations described in this Section.

5.1 Refinery Emissions

5.1.1 Initial Projection of Refinery Emissions to 2050/2055

The starting point for developing refinery inventories for the illustrative air quality analysis was the 2016v2 emissions modeling platform, which includes projection years of 2023, 2026, and 2032.⁴¹ The 2032 refinery inventory from the 2016v2 emissions modeling platform was

⁴⁰ <https://www.epa.gov/air-emissions-modeling/2016v2-platform>

⁴¹ <https://www.epa.gov/air-emissions-modeling/2016v2-platform>

projected to 2050 using AEO2021 growth factors.^{42,43} We assumed no change in refinery emissions between 2050 and 2055. The national total refinery inventory is presented in Table 5-1, and see docketed spreadsheet “2050 national refinery summary for OTAQ.xlsx”.

Table 5-1 2016v2 Emissions Modeling Platform Refinery Inventory Projected to 2032 and 2055

Pollutant	Projected emissions in 2032 (tons/yr)	Projected emissions in 2055 (tons/yr)
NO _x	69,330	71,525
PM _{2.5}	19,919	19,514
SO ₂	30,777	29,347
VOC	64,019	58,675

5.1.2 Apportioning Total Refinery Emissions to Gasoline and Diesel Fuel Production

The projected 2055 refinery emissions inventory was apportioned to the refining of gasoline and diesel fuel by assuming that refinery emissions are correlated with the refinery’s energy demand and accounting for the estimated refinery’s fraction of input energy going towards producing gasoline or diesel. The energy demand was calculated from modeled refinery energy allocations.⁴⁴ The original energy allocations were adjusted to ignore modeled outputs that are not refinery products and converted from mass-based to volume-based percentages, see Table 5-2. Relative emission factors per unit of gasoline and diesel produced⁴⁵ were then used to generate the apportioned, pollutant-specific refinery inventory shown in Table 5-3.

Table 5-2 Refinery Energy Demand Percentages

	Refinery Energy Demand
Gasoline	59.2
Diesel	6.1
Other	34.7

⁴² Specifically, a projection packet was prepared for 2032->2050 using AEO2021 (except for the categories where we have been using AEO2020 instead of AEO2021, e.g. cement) for refineries. AEO categories were mapped to SCCs and SCC+NAICS combinations (with SCC+NAICS taking precedence if a mapping exists for the refinery NAICS, which are 32411/324110) using the usual industrial source AEO-SCC and AEO-SCC-NAICS xrefs from past platforms. Only refineries NAICS and SCCs which have refinery emissions were included when making the packet, so the 2032-2050 packet is not something that can be used to project the entire ptnonipm sector. Each record in the packet references the refineries NAICS so that it can be applied to the entire ptnonipm sector without changing any non-refineries.

⁴³ <https://www.eia.gov/outlooks/archive/aeo21/>

⁴⁴ Table 1 in Wang et al, 2004. <http://dx.doi.org/10.1065/lca2003.07.129>

⁴⁵ Wang, Michael, Elgowainy, Amgad, Lee, Uisung, Bafana, Adarsh, Banerjee, Sudhanya, Benavides, Pahola T., Bobba, Pallavi, Burnham, Andrew, Cai, Hao, Gracida, Ulises, Hawkins, Troy R., Iyer, Rakesh K., Kelly, Jarod C., Kim, Taemin, Kingsbury, Kathryn, Kwon, Hoyoung, Li, Yuan, Liu, Xinyu, Lu, Zifeng, Ou, Longwen, Siddique, Nazib, Sun, Pingping, Vyawahare, Pradeep, Winjobi, Olumide, Wu, May, Xu, Hui, Yoo, Eunji, Zaimas, George G., and Zang, Guiyan. *Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model*® (2021 Excel). Computer Software. USDOE Office of Energy Efficiency and Renewable Energy (EERE). 11 Oct. 2021. Web. doi:10.11578/GREET-Excel-2021/dc.20210902.1.

Table 5-3 Refinery Inventory Apportioned to Gas, Diesel, and Other

Pollutant	Projected emissions in 2055 (tons/yr)
NO _x	71,525
gasoline	43,595
diesel	3,984
other	23,946
PM _{2.5}	19,514
gasoline	12,107
diesel	1,043
other	6,364
SO ₂	29,347
gasoline	17,503
diesel	1,715
other	10,129
VOC	58,675
gasoline	33,454
diesel	3,423
other	21,798

5.1.3 Identifying Refinery Emissions to Adjust for Illustrative Air Quality Analysis

The refineries report from the 2016v2 emissions modeling platform was reviewed to identify and remove from consideration any facilities that did not produce gasoline or diesel fuel for onroad vehicles, see docketed spreadsheet “2016v2_platform_refineries_report.xlsx”. The resulting list had 114 refineries that produce onroad fuel, see docketed spreadsheet “Refineries to Adjust LMDV and HDP3 NPRM.xlsx”.

5.1.4 Illustrative Air Quality Modeling Scenarios and Associated Refined Fuel Demand

Refinery inventories were calculated for two scenarios, a reference scenario and a LMDV regulatory scenario. Fuel demand volumes were used to adjust the original 2055 refinery inventory (Table 5-3) and create an updated 2055 reference scenario refinery inventory (that accounts for EPA’s Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards (LD GHG 2023–2026) final rule (86 FR 74434, December 30, 2021) and additional heavy-duty ZEV adoption) and a 2055 refinery inventory that reflects the LMDV regulatory scenario.

The onroad fuel consumed and total refined fuel supplied associated with the original refinery inventory that is presented in Table 5-3 are from AEO2021⁴⁶ and are presented in Table 5-4. Both volumes are projections for 2050 that we assume stay constant through 2055.

⁴⁶ <https://www.eia.gov/outlooks/aeo/data/browser/#/?id=46-AEO2021®ion=0-0&cases=ref2021&start=2019&end=2050&f=A&linechart=ref2021-d113020a.2-46-AEO2021&sourcekey=0>

Table 5-4 Fuel Volumes from AEO2021 Reference Case (billion gallons/yr)

	Onroad Fuel Consumed^a	Total Refined Fuel Supplied^b
Gasoline	121.67	126.94
Diesel	36.73	54.91

^a Onroad fuel consumed from Table 36 of AEO2021, with units converted from trillion BTU

^b Total refined fuel supplied from Table 11 of AEO2021, with units converted from million barrels per day

The fuel demanded in 2055 by onroad vehicles (gallons of gasoline and gallons of diesel) in the LMDV reference scenario and LMDV regulatory scenario was generated using MOVES, see Table 5-5 and docketed spreadsheets “LMDV reference petroelumconsumption.xlsx” and “LMDV regulatory petroelumconsumption.xlsx”.

Table 5-5 2055 Onroad Fuel Demand for Illustrative Air Quality Analysis Scenarios from MOVES (billion gallons/yr)

	LMDV Reference Onroad Fuel Demand	LMDV Regulatory Onroad Fuel Demand
Gasoline	99.55	94.48
Diesel	38.21	37.05

There are methodological differences in how onroad fuel demand is calculated by MOVES and by AEO. An adjustment factor to account for the difference between MOVES3.R1 and AEO2021reference was applied to the MOVES onroad fuel demand numbers to make them more consistent with AEO Table 36, see Table 5-6.

Table 5-6 Factor to apply to MOVES fuel demand to make consistent with AEO fuel demand

Gasoline	0.995
Diesel	0.975

The reduction in onroad fuel demand due to the LMDV reference and LMDV regulatory scenarios was generated separately for gasoline and for diesel by subtracting the fuel demands in Table 5-5, once it was adjusted to account for AEO/MOVES methodological differences, from the AEO2021 onroad fuel demand in Table 5-4.

5.1.5 Projected Change in U.S. Refinery Activity Related to Decreased Domestic Demand

It was necessary to project how the reduced onroad fuel demand associated with the LMDV reference and LMDV regulatory scenarios would affect US refinery emissions since US refined product demand is also satisfied by imports, not just production by US refineries. We projected how the change in petroleum demand would affect US refinery production, averaged over the time period 2027-2050, based on a comparison of two separate economic cases modeled by EIA in AEO2021: the Low Economic Growth Case and the Reference Case.⁴⁷ The AEO Low Economic Growth Case estimates lower refined product demand than that of the AEO Reference

⁴⁷ In this paragraph, Reference Case refers to the 2021 Annual Energy Outlook Reference Case, not the reference case used elsewhere in this chapter to evaluate the impacts of the proposal and alternative.

Case. Due to the reduced refined product demand, AEO estimates reduced US refinery production and reduced imports of crude oil refined products. The two AEO cases project that, for a volume of reduced gasoline or diesel fuel demand, 93% of the reduction is due to reduced US refinery production while seven percent can be attributed to imports of refined products, see attached spreadsheet "AEO 2021 Change in product demand on imports.xlsx". The reduced domestic demand (gallons of gasoline or diesel) is multiplied by 93% to estimate the reduction in domestically produced gasoline and diesel fuel.

5.1.6 Generation of Adjustment Factors

The reduced gallons of onroad gasoline and diesel that would be refined domestically was subtracted from the total refined fuel supplied in Table 5-4 and used to create an adjustment factor to be applied to the gasoline and diesel portions of the 2050 onroad refinery inventory, see Table 5-7. The resulting emissions, associated with refining gasoline and diesel fuel only, are presented in Table 5-8.

Table 5-7 Adjustment Factors to Apply to Apportioned 2050 Onroad Refinery Inventory

	LMDV Reference case	LMDV Regulatory Case
Gasoline	0.84	0.80
Diesel	1.03	1.01

Table 5-8 Projected 2055 Emissions from Refineries Associated with Producing Gasoline and Diesel Only

Scenario		NO_x (tons/yr)	PM_{2.5} (tons/yr)	SO₂ (tons/yr)	VOC (tons/yr)
LMDV Reference	gasoline	36,527	10,144	14,666	28,030
	diesel	4,084	1,069	1,757	3,509
LMDV Regulatory	gasoline	34,909	9,695	14,016	26,789
	diesel	4,006	1,049	1,724	3,441

A final adjustment factor, based on a ratio of the emissions associated with gas and diesel and the total refinery emissions, was then calculated for each of the illustrative air quality analysis scenarios, see Table 5-9.

Table 5-9 Adjustment Factor to Apply to 2050 Refinery Inventory

Scenario	NO_x	PM_{2.5}	SO₂	VOC
LMDV Reference	0.90	0.90	0.90	0.91
LMDV Regulatory	0.88	0.88	0.88	0.89

We recognize that there is significant uncertainty in the impact reduced fuel demand has on refinery emissions and that the refinery industry could respond in a different way to reduced domestic demand for gasoline and diesel fuel. Because many US refineries experience lower crude oil and natural gas prices than refineries elsewhere, they may continue their production of

refined products, and instead import less refined product, or increase exports of US refined products. If refineries do not decrease production in response to lower domestic demand, we would project no emission reductions from refineries rather than the reductions associated with the adjustment factors presented in Table 5-9. This method assumes that reduced demand would be spread evenly across all refineries, as a scalar of emissions.

5.2 Crude production well and pipeline emissions

5.2.1 Initial Projection of Crude Production Well Site and Pipeline Inventories to 2050/2055

The estimated emission inventories for crude production wells and associated pipelines in the 2016v2 emissions modeling platform for the year 2032 are projected to the year 2050 using AEO2021 reference case production forecast data in the year 2050 relative to that in the year 2032. The estimated crude production well and pipeline inventories were assumed to remain constant from 2050 to 2055.

5.2.2 Illustrative Air Quality Modeling Scenarios and Associated Crude Demand

The initial 2050/2055 crude production well and pipeline inventories for 2055 needed to be adjusted to reflect the impact of the LMDV reference and LMDV regulatory scenarios which reduced the domestic demand for liquid fuel, see Table 5-5.⁴⁸ The total reduced gallons of refined fuel consumed for each scenario were adjusted to account for refinery efficiency, using factors from Forman, et al (2014), to get reduced gallons of crude-equivalent finished fuel.^{49,50} Then the gallons of reduced crude-equivalent finished fuel were converted to gallons of reduced crude using the energy density of crude and gasoline and diesel fuel.⁵¹

5.2.3 Projected Change in U.S. Crude Production Activity Related to Decreased Domestic Demand

It was necessary to project how the reduced crude demand associated with the reference and LMDV regulatory scenarios would affect US crude production well and pipeline emissions since US crude demand is also satisfied by imports, not just domestic production. We projected how the change in crude demand would affect US crude production, averaged over the time period 2027-2050, based on a comparison of two separate economic cases modeled by EIA in AEO2021: the Low Economic Growth Case and the Reference Case.⁵² The AEO Low Economic Growth Case estimates lower crude demand than that of the AEO Reference Case. Due to the reduced crude demand, AEO estimates reduced US crude production and reduced imports of crude oil. The two AEO cases project that, for a volume of reduced crude demand, 8% of the reduction is due to reduced US crude production, see attached spreadsheet "AEO 2021 Change in product demand on imports.xlsx". The reduced domestic demand (gallons of crude) is multiplied by 8% to estimate the reduction in domestically produced crude.

⁴⁸ The calculations are provided on docketed spreadsheet "2055 LMDV AQM petroleum adjustment factors final.xlsx".

⁴⁹ Forman et al, 2014 dx.doi.org/10.1021/es501035a

⁵⁰ The conversion of crude oil to products may be more efficient than this value as this value represents the overall refinery efficiency, not the efficiency for converting crude oil into products.

⁵¹ Energy densities came from EIA, <https://www.eia.gov/energyexplained/units-and-calculators/>

⁵² In this paragraph, Reference Case refers to the 2021 Annual Energy Outlook Reference Case, not the reference case used elsewhere in this chapter to evaluate the impacts of the proposal and alternative.

5.2.4 Generation of Crude Production Well and Pipeline Adjustment Factors

The reduced gallons of crude that would be domestically produced was subtracted from the total crude produced in the AEO2021 reference case and used to create an adjustment factor to be applied to the crude production well and pipeline inventories, see Table 5-10 and Equation 1.

Equation 1

$$\text{Crude Production adjustment factor} = \frac{\text{AEO2021 reference case Bgal crude produced domestically in 2050} - \text{reduced crude produced domestically due to additional EV penetration}}{\text{AEO2021 reference case Bgal crude produced domestically in 2050}}$$

Table 5-10 Adjustment Factor Applied to Crude Gas Well and Pipeline Inventories to Generate AQM Scenarios

Scenario	Adjustment Factor
LMDV Reference	0.992
LMDV Regulatory Scenario	0.990

5.3 Natural gas production well and pipeline emissions

5.3.1 Initial Projection of Natural Gas Production Well Site and Pipeline Inventories to 2050/2055

Emission inventories for natural gas production wells and associated pipelines in the 2016v2 emissions modeling platform were projected from 2032 to 2050 using AEO2021 reference case production forecast data. The 2050 natural gas well and pipeline emission inventories were assumed to remain constant in the 2055 LMDV reference case.

5.3.2 Illustrative Air Quality Modeling Scenarios and Associated Natural Gas Demand

The 2050/2055 natural gas production well and pipeline inventories needed to be adjusted to reflect the impact of the LMDV regulatory scenarios, which increased the domestic demand for electricity, leading to more demand for natural gas.⁵³ Natural gas use projections (trillion cubic feet) from IPM are presented in Table 5-11, and AEO2021 reference case projections of the percentage of produced natural gas going to EGUs, are presented in Table 5-12.

Table 5-11 IPM projections of Natural Gas Usage, trillion cubic feet, in 2050

Scenario	Natural Gas Usage (Tcf)
LMDV Reference	11.61
LMDV Regulatory	11.99

⁵³ The calculations are provided on docketed spreadsheet “2055 LMDV AQM petroleum adjustment factors final.xlsx”.

Table 5-12 Projections of Natural Gas, in trillion cubic feet, in 2050

AEO2021 Reference case, Table 13	Natural Gas (Tcf)
Total Dry Gas Production	42.99
Consumption of Natural Gas by EGUs	12.13

5.3.3 Generation of Natural Gas Production Well and Pipeline Adjustment Factors

Based on the increased natural gas usage by EGUs indicated in Table 5-11, the LMDV regulatory case has 1.03% more natural gas usage than the LMDV reference case. The AEO projections from Table 5-12 indicate that 72% of the natural gas projected to be produced domestically in 2050 goes towards EGUs. The growth factor applied to the LMDV reference case natural gas well site and pipeline pump emission inventories to get the LMDV regulatory scenario natural gas well and pipeline pump emission inventories was 1.01, see Equation 2.

Equation 2

$$\text{Growth factor} = (1-0.28) + (0.28*1.03)$$

6 Inventory Summary Tables

This section includes summary tables of emission inventories used in the illustrative AQM analysis and described in this document.

Table 6-1 Modeled PM_{2.5} Emissions Used in Illustrative AQ Modeling (tons)

PM _{2.5}	2016 Base Year	2055 Reference Case	2055 LMDV Regulatory Case	Reference - LMDV Regulatory
Onroad Total (48 state)	104,005	35,737	26,833	8,904
Upstream Total (48 state)	167,795	92,358	94,533	-2,174
EGU	133,570	54,589	57,033	-2,444
Refinery	19,958	18,855	18,468	387
Crude Production Wells + Pipeline Pumps	3,393	4,824	4,814	10
Natural Gas Production Wells + Pipeline Pumps	10,875	14,091	14,217	-127
Total	271,800	128,096	121,365	6,730

Table 6-2 Modeled NO_x Emissions Used in Illustrative AQ Modeling (tons)

NO _x	2016 Base Year	2055 Reference Case	2055 LMDV Regulatory Case	Reference - LMDV Regulatory
Onroad Total (48 state)	3,444,356	729,707	683,096	46,610
Upstream Total (48 state)	2,067,563	920,948	933,078	-12,130
EGU	1,319,734	232,631	243,010	-10,379
Refinery	78,332	67,470	66,067	1,403
Crude Production Wells + Pipeline Pumps	161,605	221,243	220,800	442
Natural Gas Production Wells + Pipeline Pumps	507,891	399,604	403,201	-3,596
Total	5,511,919	1,650,655	1,616,174	34,481

Table 6-3 Modeled SO₂ Emissions Used in Illustrative AQ Modeling (tons)

SO ₂	2016 Base Year	2055 Reference Case	2055 LMDV Regulatory Case	Reference - LMDV Regulatory
Onroad Total (48 state)	1,342,456	498,495	392,534	105,961
Upstream Total (48 state)	2,415,830	2,762,121	2,770,666	-8,544
EGU	33,763	32,493	34,065	-1,572
Refinery	67,853	56,946	55,876	1,070
Crude Production Wells + Pipeline Pumps	1,229,169	1,455,550	1,452,639	2,911
Natural Gas Production Wells + Pipeline Pumps	1,085,046	1,217,132	1,228,086	-10,954
Total	3,758,286	3,260,616	3,163,200	97,417

Table 6-4 Modeled VOC Emissions Used in Illustrative AQ Modeling (tons)

VOC	2016 Base Year	2055 Reference Case	2055 LMDV Regulatory Case	Reference - LMDV Regulatory
Onroad Total (48 state)	1,342,456	498,495	392,534	105,961
Upstream Total (48 state)	2,415,830	2,762,121	2,770,666	-8,544
EGU	33,763	32,493	34,065	-1,572
Refinery	67,853	56,946	55,876	1,070
Crude Production Wells + Pipeline Pumps	1,229,169	1,455,550	1,452,639	2,911
Natural Gas Production Wells + Pipeline Pumps	1,085,046	1,217,132	1,228,086	-10,954
Total	3,758,286	3,260,616	3,163,200	97,417

Table 6-5 Modeled Onroad Emissions (short tons)

Pollutant	2016 Base Year	2055 Reference Case	2055 LMDV Regulatory Case	Base - Reference	% Change 2016 Base - 2055 Reference	Reference - LMDV Regulatory	% Change Reference - LMDV Regulatory
PM_{2.5}	104,005	35,737	26,833	68,268	-66%	8,904	-25%
NO_x	3,444,356	729,707	683,096	2,714,649	-79%	46,610	-6%
SO₂	24,918	7,280	7,112	17,638	-71%	168	-2%
VOC	1,342,456	498,495	392,534	843,961	-63%	105,961	-21%
CO	18,986,388	5,770,997	4,465,361	13,215,391	-70%	1,305,636	-23%
Acrolein	1,387	226	176	1,161	-84%	50	-22%
Acetaldehyde	13,454	4,207	3,443	9,247	-69%	765	-18%
Benzene	25,918	8,056	5,721	17,862	-69%	2,336	-29%
1,3-Butadiene	3,619	874	584	2,745	-76%	290	-33%
Ethylbenzene	19,865	7,880	6,154	11,985	-60%	1,727	-22%
Formaldehyde	18,286	3,433	2,945	14,853	-81%	488	-14%
Naphthalene	2,380	323	228	2,057	-86%	95	-29%

Table 6-6 Nonroad Emissions (short tons)

Pollutant	Year	
	2016	2055
PM_{2.5}	106,806	56,535
NO_x	1,115,733	671,502
SO₂	1,467	1,356
VOC	1,167,957	965,024
CO	11,384,766	15,262,152
Acrolein	2,080	595
Acetaldehyde	11,177	5,531
Benzene	29,135	28,423
1,3-Butadiene	4,591	4,890
Ethylbenzene	20,446	17,258
Formaldehyde	28,435	13,317
Naphthalene	1,944	1,413

Table 6-7 Fugitive Dust Emissions (short tons)

Pollutant	Year	
	2016	2055
PM_{2.5}	880,002	916,040

7 Air Quality Modeling Methodology

7.1 Air Quality Model – CMAQ

CMAQ is a non-proprietary computer model that simulates the formation and fate of photochemical oxidants, primary and secondary PM concentrations, acid deposition, and air toxics, over regional and urban spatial scales for given inputs of meteorological conditions and emissions. CMAQ includes numerous science modules that simulate the emission, production, decay, deposition and transport of organic and inorganic gas-phase and particle pollutants in the atmosphere. The CMAQ model is a well-known and well-respected tool and has been used in numerous national and international applications.⁵⁴ The air quality modeling completed for the rulemaking proposal used the 2016v2 platform with the most recent multi-pollutant CMAQ code available at the time of air quality modeling (CMAQ version 5.3.2).⁵⁵ The 2016 CMAQ runs utilized the CB6r3 chemical mechanism (Carbon Bond with linearized halogen chemistry) for gas-phase chemistry, and AERO7 (aerosol model with non-volatile primary organic aerosol) for aerosols. The CMAQ model is regularly peer-reviewed, CMAQ versions 5.2 and 5.3 beta were most recently peer-reviewed in 2019 for the U.S. EPA.⁵⁶

7.2 CMAQ Domain and Configuration

The CMAQ modeling analyses used a domain covering the continental United States, as shown in Figure 7-1. This single domain covers the entire continental U.S. (CONUS) and large portions of Canada and Mexico using 12 km × 12 km horizontal grid spacing. The 2016 simulation used a Lambert Conformal map projection centered at (-97, 40) with true latitudes at 33 and 45 degrees north. The model extends vertically from the surface to 50 millibars (approximately 17,600 meters) using a sigma-pressure coordinate system with 35 vertical layers. Table 7-1 provides some basic geographic information regarding the CMAQ domains and Table 7-2 provides the vertical layer structure for the CMAQ domain.

Table 7-1 Geographic elements of domains used in air quality modeling

	CMAQ Modeling Configuration
Grid Resolution	12 km National Grid
Map Projection	Lambert Conformal Projection
Coordinate Center	97 deg W, 40 deg N
True Latitudes	33 deg N and 45 deg N
Dimensions	396 × 246 × 35
Vertical extent	35 Layers: Surface to 50 millibar level (See Table 7-2)

⁵⁴ More information available at: <https://www.epa.gov/cmaq>.

⁵⁵ Model code for CMAQ v5.3.2 is available from the Community Modeling and Analysis System (CMAS) at: <http://www.cmascenter.org>.

⁵⁶ The Sixth External Peer Review of the Community Multiscale Air Quality (CMAQ) Modeling System. Available online at: https://www.epa.gov/sites/production/files/2019-08/documents/sixth_cmaq_peer_review_comment_report_6.19.19.pdf.

Table 7-2 Vertical layer structure for CMAQ domain

Vertical Layers	Sigma P	Pressure (mb)	Approximate Height (m)
35	0.0000	50.00	17,556
34	0.0500	97.50	14,780
33	0.1000	145.00	12,822
32	0.1500	192.50	11,282
31	0.2000	240.00	10,002
30	0.2500	287.50	8,901
29	0.3000	335.00	7,932
28	0.3500	382.50	7,064
27	0.4000	430.00	6,275
26	0.4500	477.50	5,553
25	0.5000	525.00	4,885
24	0.5500	572.50	4,264
23	0.6000	620.00	3,683
22	0.6500	667.50	3,136
21	0.7000	715.00	2,619
20	0.7400	753.00	2,226
19	0.7700	781.50	1,941
18	0.8000	810.00	1,665
17	0.8200	829.00	1,485
16	0.8400	848.00	1,308
15	0.8600	867.00	1,134
14	0.8800	886.00	964
13	0.9000	905.00	797
12	0.9100	914.50	714
11	0.9200	924.00	632
10	0.9300	933.50	551
9	0.9400	943.00	470
8	0.9500	952.50	390
7	0.9600	962.00	311
6	0.9700	971.50	232
5	0.9800	981.00	154
4	0.9850	985.75	115
3	0.9900	990.50	77
2	0.9950	995.25	38

Vertical Layers	Sigma P	Pressure (mb)	Approximate Height (m)
1	0.9975	997.63	19
0	1.0000	1000.00	0



Figure 7-1 Map of the CMAQ 12 km modeling domain (noted by the purple box)

7.3 CMAQ Inputs

The key inputs to the CMAQ model include emissions from anthropogenic and biogenic sources, meteorological data, and initial and boundary conditions.

The emissions inputs are summarized in earlier sections of this document.

The CMAQ meteorological input files were derived from simulations of the Weather Research and Forecasting Model (WRF) version 3.8 for the entire 2016 year.^{57,58} The WRF Model is a state-of-the-science mesoscale numerical weather prediction system developed for both operational forecasting and atmospheric research applications.⁵⁹ The meteorological outputs from WRF were processed to create 12 km model-ready inputs for CMAQ using the Meteorology-Chemistry Interface Processor (MCIP) version 4.3. These inputs included hourly varying horizontal wind components (i.e., speed and direction), temperature, moisture, vertical diffusion rates, and rainfall rates for each grid cell in each vertical layer.⁶⁰

The boundary and initial species concentrations were provided by a northern hemispheric CMAQ modeling platform for the year 2016.^{61,62} The hemispheric-scale platform uses a polar stereographic projection at 108 km resolution to completely and continuously cover the northern hemisphere for 2016. Meteorology is provided by WRF v3.8. Details on the emissions used for hemispheric CMAQ can be found in the 2016 hemispheric emissions modeling platform TSD.⁶³ The atmospheric processing (transformation and fate) was simulated by CMAQ (v5.2.1) using the CB6r3 and the aerosol model with non-volatile primary organic carbon (AE6nvPOA). The CMAQ model also included the on-line windblown dust emission sources (excluding agricultural land), which are not always included in the regional platform but are important for large-scale transport of dust.

7.4 CMAQ Model Performance Evaluation

An operational model performance evaluation for ozone, PM_{2.5} and its related speciated components, specific air toxics (i.e., formaldehyde, acetaldehyde, benzene, and 1,3-butadiene), as well as nitrate and sulfate deposition were conducted using 2016 state/local monitoring sites data in order to estimate the ability of the CMAQ modeling system to replicate the base year concentrations for the 12 km Continental United States domain (Section 7.2, Figure 7-1). Included in this evaluation are statistical measures of model versus observed pairs that were paired in space and time on a daily or weekly basis, depending on the sampling frequency of each network (measured data). For certain time periods with missing ozone, PM_{2.5}, air toxic, and nitrate and sulfate deposition observations we excluded the CMAQ predictions from those time periods in our calculations. It should be noted when pairing model and observed data that each

⁵⁷ Skamarock, W.C., et al. (2008) A Description of the Advanced Research WRF Version 3. <https://opensky.ucar.edu/islandora/object/technotes:500>.

⁵⁸ USEPA (2019). Meteorological Model Performance for Annual 2016 Simulation WRF v3.8 <https://www.epa.gov/scram/air-modeling-reports-and-journal-articles>.

⁵⁹ <https://www.mmm.ucar.edu/models/wrf>.

⁶⁰ Byun, D.W., Ching, J. K.S. (1999). Science algorithms of EPA Models-3 Community Multiscale Air Quality (CMAQ) modeling system, EPA/600/R-99/030, Office of Research and Development. Please also see: <https://www.cmascenter.org/>.

⁶¹ Henderson, B., et al. (2018) Hemispheric-CMAQ Application and Evaluation for 2016, Presented at 2019 CMAS Conference, available https://cmascenter.org/conference//2018/slides/0850_henderson_hemispheric-cmaq_application_2018.pptx.

⁶² Mathur, R., et al. (2017) Extending the Community Multiscale Air Quality (CMAQ) modeling system to hemispheric scales: overview of process considerations and initial applications, Atmos. Chem. Phys., 17, 12449-12474, <https://doi.org/10.5194/acp-17-12449-2017>.

⁶³ USEPA (2019). Technical Support Document: Preparation of Emissions Inventories for the Version 7.1 2016 Hemispheric Emissions Modeling Platform. Office of Air Quality Planning and Standards.

CMAQ concentration represents a grid-cell volume-averaged value, while the ambient network measurements are made at specific locations.

Model performance statistics were calculated for several spatial scales and temporal periods (statistics are defined in Section 7.4.2). Statistics were calculated for individual monitoring sites and for each of the nine National Oceanic and Atmospheric Administration (NOAA) climate regions of the 12-km U.S. modeling domain (Figure 7-2).⁶⁴ The regions include the Northeast, Ohio Valley, Upper Midwest, Southeast, South, Southwest, Northern Rockies, Northwest and West^{65,66} as were originally identified in Karl and Koss (1984).⁶⁷ The statistics for each site and climate region were calculated by season (“winter” is defined as average of December, January, and February; “spring” is defined as average of March, April, and May; “summer” is defined as average of June, July, and August; and “fall” is defined as average of September, October, and November). For 8-hour daily maximum ozone, we also calculated performance statistics by region for the April through September ozone season.⁶⁸ In addition to the performance statistics, we prepared several graphical presentations of model performance. These graphical presentations include regional maps which show the mean bias, mean error, normalized mean bias and normalized mean error calculated for each season at individual monitoring sites.

⁶⁴ NOAA, National Centers for Environmental Information scientists have identified nine climatically consistent regions within the contiguous U.S., <http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php>.

⁶⁵ The nine climate regions are defined by States where: Northeast includes CT, DE, ME, MA, MD, NH, NJ, NY, PA, RI, and VT; Ohio Valley includes IL, IN, KY, MO, OH, TN, and WV; Upper Midwest includes IA, MI, MN, and WI; Southeast includes AL, FL, GA, NC, SC, and VA; South includes AR, KS, LA, MS, OK, and TX; Southwest includes AZ, CO, NM, and UT; Northern Rockies includes MT, NE, ND, SD, WY; Northwest includes ID, OR, and WA; and West includes CA and NV.

⁶⁶ Note most monitoring sites in the West region are located in California (see Figure 7-2), therefore statistics for the West will be mostly representative of California ozone air quality.

⁶⁷ Karl, T. R. and Koss, W. J., 1984: "Regional and National Monthly, Seasonal, and Annual Temperature Weighted by Area, 1895-1983." Historical Climatology Series 4-3, National Climatic Data Center, Asheville, NC, 38 pp.

⁶⁸ In calculating the ozone season statistics, we limited the data to those observed and predicted pairs with observations that exceeded 60 ppb in order to focus on concentrations at the upper portion of the distribution of values.

U.S. Climate Regions

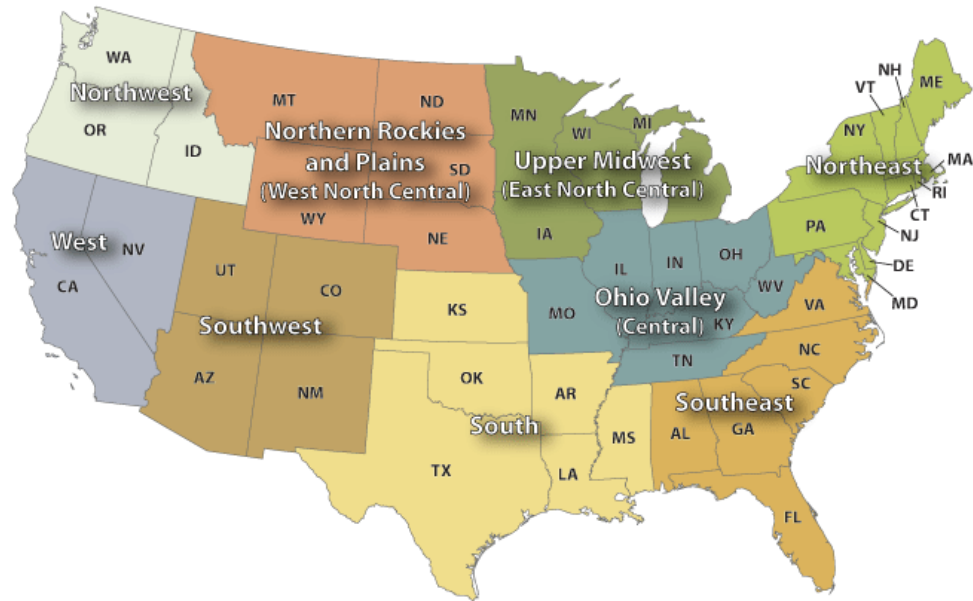


Figure 7-2 NOAA Nine Climate Regions (source: <http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php#references>)

7.4.1 Monitoring Networks

The model evaluation for ozone was based upon comparisons of model predicted 8-hour daily maximum concentrations to the corresponding ambient measurements for 2016 at monitoring sites in the EPA Air Quality System (AQS) and the Clean Air Status and Trends Network (CASTNet). The observed ozone data were measured and reported on an hourly basis. The PM_{2.5} evaluation focuses on concentrations of PM_{2.5} total mass and its components including sulfate (SO₄), nitrate (NO₃), total nitrate (TNO₃), ammonium (NH₄), elemental carbon (EC), and organic carbon (OC) as well as wet deposition for nitrate and sulfate. The PM_{2.5} performance statistics were calculated for each season (e.g., “winter” is defined as December, January, and February). PM_{2.5} ambient measurements for 2016 were obtained from the following networks: Chemical Speciation Network (CSN), Interagency Monitoring of PROtected Visual Environments (IMPROVE), Clean Air Status and Trends Network (CASTNet), and National Acid Deposition Program/National Trends (NADP/NTN). NADP/NTN collects and reports wet deposition measurements as weekly average data. The pollutant species included in the evaluation for each monitoring network are listed in Table 7-3. For PM_{2.5} species that are measured by more than one network, we calculated separate sets of statistics for each network. The CSN and IMPROVE networks provide 24-hour average concentrations on a 1 in every 3-day, or 1 in every 6-day sampling cycle. The PM_{2.5} species data at CASTNet sites are weekly integrated samples. In this analysis we use the term “urban sites” to refer to CSN sites; “suburban/rural sites” to refer to CASTNet sites; and “rural sites” to refer to IMPROVE sites.

Table 7-3 PM_{2.5} monitoring networks and pollutants species included in the CMAQ performance evaluation

Ambient Monitoring Networks	Particulate Species							Wet Deposition Species	
	PM _{2.5} Mass	SO ₄	NO ₃	TNO ₃ ^a	EC	OC	NH ₄	SO ₄	NO ₃
IMPROVE	X	X	X		X	X			
CASTNet		X		X			X		
CSN	X	X	X		X	X	X		
NADP								X	X

^a TNO₃ = (NO₃ + HNO₃)

The air toxics evaluation focuses on specific species relevant this proposed rulemaking, i.e., formaldehyde, acetaldehyde, benzene, and 1,3-butadiene. Similar to the PM_{2.5} evaluation, the air toxics performance statistics were calculated for each season to estimate the ability of the CMAQ modeling system to replicate the base year concentrations for the 12 km continental U.S. domain. Toxic measurements for 2016 were obtained from the air toxics archive, <https://www.epa.gov/amtic/amtic-air-toxics-data-ambient-monitoring-archive>. While most of the data in the archive are from the AQS database including the National Air Toxics Trends Stations (NATTS), additional data (e.g., special studies) are included in the archive but not reported in the AQS.

7.4.2 Model Performance Statistics

The Atmospheric Model Evaluation Tool (AMET) was used to conduct the evaluation described in this document.⁶⁹ There are various statistical metrics available and used by the science community for model performance evaluation. For this evaluation of the 2016 CMAQ modeling platform, we have selected the mean bias, mean error, normalized mean bias, and normalized mean error to characterize model performance, statistics which are consistent with the recommendations in Simon et al. (2012)⁷⁰ and the draft photochemical modeling guidance.⁷¹

Mean bias (MB) is used as average of the difference (predicted – observed) divided by the total number of replicates (*n*). Mean bias is given in units of ppb and is defined as:

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

⁶⁹ Appel, K.W., Gilliam, R.C., Davis, N., Zubrow, A., and Howard, S.C.: Overview of the Atmospheric Model Evaluation Tool (AMET) v1.1 for evaluating meteorological and air quality models, *Environ. Modell. Softw.*, 26, 4, 434-443, 2011. (<http://www.cmascenter.org/>).

⁷⁰ Simon, H., Baker, K., Phillips, S., 2012: Compilation and interpretation of photochemical model performance statistics published between 2006 and 2012. *Atmospheric Environment* 61, 124-139.

⁷¹ U.S. Environmental Protection Agency (US EPA), Draft Modeling Guidance for Demonstrating Attainment of Air Quality Goals for Ozone, PM_{2.5}, and Regional Haze. December 2014, U.S. EPA, Research Triangle Park, NC, 27711.

Mean error (ME) calculates the absolute value of the difference (predicted – observed) divided by the total number of replicates (n). Mean error is given in units of ppb and is defined as:

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

Normalized mean bias (NMB) is used as a normalization to facilitate a range of concentration magnitudes. This statistic averages the difference (predicted – observed) over the sum of observed values. NMB is a useful model performance indicator because it avoids over inflating the observed range of values, especially at low concentrations. Normalized mean bias is given in percentage units and is defined as:

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

Normalized mean error (NME) is also similar to NMB, where the performance statistic is used as a normalization of the mean error. NME calculates the absolute value of the difference (predicted – observed) over the sum of observed values. Normalized mean error is given in percentage units and is defined as:

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

The “acceptability” of model performance was judged by comparing our CMAQ 2016 performance results in light of the range of performance found in recent regional ozone and

PM_{2.5} model applications.^{72,73,74,75,76,77,78,79,80,81} These other modeling studies represent a wide range of modeling analyses that cover various models, model configurations, domains, years and/or episodes, chemical mechanisms, and aerosol modules. Overall, the ozone and PM_{2.5} model performance results for the 2016 CMAQ simulations are within the range found in other recent peer-reviewed and regulatory applications. The model performance results, as described in this document, demonstrate that that our applications of CMAQ using this 2016 modeling platform provide a scientifically credible approach for assessing ozone and PM_{2.5} concentrations for the purposes of this proposed rulemaking.

7.4.3 Evaluation for 8-hour Daily Maximum Ozone

The 8-hour ozone model performance bias and error statistics for each climate region, for each season defined above and for each monitor network (AQS and CASTNet) are provided in Table 7-4. As indicated by the statistics in Table 7-4, bias and error for 8-hour daily maximum ozone are relatively low in each climate region. Spatial plots of the mean bias and error as well as the normalized mean bias and error for individual monitors are shown in Figure 7-3 through Figure 7-6. The statistics shown in these figures were calculated over the ozone season using data pairs on days with observed 8-hour ozone of ≥ 60 ppb. Figure 7-3 shows MB for 8-hour ozone ≥ 60 ppb during the ozone season in the range of ± 15 ppb at the majority of ozone AQS and CASTNet measurement sites. At both AQS and CASTNet sites, NMB is within the range of

⁷² National Research Council (NRC), 2002. Estimating the Public Health Benefits of Proposed Air Pollution Regulations, Washington, DC: National Academies Press.

⁷³ Appel, K.W., Roselle, S.J., Gilliam, R.C., and Pleim, J.E., 2010: Sensitivity of the Community Multiscale Air Quality (CMAQ) model v4.7 results for the eastern United States to MM5 and WRF meteorological drivers. Geoscientific Model Development, 3, 169-188.

⁷⁴ Foley, K.M., Roselle, S.J., Appel, K.W., Bhave, P.V., Pleim, J.E., Otte, T.L., Mathur, R., Sarwar, G., Young, J.O., Gilliam, R.C., Nolte, C.G., Kelly, J.T., Gilliland, A.B., and Bash, J.O., 2010: Incremental testing of the Community multiscale air quality (CMAQ) modeling system version 4.7. Geoscientific Model Development, 3, 205-226.

⁷⁵ Hogrefe, G., Civeroio, K.L., Hao, W., Ku, J.-Y., Zalewsky, E.E., and Sistla, G., Rethinking the Assessment of Photochemical Modeling Systems in Air Quality Planning Applications. Air & Waste Management Assoc., 58:1086-1099, 2008.

⁷⁶ Phillips, S., K. Wang, C. Jang, N. Possiel, M. Strum, T. Fox, 2007. Evaluation of 2002 Multi-pollutant Platform: Air Toxics, Ozone, and Particulate Matter, 7th Annual CMAS Conference, Chapel Hill, NC, October 6-8, 2008. (<http://www.cmascenter.org/conference/2008/agenda.cfm>).

⁷⁷ Simon, H., Baker, K.R., and Phillips, S., 2012. Compilation and interpretation of photochemical model performance statistics published between 2006 and 2012. Atmospheric Environment 61, 124-139. <http://dx.doi.org/10.1016/j.atmosenv.2012.07.012>.

⁷⁸ Tesche, T.W., Morris, R., Tonnesen, G., McNally, D., Boylan, J., Brewer, P., 2006. CMAQ/CAMx annual 2002 performance evaluation over the eastern United States. Atmospheric Environment 40, 4906-4919.

⁷⁹ U.S. Environmental Protection Agency; Technical Support Document for the Final Clean Air Interstate Rule: Air Quality Modeling; Office of Air Quality Planning and Standards; RTP, NC; March 2005 (CAIR Docket OAR-2005-0053-2149).

⁸⁰ U.S. Environmental Protection Agency, Proposal to Designate an Emissions Control Area for Nitrogen Oxides, Sulfur Oxides, and Particulate Matter: Technical Support Document. EPA-420-R-007, 329pp., 2009. (<http://www.epa.gov/otaq/regs/nonroad/marine/ci/420r09007.pdf>).

⁸¹ U.S. Environmental Protection Agency, 2010, Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. EPA-420-R-10-006. February 2010. Sections 3.4.2.1.2 and 3.4.3.3. Docket EPA-HQ-OAR-2009-0472-11332.

±30 percent (Figure 7-5). Mean error for 8-hour maximum ozone ≥ 60 ppb, as seen from Figure 7-4, is 20 ppb or less at most of the sites across the modeling domain.

Table 7-4 Daily Maximum 8-hour Ozone Performance Statistics by Climate Region, by Season, and by Monitoring Network for the 2016 CMAQ Model Simulation

Climate Region	Monitor Network	Season	No. of Obs	MB (ppb)	ME (ppb)	NMB (%)	NME (%)
Northeast	AQS	Winter	11,462	-2.5	4.7	-7.7	14.7
		Spring	15,692	-6.7	7.7	-15.0	17.3
		Summer	16,686	-0.9	6.2	-1.9	13.7
		Fall	13,780	-0.1	4.7	-0.4	13.7
	CASTNet	Winter	1,283	-3.2	4.8	-9.4	13.9
		Spring	1,336	-7.2	8.0	-16.0	17.7
		Summer	1,315	-1.7	5.8	-3.9	13.6
		Fall	1,306	0.0	4.7	0.1	13.8
Ohio Valley	AQS	Winter	4,178	-0.5	4.4	-1.7	14.7
		Spring	15,498	-4.5	6.5	9.9	14.2
		Summer	20,495	0.1	6.2	0.3	13.7
		Fall	14,025	0.1	4.9	0.3	12.6
	CASTNet	Winter	1,574	-1.1	4.3	-3.4	13.3
		Spring	1,600	-5.4	6.9	-11.6	14.9
		Summer	1,551	-0.7	5.8	-1.6	13.4
		Fall	1,528	-1.8	5.1	-4.5	12.8
Upper Midwest	AQS	Winter	1,719	-1.1	4.5	-3.5	14.5
		Spring	6,892	-6.5	7.7	-14.4	17.3
		Summer	9,742	-1.6	5.9	-3.7	14.0
		Fall	6,050	1.4	4.3	4.3	13.5
	CASTNet	Winter	435	-2.2	4.5	-6.7	13.4
		Spring	434	-7.9	8.5	-17.6	18.9
		Summer	412	-3.5	5.8	-8.6	13.9
		Fall	426	-0.4	4.2	-1.3	13.2
Southeast	AQS	Winter	7,128	-3.7	5.4	-10.3	15.1

Climate Region	Monitor Network	Season	No. of Obs	MB (ppb)	ME (ppb)	NMB (%)	NME (%)
		Spring	14,569	-5.4	6.9	-11.6	14.9
		Summer	15,845	0.6	5.3	1.5	13.3
		Fall	12,583	-0.9	4.7	-2.3	11.6
	CASTNet	Winter	887	-4.1	5.4	-11.1	14.4
		Spring	947	-7.1	8.0	-14.9	16.6
		Summer	926	-0.3	5.1	-0.8	13.1
		Fall	928	-2.4	5.3	-5.7	12.8
South	AQS	Winter	11,432	-3.1	5.5	-9.1	16.5
		Spring	13,093	-3.7	7.0	-8.5	15.9
		Summer	12,829	0.2	6.0	0.6	15.5
		Fall	12,443	-1.3	5.0	-3.4	12.7
	CASTNet	Winter	523	-3.4	5.2	-9.3	14.4
		Spring	532	-5.0	7.2	-11.0	15.9
		Summer	508	-1.6	6.5	-4.2	16.7
		Fall	528	-1.3	4.4	-3.5	11.4
Southwest	AQS	Winter	9,990	-4.4	6.2	-11.2	15.8
		Spring	11,381	-7.8	8.5	-15.2	16.6
		Summer	12,027	-6.3	7.8	-11.7	14.5
		Fall	11,097	-1.7	4.4	-4.2	10.7
	CASTNet	Winter	757	-7.0	7.3	-15.6	16.3
		Spring	810	-8.8	8.5	-16.8	17.5
		Summer	812	-6.4	7.3	-12.0	13.7
		Fall	791	-3.1	4.3	-7.0	9.9
Northern Rockies	AQS	Winter	4,719	-2.6	5.1	-7.0	13.6
		Spring	4,975	-5.8	6.9	-13.2	15.8
		Summer	5,054	-3.9	5.7	-8.2	12.4
		Fall	4,876	-0.1	4.4	-0.2	12.9
	CASTNet	Winter	667	-3.8	6.2	-9.7	15.7
		Spring	696	-7.6	8.2	-16.5	17.7

Climate Region	Monitor Network	Season	No. of Obs	MB (ppb)	ME (ppb)	NMB (%)	NME (%)
		Summer	693	-5.1	6.2	-10.5	12.8
		Fall	605	-1.4	4.9	-3.6	13.2
Northwest	AQS	Winter	677	-3.3	6.1	-10.2	18.7
		Spring	1,288	-6.5	8.2	-16.1	20.4
		Summer	2,444	-0.9	6.4	-2.4	16.9
		Fall	1,236	1.0	5.3	3.1	16.8
	CASTNet	Winter	-	-	-	-	-
		Spring	-	-	-	-	-
		Summer	-	-	-	-	-
		Fall	-	-	-	-	-
West	AQS	Winter	14,539	-3.9	6.1	-11.4	17.6
		Spring	17,191	-7.9	8.6	-17.3	18.6
		Summer	18,132	-6.5	9.0	-12.3	17.0
		Fall	16,211	-4.6	6.8	-10.6	15.8
	CASTNet	Winter	506	-3.7	5.3	-9.3	13.5
		Spring	519	-8.3	8.6	-17.3	17.8
		Summer	526	-10.9	11.6	-18.1	19.1
		Fall	530	-5.6	6.6	-11.9	14.2

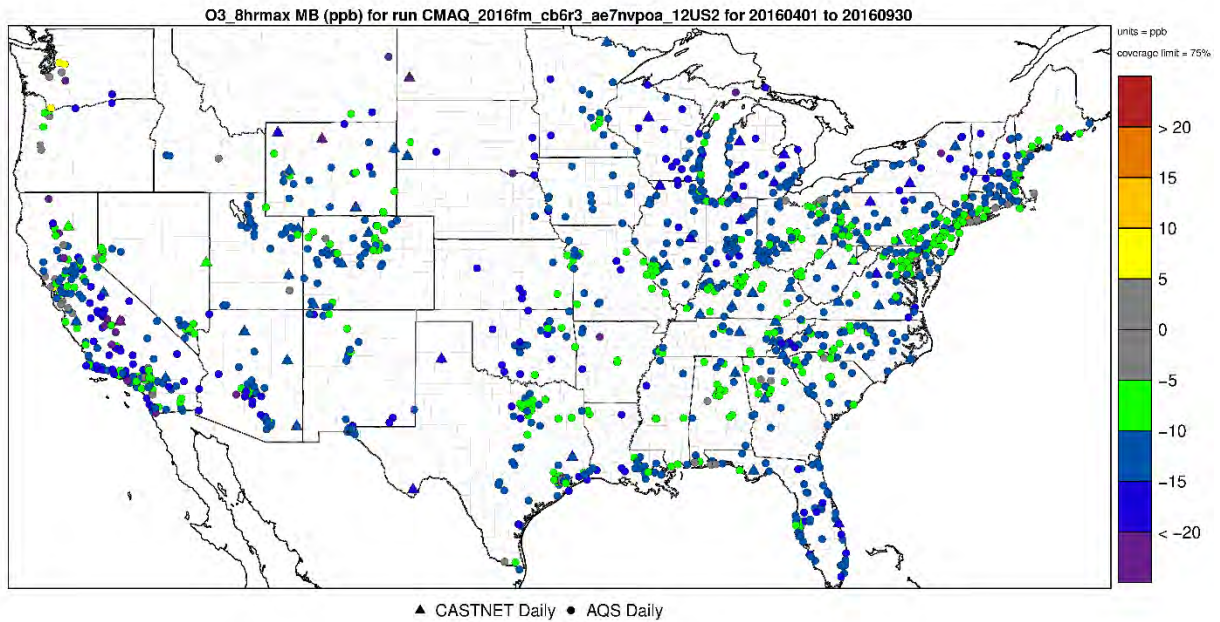


Figure 7-3 Mean Bias (ppb) of 8-hour daily maximum ozone greater than 60 ppb over the period April-September 2016 at AQS and CASTNet monitoring sites in the modeling domain

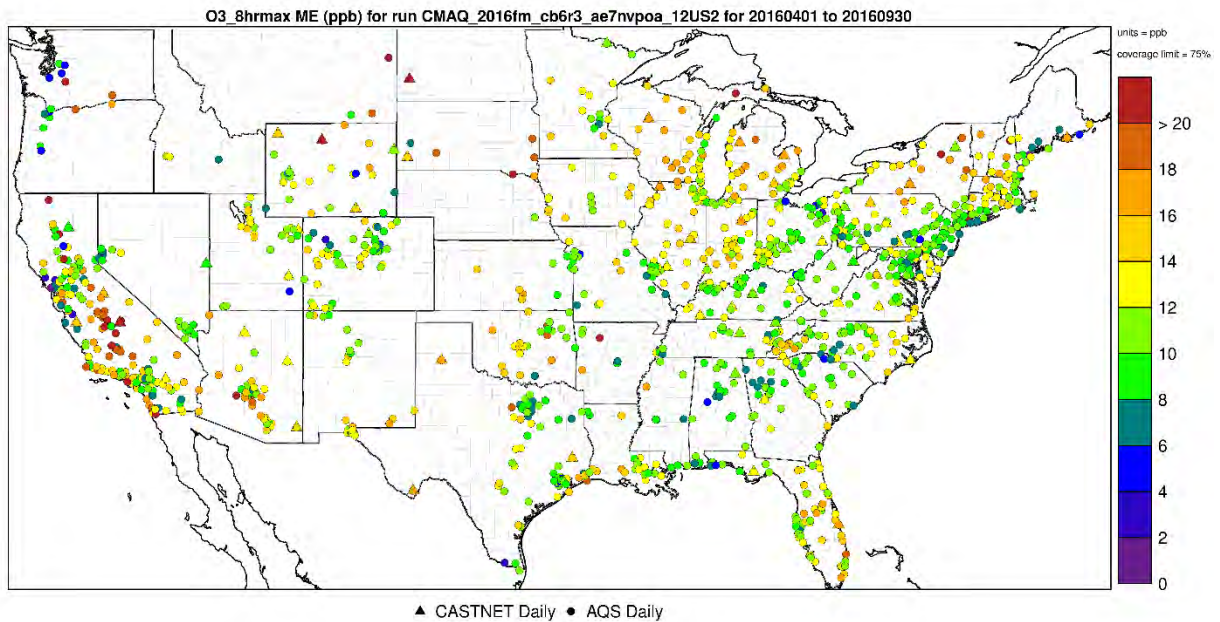


Figure 7-4 Mean Error (ppb) of 8-hour daily maximum ozone greater than 60 ppb over the period April-September 2016 at AQS and CASTNet monitoring sites in the modeling domain

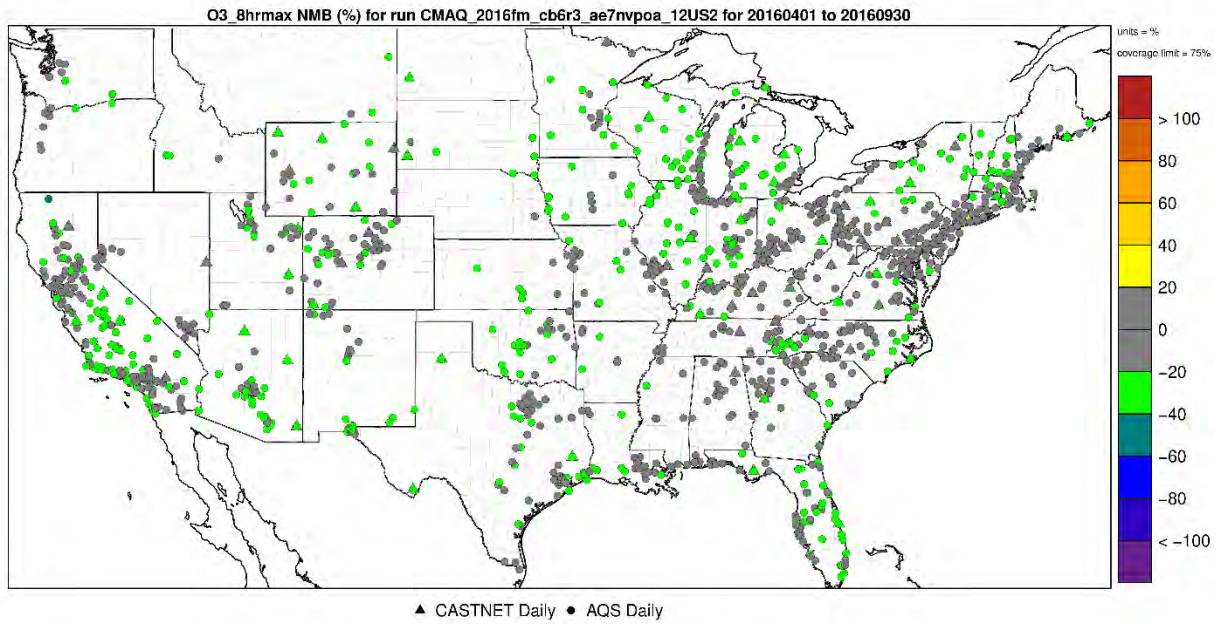


Figure 7-5 Normalized Mean Bias (%) of 8-hour daily maximum ozone greater than 60 ppb over the period April-September AQS and CASTNet 2016 at monitoring sites in the modeling domain

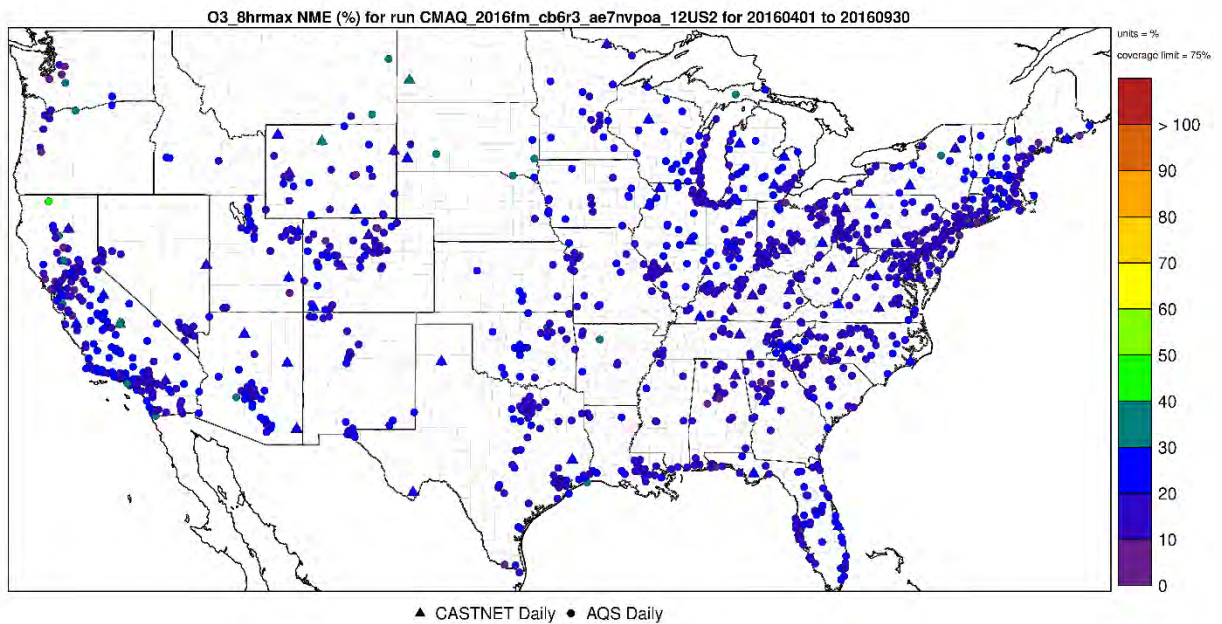


Figure 7-6 Normalized Mean Error (%) of 8-hour daily maximum ozone greater than 60 ppb over the period April-September AQS and CASTNet 2016 at monitoring sites in the modeling domain

7.4.4 Seasonal Evaluation of PM_{2.5} Component Species

The evaluation of 2016 model predictions for PM_{2.5} covers the performance for the individual PM_{2.5} component species (i.e., sulfate, nitrate, organic carbon, elemental carbon, and ammonium). Performance results are provided for each PM_{2.5} species. As indicated above, for each species we present tabular summaries of bias and error statistics by climate region for each season. These statistics are based on the set of observed-predicted pairs of data for the particular quarter at monitoring sites within the nine NOAA climate regions. Separate statistics are provided for each monitoring network, as applicable for the particular species measured. For sulfate and nitrate we also provide a more refined temporal and spatial analysis of model performance that includes spatial maps which show the mean bias and error and the normalized mean bias and error by site, aggregated by season.

7.4.4.1 Seasonal Evaluation for Sulfate

The model performance bias and error statistics for sulfate for each climate region and each season by monitor network are provided in Table 7-5. Spatial plots of the normalized mean bias and error by season for individual monitors are shown in Figure 7-7 through Figure 7-22.

Table 7-5 Sulfate Performance Statistics by Climate Region, by Season, and by Monitoring Network for the 2016 CMAQ Model Simulation

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
Northeast	IMPROVE	Winter	431	-0.1	0.2	-7.0	31.4
		Spring	477	0.0	0.2	12.5	39.2
		Summer	486	-0.1	0.2	-9.8	30.5
		Fall	456	0.0	0.2	-1.0	29.7
	CSN	Winter	716	0.1	0.5	5.9	45.9
		Spring	768	0.1	0.3	8.8	36.7
		Summer	782	-0.2	0.2	-21.2	23.2
		Fall	736	0.1	0.3	13.3	39.0
	CASTNet	Winter	221	-0.2	0.2	-23.4	24.9
		Spring	242	-0.2	0.2	-17.3	20.3
		Summer	252	-0.2	0.2	-21.2	23.2
		Fall	242	-0.1	0.2	-16.9	21.4
Ohio Valley	IMPROVE	Winter	220	-0.2	0.3	-18.0	31.2
		Spring	244	-0.2	0.3	-17.8	28.5
		Summer	239	-0.4	0.5	-27.3	36.6
		Fall	227	-0.3	0.4	-17.4	27.4

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
	CSN	Winter	546	-0.2	0.3	-14.4	35.3
		Spring	562	0.0	0.4	2.5	34.6
		Summer	553	-0.1	0.5	-6.9	30.5
		Fall	541	0.0	0.4	0.2	31.5
	CASTNet	Winter	212	-0.4	0.4	-29.9	31.0
		Spring	228	-0.3	0.3	-23.4	25.1
		Summer	224	-0.4	0.4	-24.7	27.1
		Fall	226	-0.3	0.3	-23.8	24.3
Upper Midwest	IMPROVE	Winter	200	-0.1	0.2	-6.5	27.7
		Spring	208	0.0	0.2	-0.4	30.5
		Summer	210	-0.1	0.2	-12.0	30.0
		Fall	215	0.0	0.2	-0.4	35.3
	CSN	Winter	326	0.1	0.3	8.3	34.7
		Spring	354	0.2	0.4	39.2	22.9
		Summer	314	0.0	0.3	4.6	33.0
		Fall	310	0.2	0.4	33.9	49.4
	CASTNet	Winter	59	-0.2	0.3	-22.4	25.9
		Spring	63	-0.1	0.1	-7.9	13.7
		Summer	63	-0.1	0.1	-12.5	17.7
		Fall	57	-0.1	0.1	-13.3	18.5
Southeast	IMPROVE	Winter	342	-0.1	0.3	-10.2	-6.0
		Spring	379	-0.3	0.4	-21.7	30.7
		Summer	394	-0.4	0.5	-35.1	40.8
		Fall	366	-0.2	0.3	-16.3	27.2
	CSN	Winter	512	0.1	0.3	11.4	36.5
		Spring	551	0.0	0.4	-3.9	31.3
		Summer	523	-0.2	0.4	-21.1	34.3
		Fall	505	0.0	0.3	1.3	26.4
	CASTNet	Winter	150	-0.3	0.4	-29.9	32.2

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
		Spring	164	-0.5	0.5	-33.6	34.3
		Summer	164	-0.6	0.6	-40.9	41.2
		Fall	154	-0.4	0.4	-29.8	31.1
South	IMPROVE	Winter	240	0.0	0.3	3.7	33.8
		Spring	273	-0.2	0.4	-16.0	37.6
		Summer	252	-0.6	0.7	-44.1	48.1
		Fall	264	-0.2	0.4	-17.7	32.5
	CSN	Winter	326	0.0	0.4	3.9	41.4
		Spring	351	-0.3	0.7	-21.9	45.4
		Summer	336	-0.6	0.7	-36.8	46.4
		Fall	329	-0.2	0.5	-13.7	35.0
	CASTNet	Winter	92	-0.3	0.3	-26.3	27.7
		Spring	102	-0.5	0.5	-33.0	34.2
		Summer	96	-0.8	0.8	-48.7	48.9
		Fall	102	-0.4	0.4	-28.9	29.9
Southwest	IMPROVE	Winter	910	0.1	0.2	55.6	82.1
		Spring	991	0.2	0.3	59.5	69.9
		Summer	985	-0.3	0.3	-39.4	50.3
		Fall	962	-0.1	0.2	-12.2	43.4
	CSN	Winter	246	-0.1	0.4	-9.3	71.2
		Spring	255	0.3	0.3	68.1	75.0
		Summer	250	-0.3	0.4	-38.2	49.4
		Fall	255	0.3	0.3	60.4	68.5
	CASTNet	Winter	101	0.1	0.1	37.5	60.4
		Spring	115	0.2	0.2	40.9	44.9
		Summer	114	-0.2	0.2	-35.9	40.9
		Fall	115	-0.1	0.2	-17.6	36.0
Northern Rockies	IMPROVE	Winter	542	0.1	0.2	31.3	65.7
		Spring	573	0.1	0.2	34.5	53.1

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)	
		Summer	603	0.0	0.2	10.1	42.0	
		Fall	574	0.1	0.2	17.5	48.5	
	CSN	Winter	139	0.3	0.1	19.3	52.2	
		Spring	151	0.1	0.2	21.5	45.7	
		Summer	153	0.0	0.2	3.0	37.0	
		Fall	136	0.1	0.2	15.5	41.2	
	CASTNet	Winter	126	0.0	0.1	-10.0	38.8	
		Spring	139	0.1	0.1	12.1	26.9	
		Summer	138	-0.1	0.1	-11.8	23.8	
		Fall	129	0.0	0.1	-2.5	28.1	
	Northwest	IMPROVE	Winter	427	0.1	0.1	76.4	97.9
			Spring	505	0.2	0.2	60.1	69.6
Summer			519	0.0	0.2	12.1	51.1	
Fall			499	0.1	0.2	34.7	70.5	
CSN		Winter	156	0.3	0.4	>100	>100	
		Spring	146	0.3	0.4	85.8	89.9	
		Summer	166	0.1	0.3	15.3	52.6	
		Fall	161	0.3	0.3	74.2	95.8	
CASTNet		Winter	-	-	-	-	-	
		Spring	-	-	-	-	-	
		Summer	-	-	-	-	-	
		Fall	-	-	-	-	-	
West	IMPROVE	Winter	565	0.2	0.2	79.0	>100	
		Spring	608	0.1	0.3	24.1	57.3	
		Summer	603	-0.2	0.3	-31.2	48.3	
		Fall	576	0.0	0.2	-6.9	48.5	
	CSN	Winter	340	0.1	0.3	23.2	66.5	
		Spring	352	0.0	0.4	-5.5	48.5	
		Summer	349	-0.7	0.8	-50.6	55.6	

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
		Fall	330	-0.2	0.4	-23.5	45.6
	CASTNet	Winter	69	0.1	0.2	31.2	65.4
		Spring	73	-0.1	0.2	-11.9	37.7
		Summer	75	-0.5	0.5	-49.4	51.9
		Fall	76	-0.2	0.3	-30.1	42.6

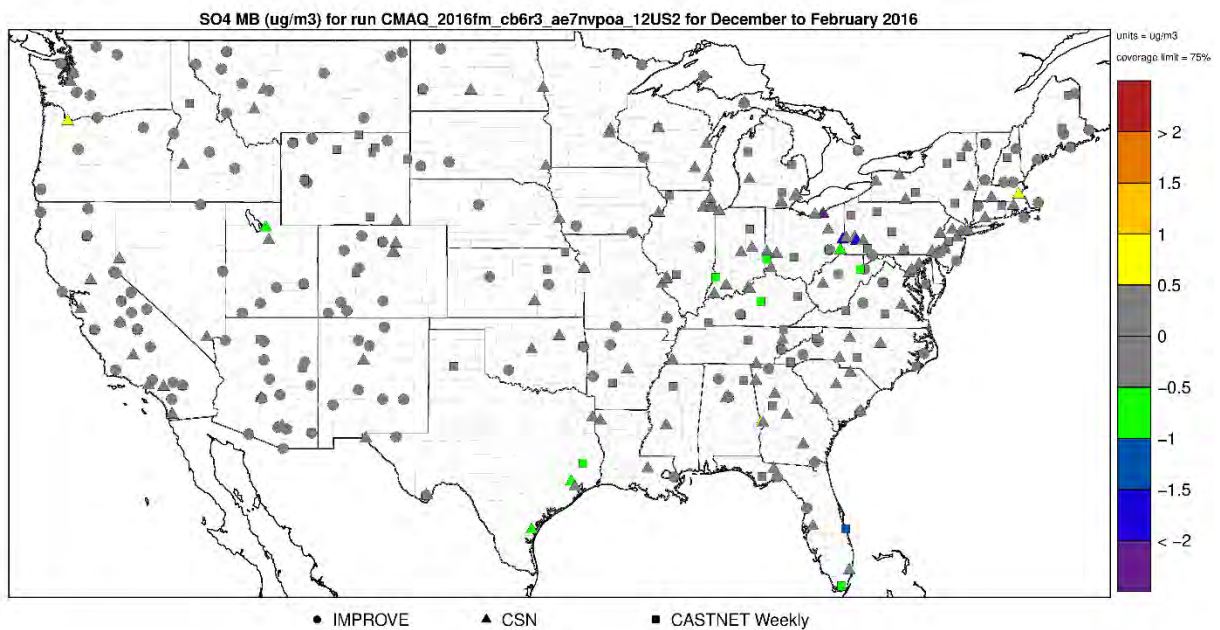


Figure 7-7 Mean Bias (ug/m³) of sulfate during winter 2016 at monitoring sites in the modeling domain

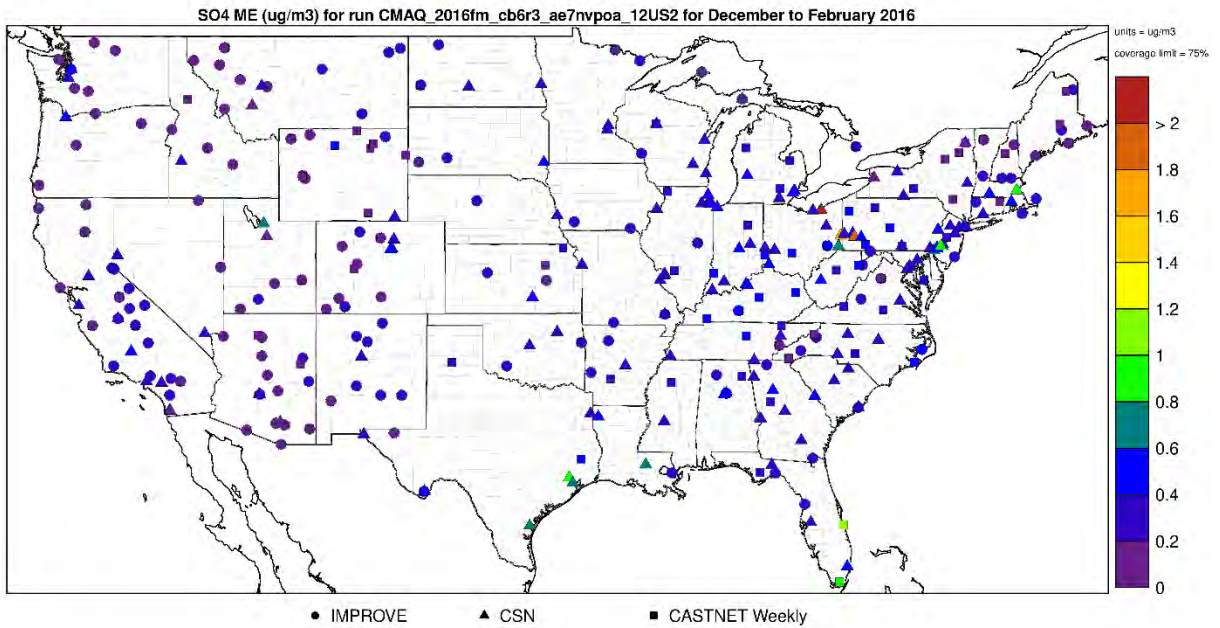


Figure 7-8 Mean Error (ug/m3) of sulfate during winter 2016 at monitoring sites in the modeling domain

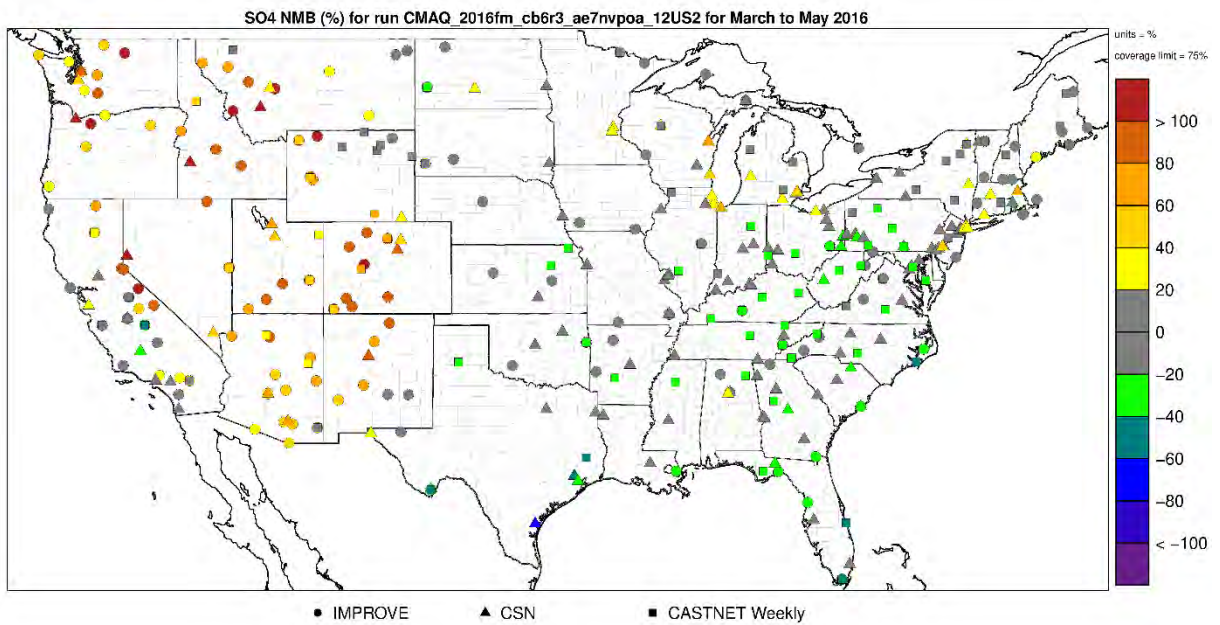


Figure 7-9 Normalized Mean Bias (%) of sulfate during winter 2016 at monitoring sites in the modeling domain

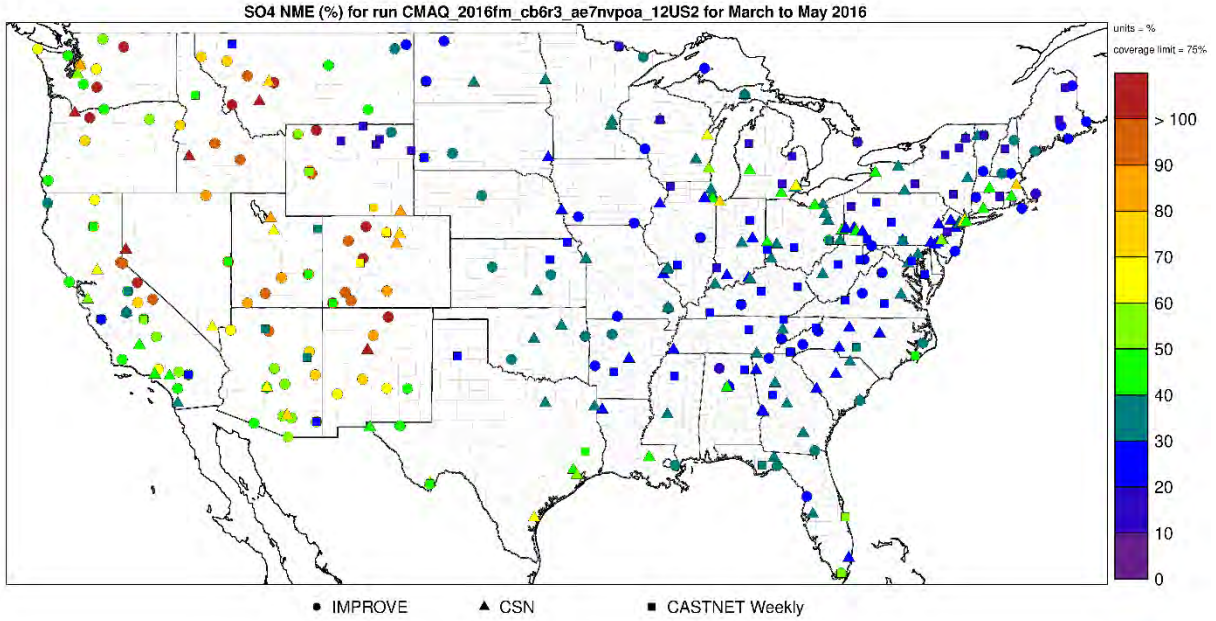


Figure 7-10 Normalized Mean Error (%) of sulfate during winter 2016 at monitoring sites in the modeling domain

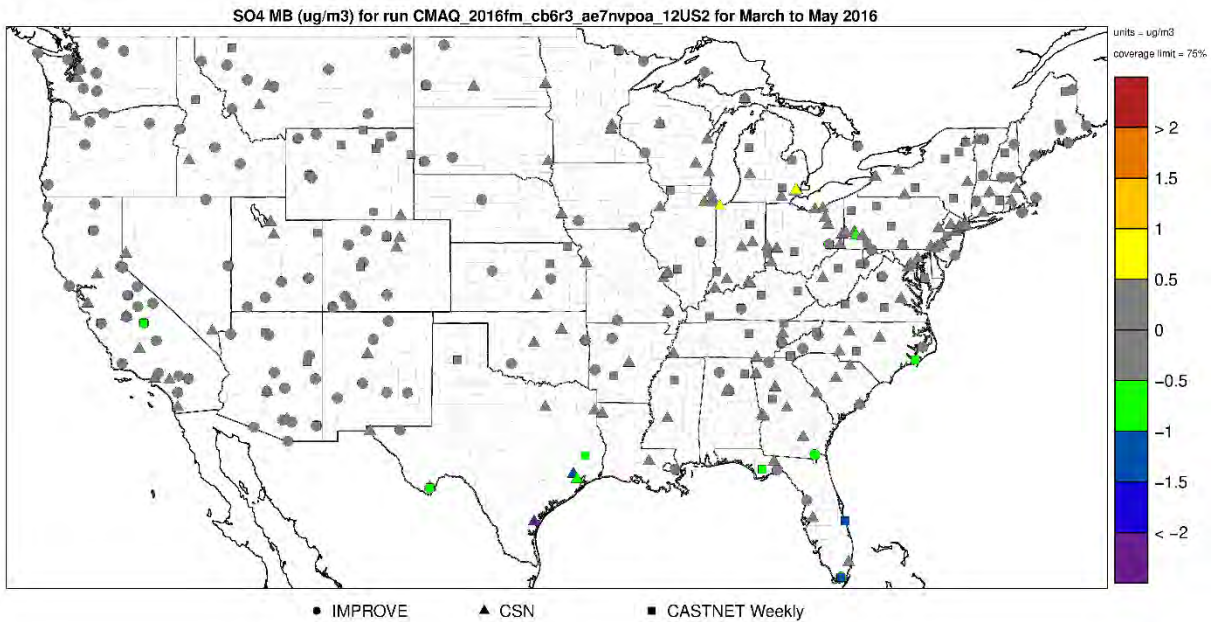


Figure 7-11 Mean Bias (ug/m³) of sulfate during spring 2016 at monitoring sites in the modeling domain

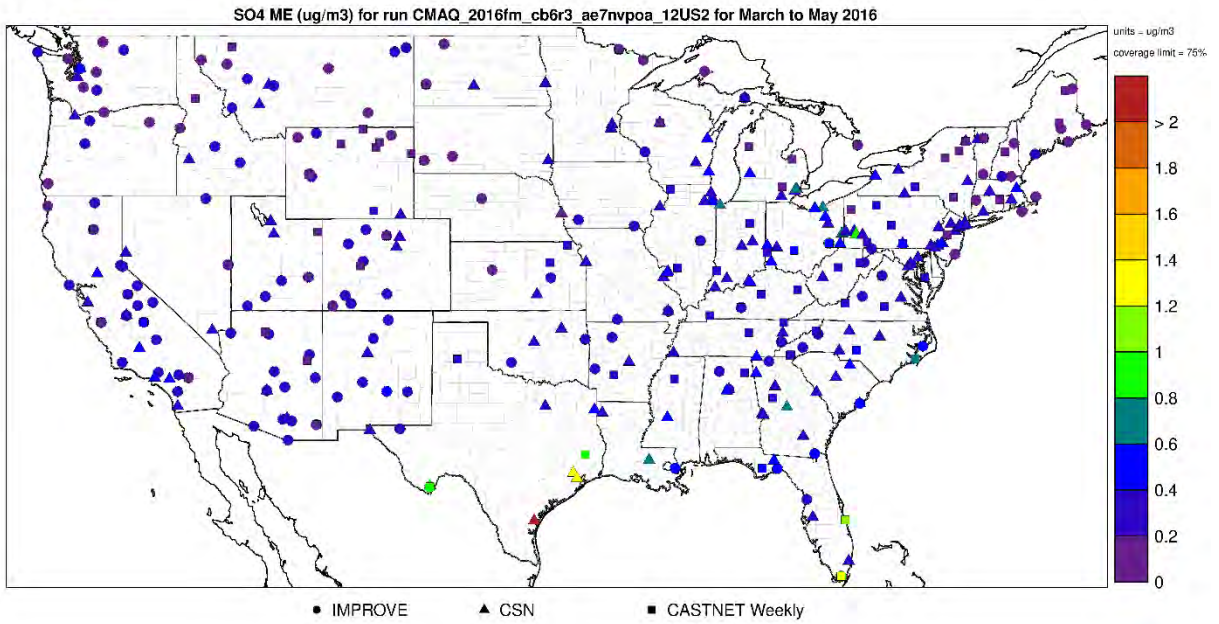


Figure 7-12 Mean Error ($\mu\text{g}/\text{m}^3$) of sulfate during spring 2016 at monitoring sites in the modeling domain

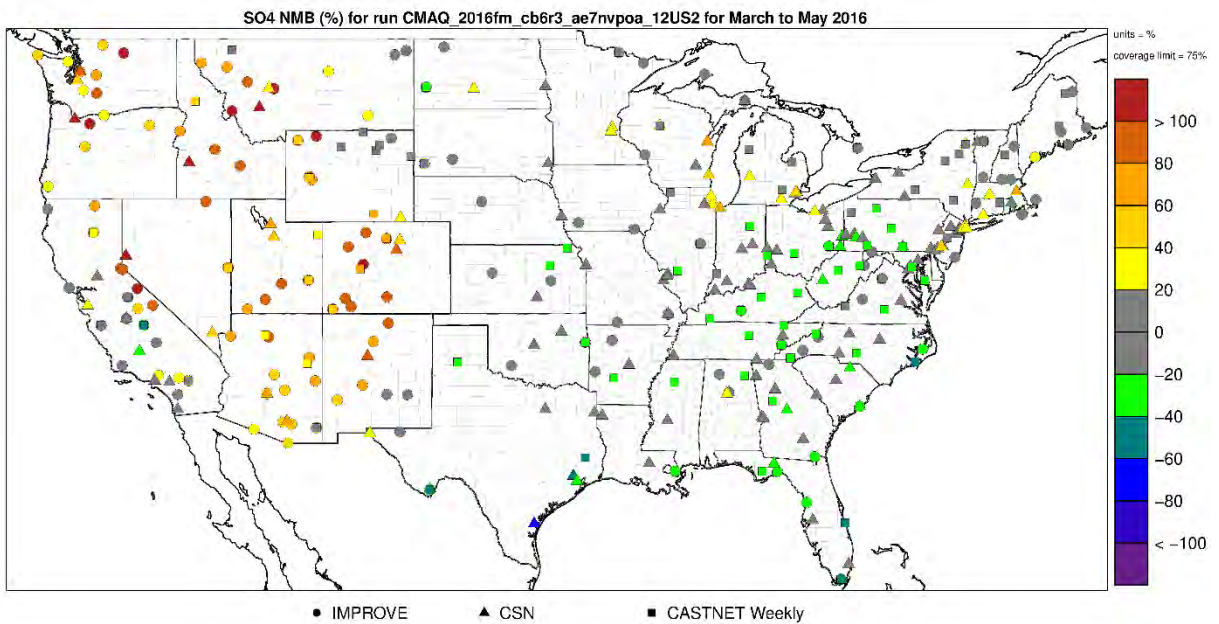


Figure 7-13 Normalized Mean Bias (%) of sulfate during spring 2016 at monitoring sites in the modeling domain

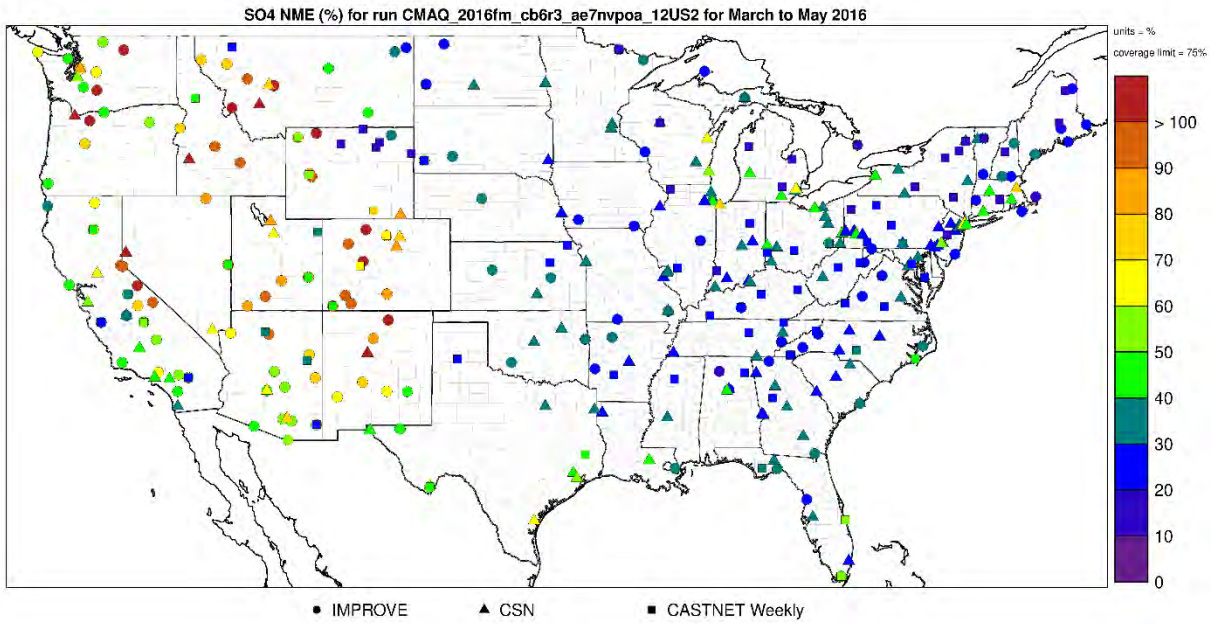


Figure 7-14 Normalized Mean Error (%) of sulfate during spring 2016 at monitoring sites in the modeling domain

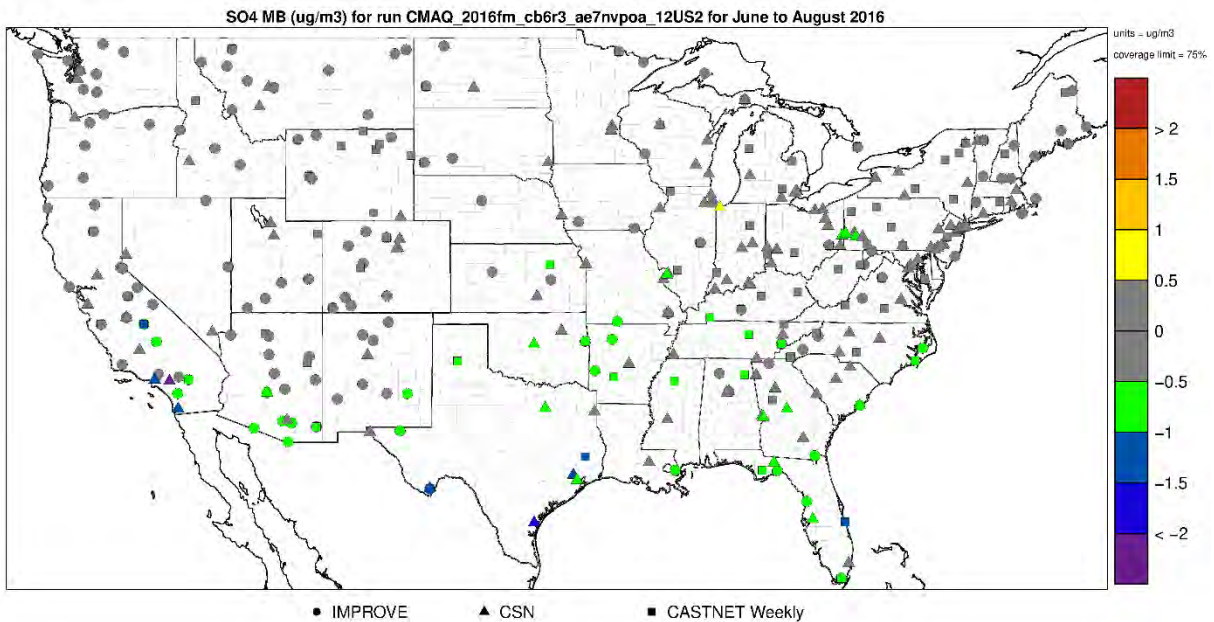


Figure 7-15 Mean Bias (ug/m3) of sulfate during summer 2016 at monitoring sites in the modeling domain

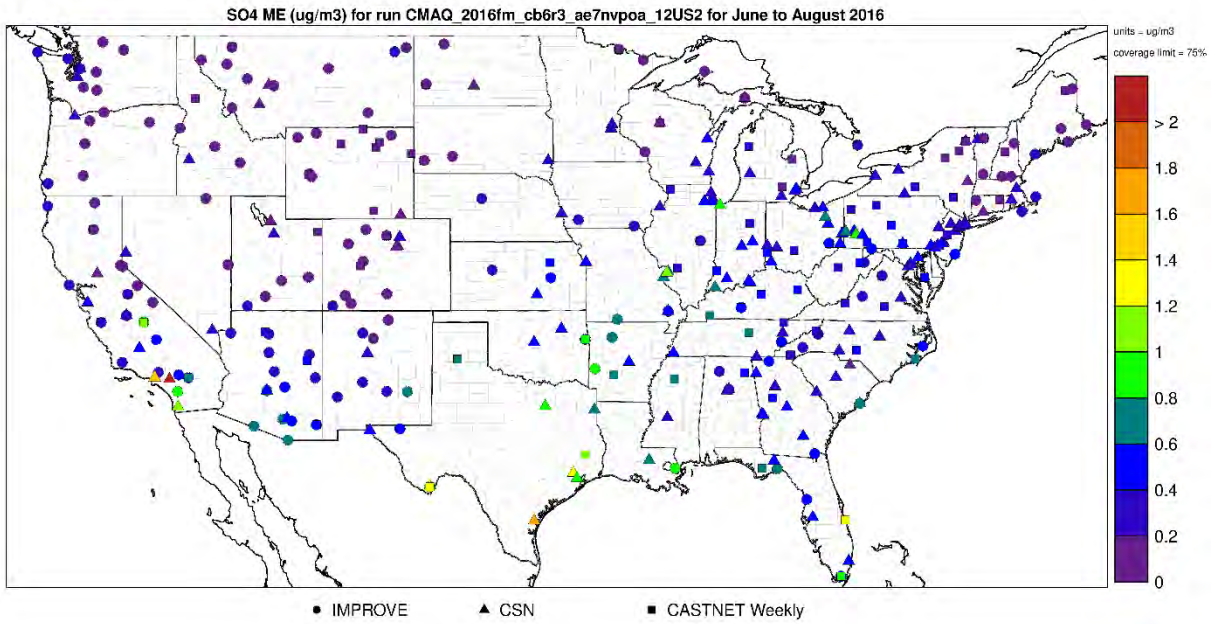


Figure 7-16 Mean Error (ug/m3) of sulfate during summer 2016 at monitoring sites in the modeling domain

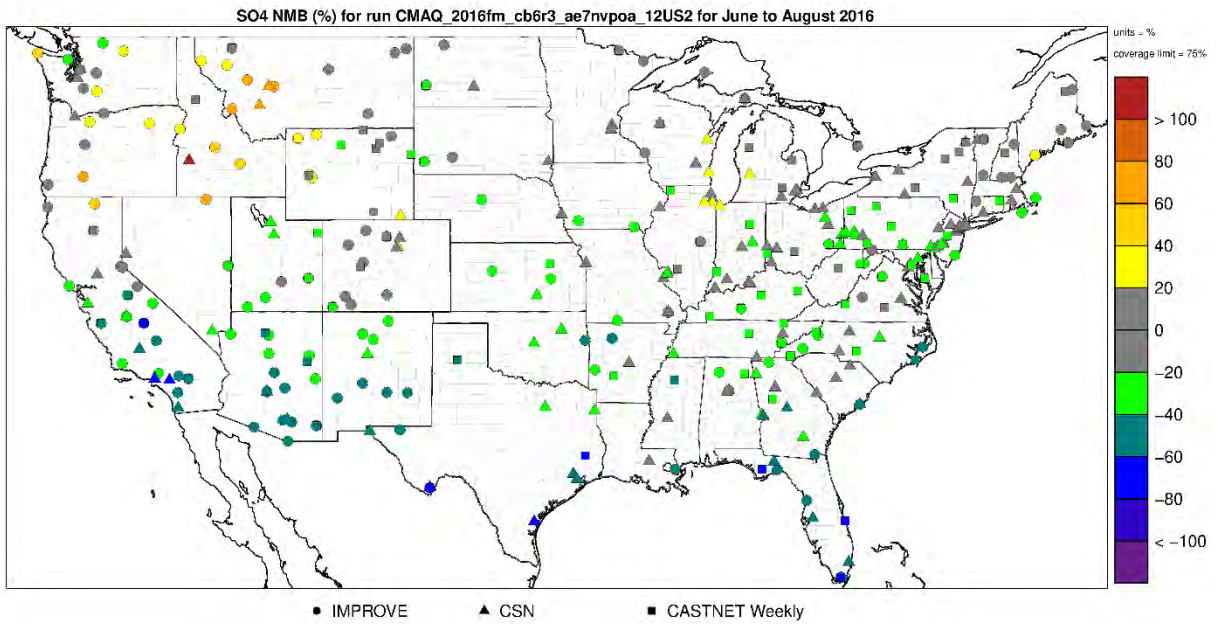


Figure 7-17 Normalized Mean Bias (%) of sulfate during summer 2016 at monitoring sites in the modeling domain

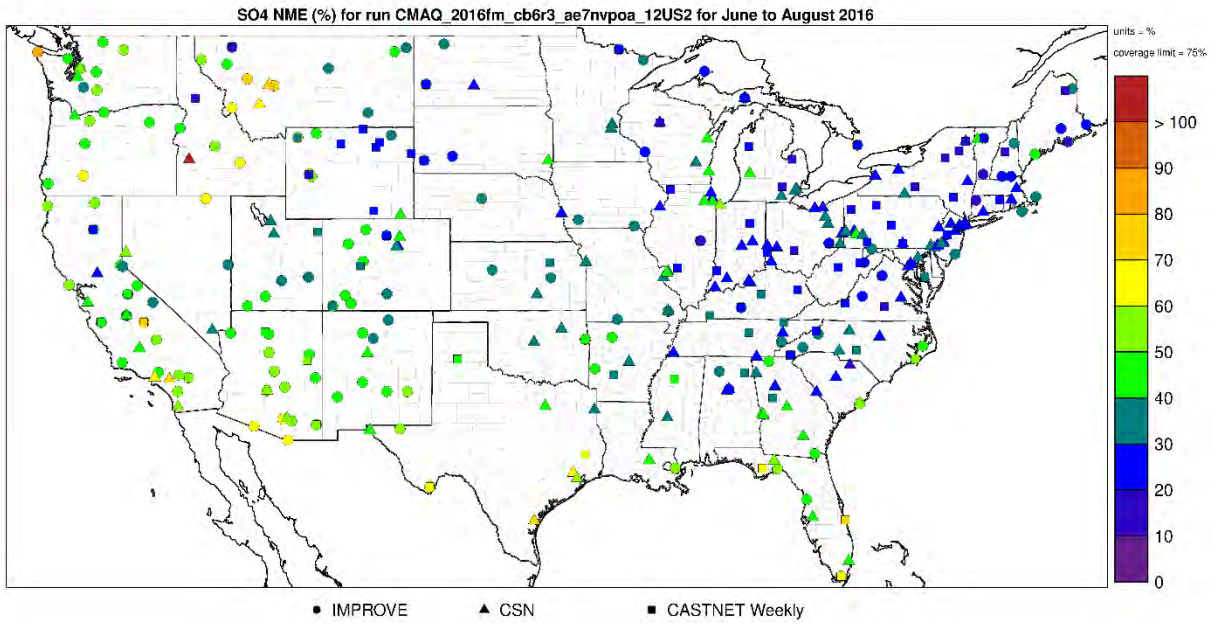


Figure 7-18 Normalized Mean Error (%) of sulfate during summer 2016 at monitoring sites in the modeling domain

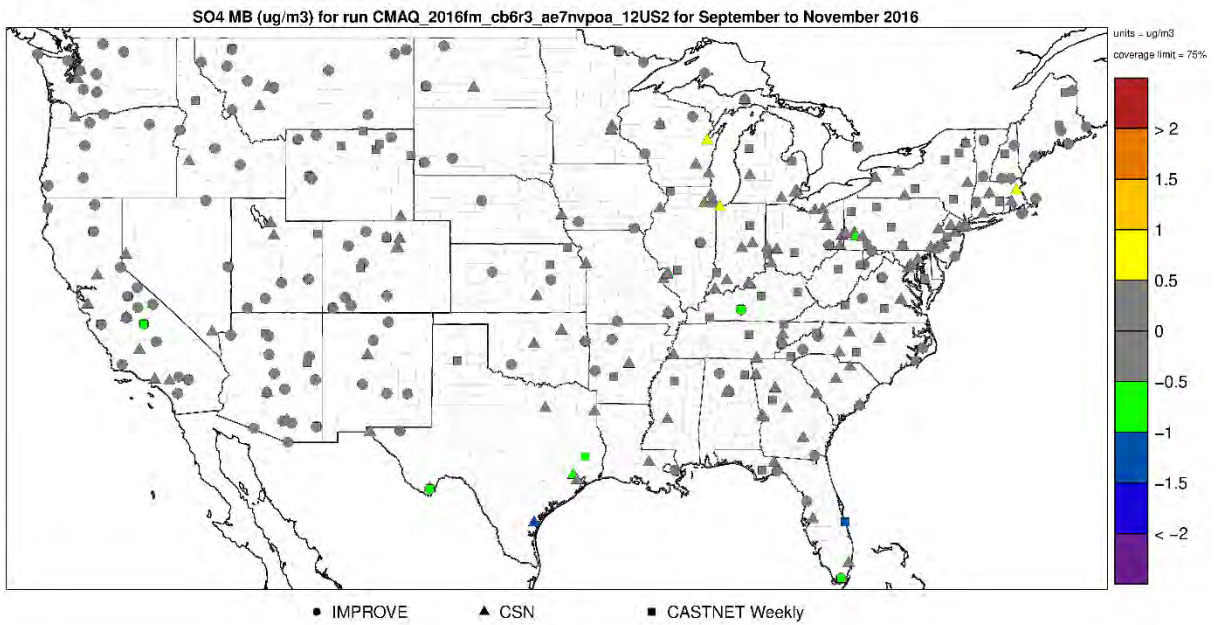


Figure 7-19 Mean Bias (ug/m³) of sulfate during fall 2016 at monitoring sites in the modeling domain

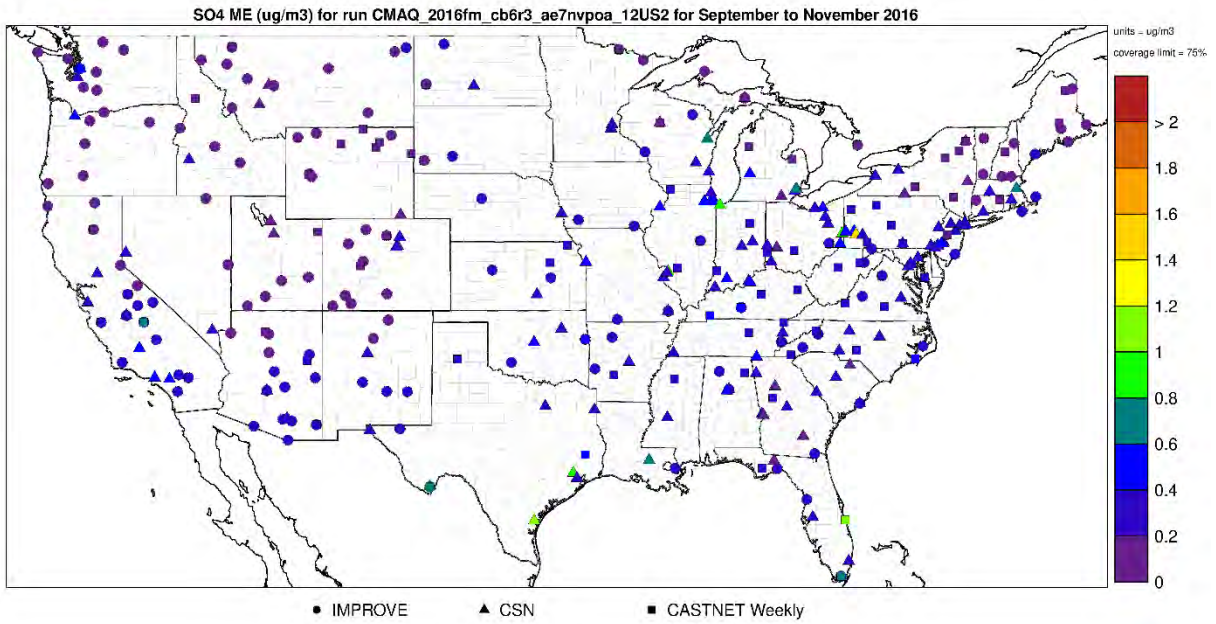


Figure 7-20 Mean Error (ug/m^3) of sulfate during fall 2016 at monitoring sites in the modeling domain

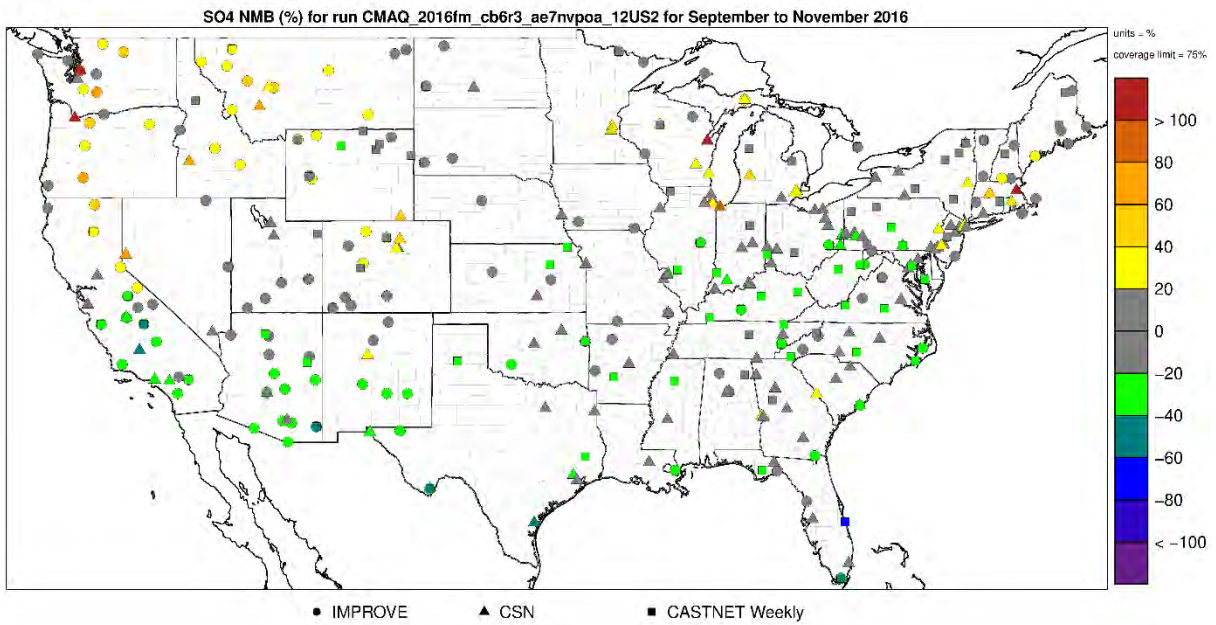


Figure 7-21 Normalized Mean Bias (%) of sulfate during fall 2016 at monitoring sites in the modeling domain

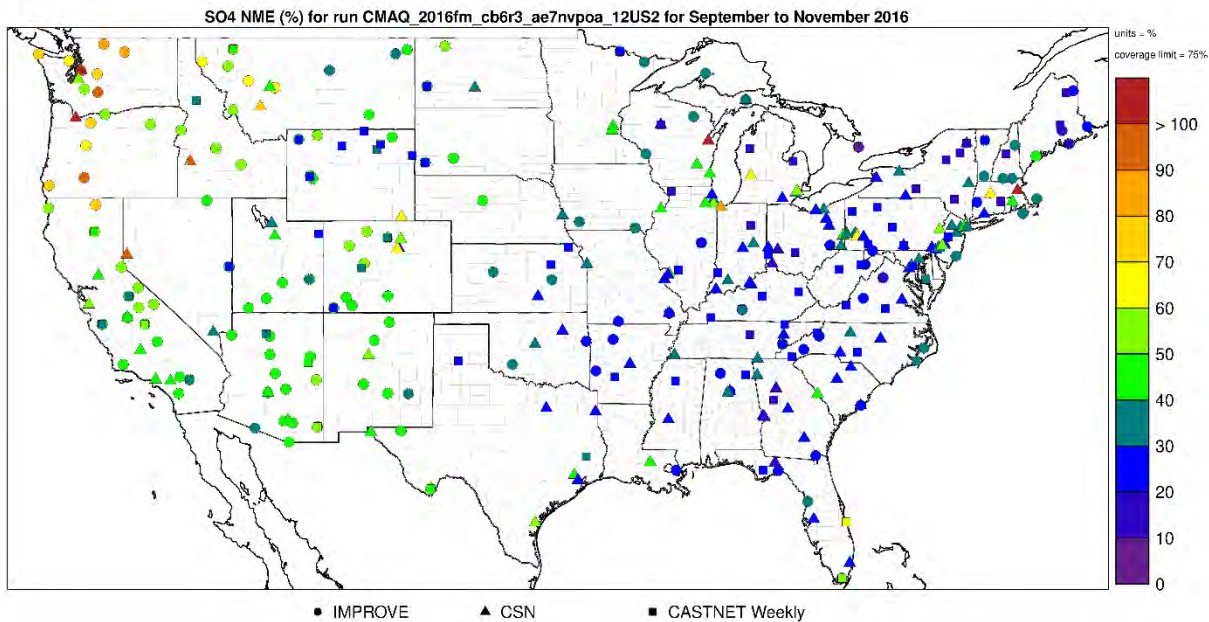


Figure 7-22 Normalized Mean Error (%) of sulfate during fall 2016 at monitoring sites in the modeling domain

7.4.4.2 Seasonal Evaluation for Nitrate

The model performance bias and error statistics for nitrate for each climate region and each season are provided in Table 7-6. This table includes statistics for particulate nitrate as measured at CSN and IMPROVE sites and total nitrate (TNO₃=NO₃+HNO₃) as measured at CASTNet sites. Spatial plots of the mean bias and error as well as normalized mean bias and error by season for individual monitors are shown in Figure 7-23 through Figure 7-54.

Table 7-6 Nitrate and Total Nitrate Performance Statistics by Climate Region, by Season, and by Monitoring Network for the 2016 CMAQ Model Simulation

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
Northeast	IMPROVE (NO ₃)	Winter	431	0.7	0.8	>100	>100
		Spring	477	0.0	0.2	4.4	69.0
		Summer	486	0.0	0.2	18.9	>100
		Fall	456	0.1	0.2	33.6	90.8
	CSN (NO ₃)	Winter	715	1.0	1.2	58.1	72.1
		Spring	770	0.1	0.5	13.9	58.4
		Summer	778	-0.1	0.2	-40.6	67.0
		Fall	737	0.2	0.4	26.7	68.5

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
	CASTNet (TNO ₃)	Winter	221	0.3	0.4	21.4	28.4
		Spring	242	-0.1	0.3	-10.9	27.4
		Summer	252	0.0	0.3	4.9	29.8
		Fall	242	0.1	0.3	6.4	31.9
Ohio Valley	IMPROVE (NO ₃)	Winter	220	-0.2	0.7	-13.8	54.0
		Spring	244	-0.2	0.3	-47.7	62.9
		Summer	239	0.0	0.2	-23.8	87.4
		Fall	227	-0.2	0.3	-37.4	68.2
	CSN (NO ₃)	Winter	543	0.1	1.0	2.2	43.3
		Spring	562	0.0	0.5	-0.4	64.9
		Summer	552	0.0	0.3	-3.4	82.6
		Fall	538	0.0	0.5	3.0	60.7
	CASTNet (TNO ₃)	Winter	212	-0.3	0.6	-12.1	22.4
		Spring	228	-0.3	0.5	-20.3	27.3
		Summer	224	0.1	0.4	9.9	31.2
		Fall	226	0.0	0.6	-1.6	34.3
Upper Midwest	IMPROVE (NO ₃)	Winter	200	-0.3	0.7	-20.2	48.1
		Spring	208	-0.2	0.3	-43.2	60.3
		Summer	210	0.0	0.1	-2.9	82.3
		Fall	215	-0.1	0.3	-37.1	68.7
	CSN (NO ₃)	Winter	326	0.1	1.0	2.9	38.5
		Spring	354	0.0	0.6	0.1	58.3
		Summer	313	0.0	0.3	1.4	88.2
		Fall	307	0.0	0.4	2.0	57.4
	CASTNet (TNO ₃)	Winter	59	-0.4	0.6	-17.1	24.1
		Spring	63	-0.2	0.4	-15.0	30.9
		Summer	63	0.0	0.3	4.3	30.3
		Fall	57	-0.1	0.4	-12.3	32.0
Southeast	IMPROVE	Winter	342	0.2	0.4	36.0	78.1

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
	(NO ₃)	Spring	379	-0.1	0.2	-39.7	70.6
		Summer	394	0.0	0.1	-18.7	73.0
		Fall	366	-0.1	0.2	-20.2	67.8
	CSN (NO ₃)	Winter	573	0.7	0.8	>100	>100
		Spring	643	-0.1	0.2	-19.8	70.0
		Summer	608	-0.1	0.2	-23.2	79.9
		Fall	560	0.1	0.2	19.5	80.8
	CASTNet (TNO ₃)	Winter	150	0.0	0.5	1.5	36.6
		Spring	164	-0.5	0.5	43.8	-35.2
		Summer	164	-0.2	0.4	-21.7	37.7
		Fall	154	-0.2	0.5	-13.8	39.6
	South	IMPROVE (NO ₃)	Winter	240	-0.1	0.5	-14.2
Spring			273	-0.1	0.2	-42.1	70.2
Summer			252	-0.1	0.2	-65.7	82.5
Fall			264	-0.1	0.2	-48.0	67.9
CSN (NO ₃)		Winter	326	0.1	0.5	9.2	58.5
		Spring	349	-0.1	0.2	-35.8	70.0
		Summer	335	-0.1	0.2	-29.1	79.3
		Fall	330	0.0	0.2	-14.5	76.6
CASTNet (TNO ₃)		Winter	92	-0.4	0.5	-21.4	30.9
		Spring	102	-0.4	0.4	-37.5	38.4
		Summer	96	-0.4	0.5	-37.6	42.3
		Fall	102	-0.2	0.3	-18.4	34.0
Southwest	IMPROVE (NO ₃)	Winter	910	-0.2	0.2	-55.5	78.5
		Spring	991	-0.1	0.1	-60.2	82.4
		Summer	985	-0.1	0.1	-93.4	95.2
		Fall	962	-0.1	0.1	-72.8	84.0
	CSN (NO ₃)	Winter	272	-0.1	0.5	-13.2	53.3
		Spring	255	-0.2	0.3	-53.4	66.0

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
		Summer	250	-0.2	0.3	-75.7	97.4
		Fall	257	-0.3	0.4	-55.1	79.5
	CASTNet (TNO ₃)	Winter	101	-0.2	0.3	-33.6	46.9
		Spring	115	-0.1	0.2	-29.2	37.3
		Summer	114	-0.3	0.3	-39.8	42.5
		Fall	115	-0.1	0.2	-12.9	30.2
Northern Rockies	IMPROVE (NO ₃)	Winter	542	-0.1	0.3	-41.9	69.6
		Spring	573	-0.1	0.1	-46.6	74.5
		Summer	603	-0.1	0.1	-78.4	85.8
		Fall	574	0.0	0.1	-29.8	80.3
	CSN (NO ₃)	Winter	139	-0.2	0.7	-13.6	54.7
		Spring	151	-0.2	0.3	-33.8	56.3
		Summer	153	-0.1	0.1	-43.8	76.9
		Fall	135	0.0	0.2	-6.8	65.6
	CASTNet (TNO ₃)	Winter	126	-0.3	0.3	-42.4	49.7
		Spring	139	-0.1	0.2	32.0	36.2
		Summer	138	-0.2	0.2	-35.6	36.0
		Fall	129	-0.1	0.1	-24.7	33.0
Northwest	IMPROVE (NO ₃)	Winter	427	-0.1	0.3	-27.0	94.6
		Spring	505	0.1	0.2	49.3	>100
		Summer	519	0.1	0.3	90.5	>100
		Fall	499	0.0	0.2	26.2	>100
	CSN (NO ₃)	Winter	157	-0.2	1.0	-14.4	87.3
		Spring	166	1.3	1.3	>100	>100
		Summer	153	1.2	1.2	>100	>100
		Fall	161	0.6	0.8	>100	>100
	CASTNet (TNO ₃)	Winter	-	-	-	-	-
		Spring	-	-	-	-	-
		Summer	-	-	-	-	-

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
		Fall	-	-	-	-	-
West	IMPROVE (NO ₃)	Winter	565	-0.2	0.3	-36.7	64.0
		Spring	608	-0.1	0.2	-34.4	57.7
		Summer	603	-0.2	0.3	-55.5	81.3
		Fall	576	-0.2	0.3	-53.5	73.0
	CSN (NO ₃)	Winter	341	-2.0	2.1	-59.8	64.7
		Spring	352	-0.9	1.0	-57.1	63.0
		Summer	348	-0.7	0.8	-55.1	65.4
		Fall	332	-1.3	1.5	-66.3	75.0
	CASTNet (TNO ₃)	Winter	69	-0.3	0.4	-44.2	52.1
		Spring	73	-0.5	0.5	-49.0	49.7
		Summer	75	-0.9	0.9	-54.4	54.6
		Fall	76	-0.6	0.6	-48.4	51.3

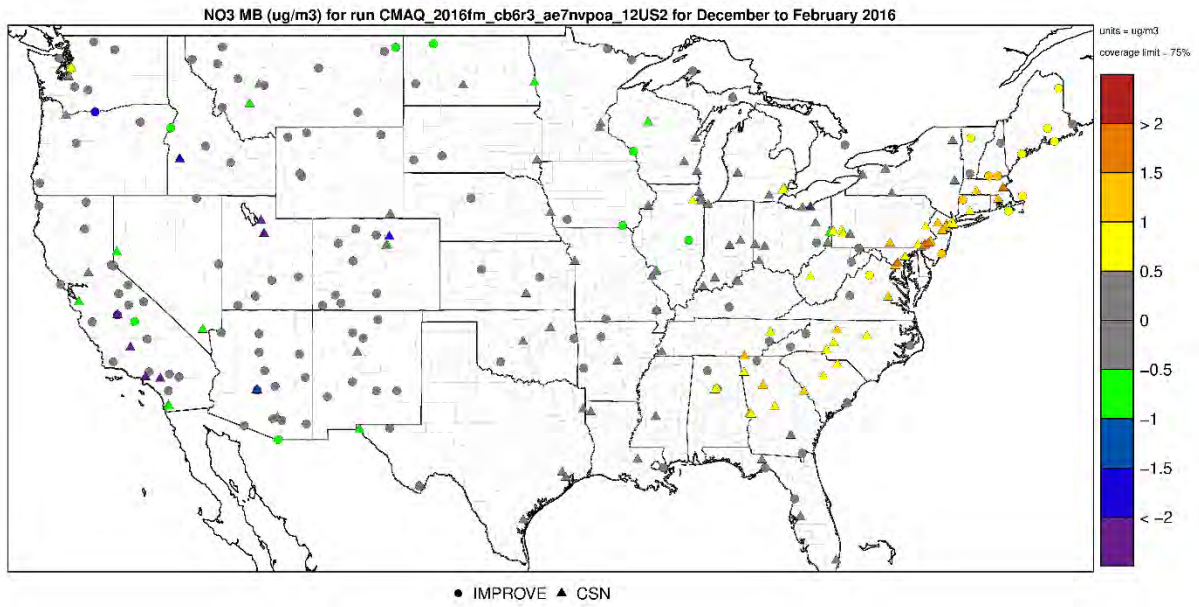


Figure 7-23 Mean Bias (ug/m^3) for nitrate during winter 2016 at monitoring sites in the modeling domain

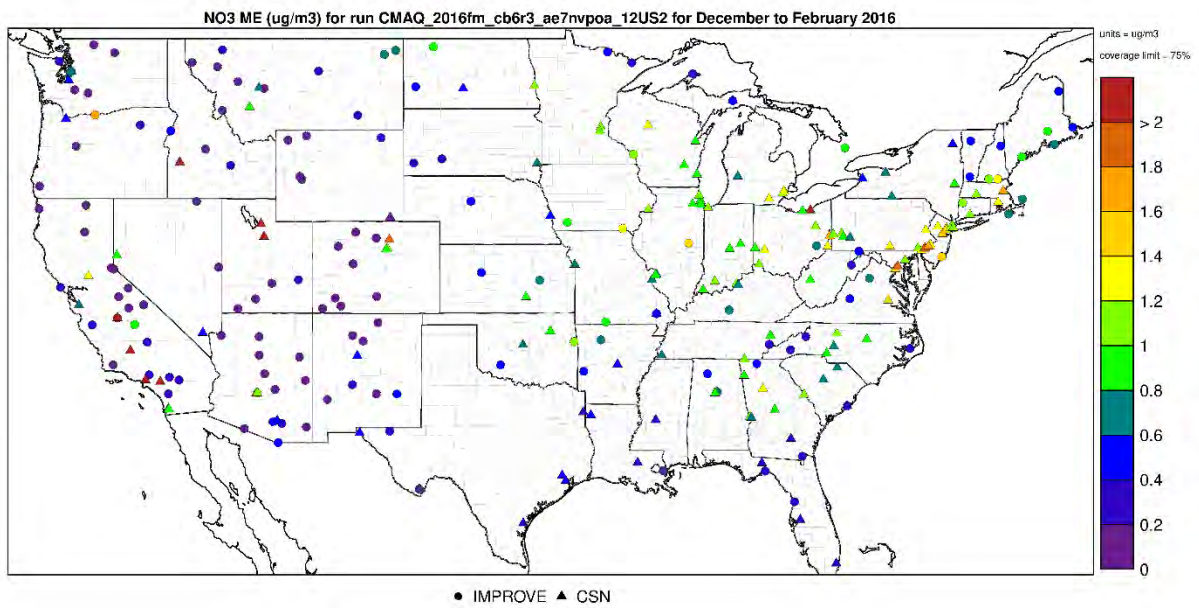


Figure 7-24 Mean Error (ug/m^3) for nitrate during winter 2016 at monitoring sites in the modeling domain

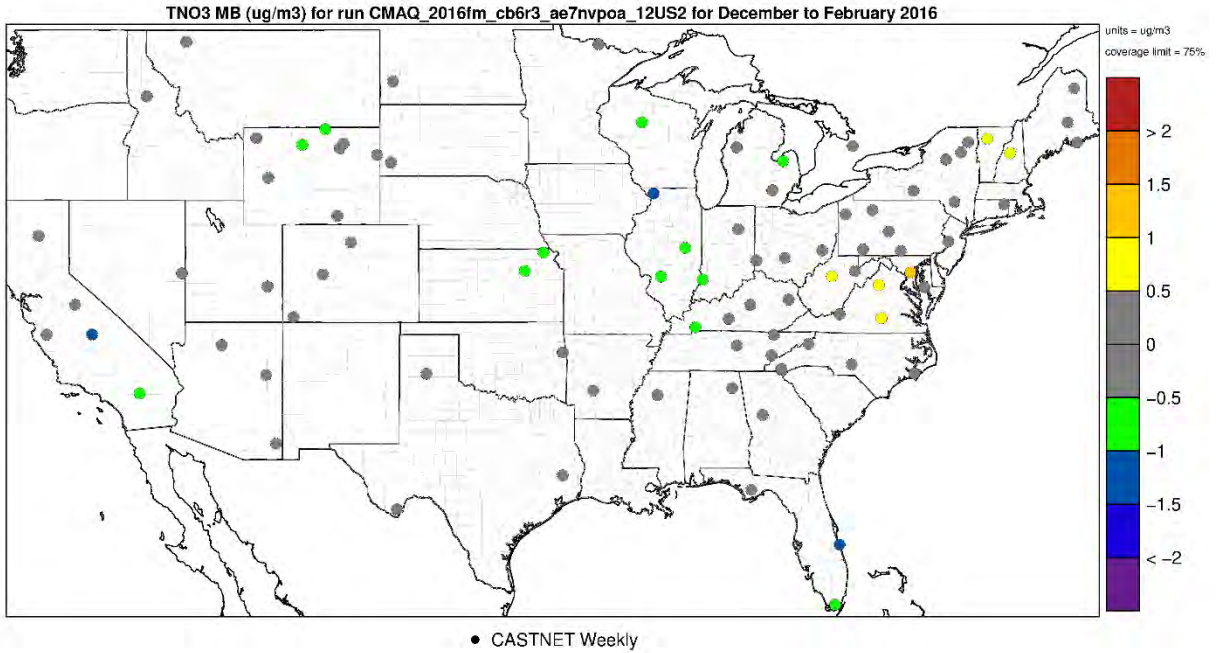


Figure 7-25 Mean Bias (ug/m³) for total nitrate during winter 2016 at monitoring sites in the modeling domain

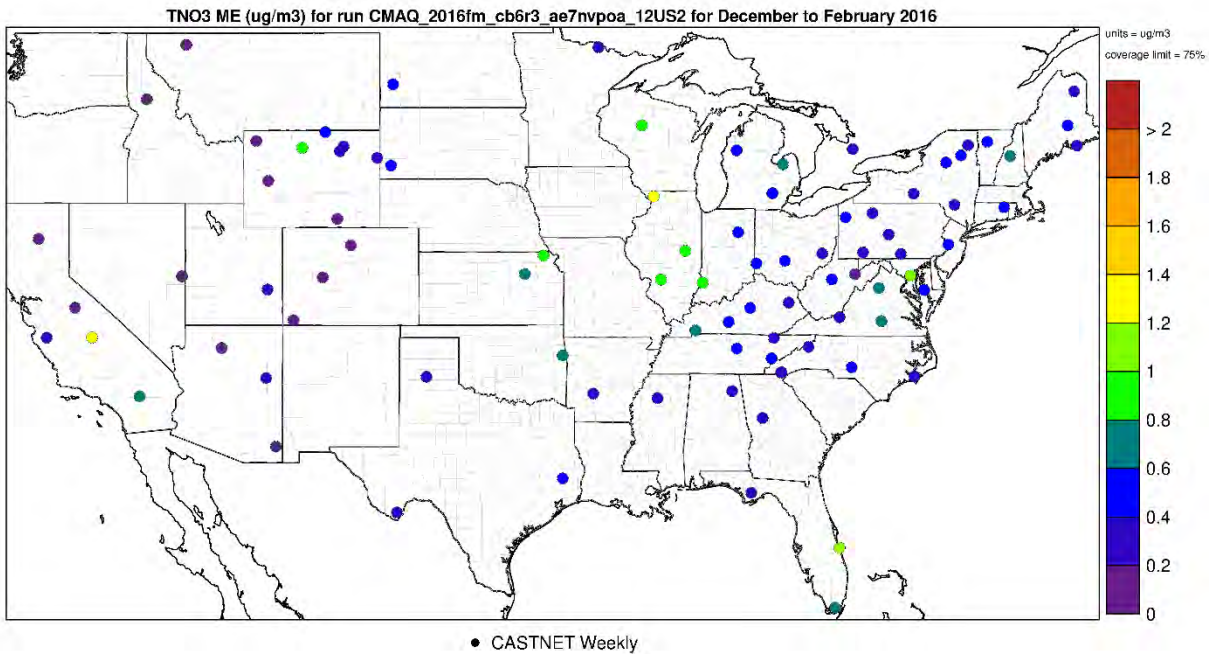


Figure 7-26 Mean Error (ug/m³) for total nitrate during winter 2016 at monitoring sites in the modeling domain

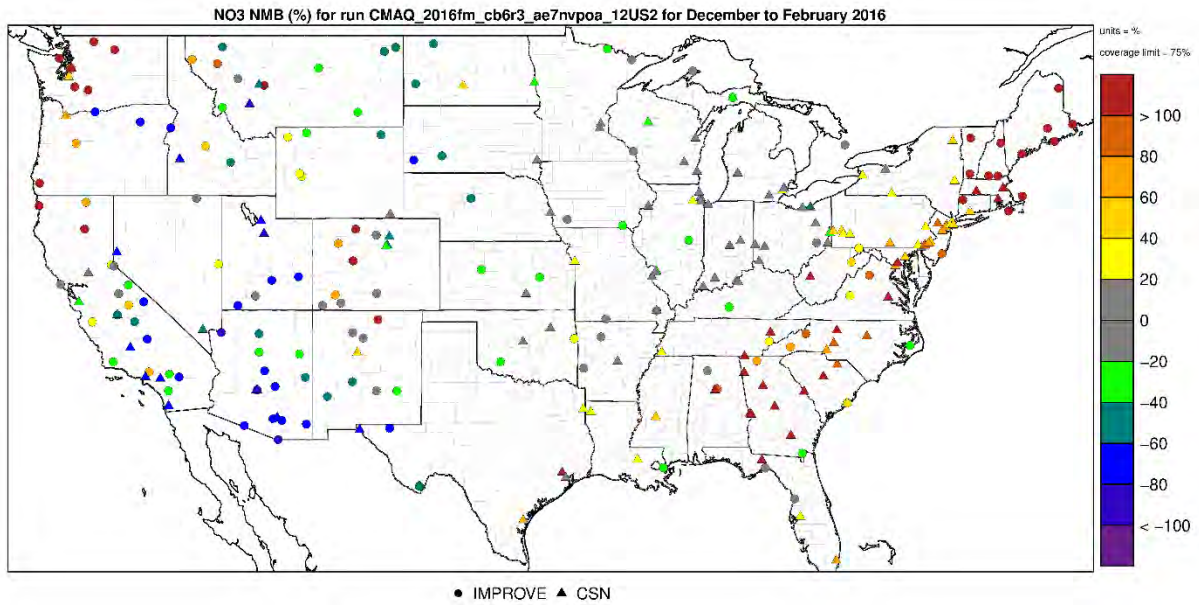


Figure 7-27 Normalized Mean Bias (%) for nitrate during winter 2016 at monitoring sites in the modeling domain

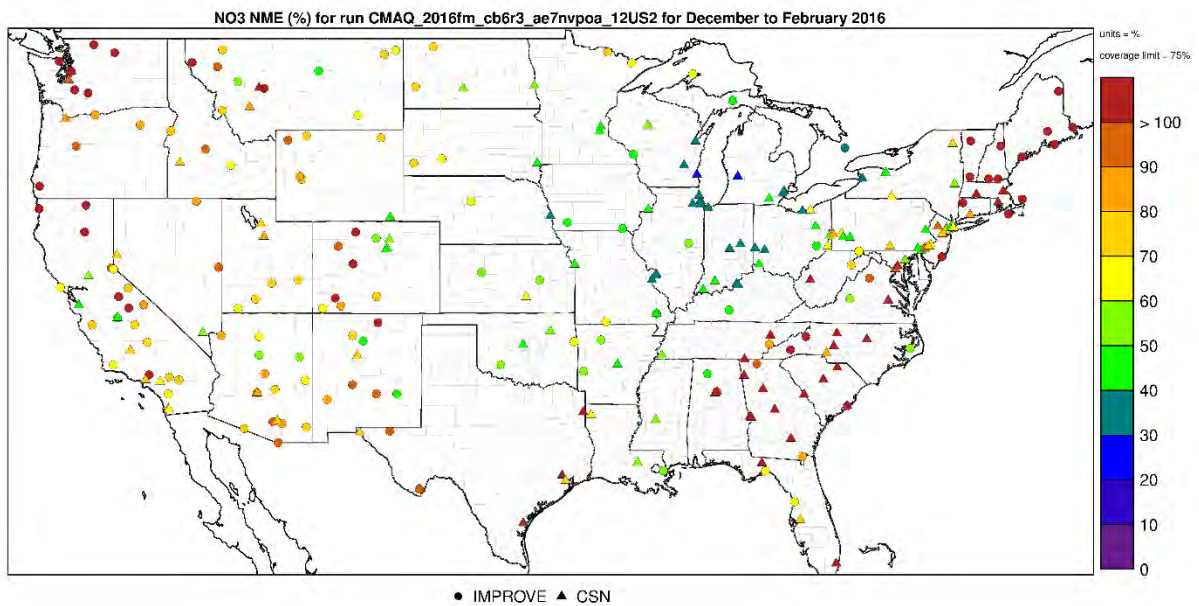


Figure 7-28 Normalized Mean Error (%) for nitrate during winter 2016 at monitoring sites in the modeling domain

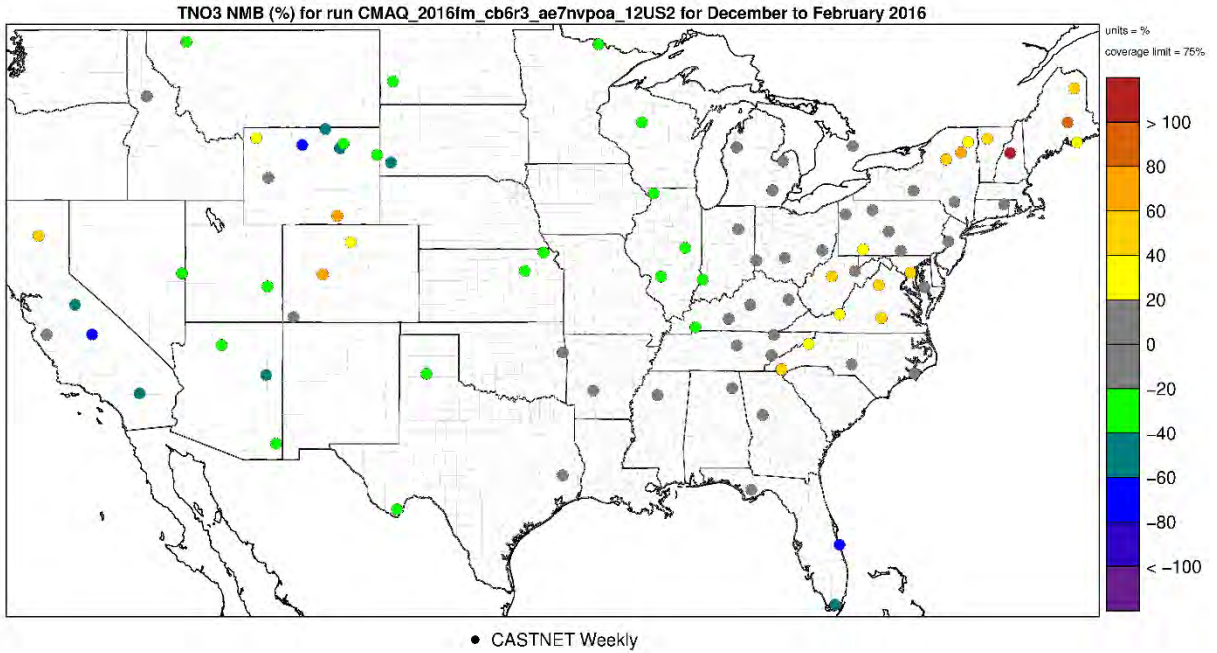


Figure 7-29 Normalized Mean Bias (%) for total nitrate during winter 2016 at monitoring sites in the modeling domain

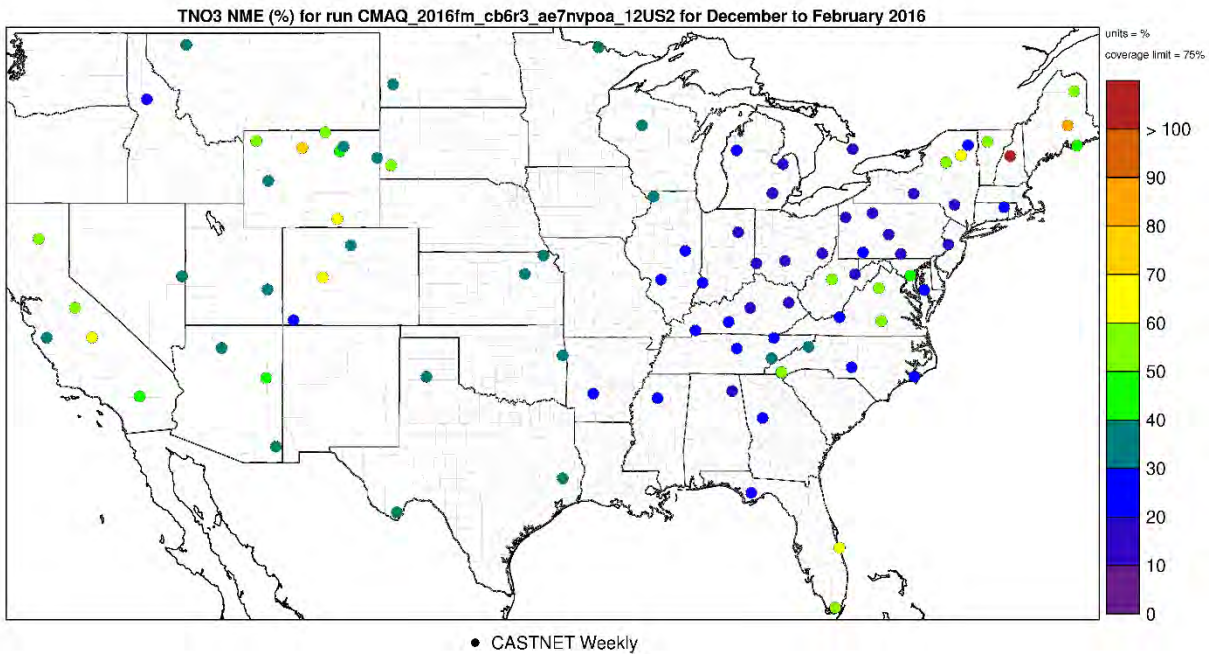


Figure 7-30 Normalized Mean Error (%) for total nitrate during winter 2016 at monitoring sites in the modeling domain

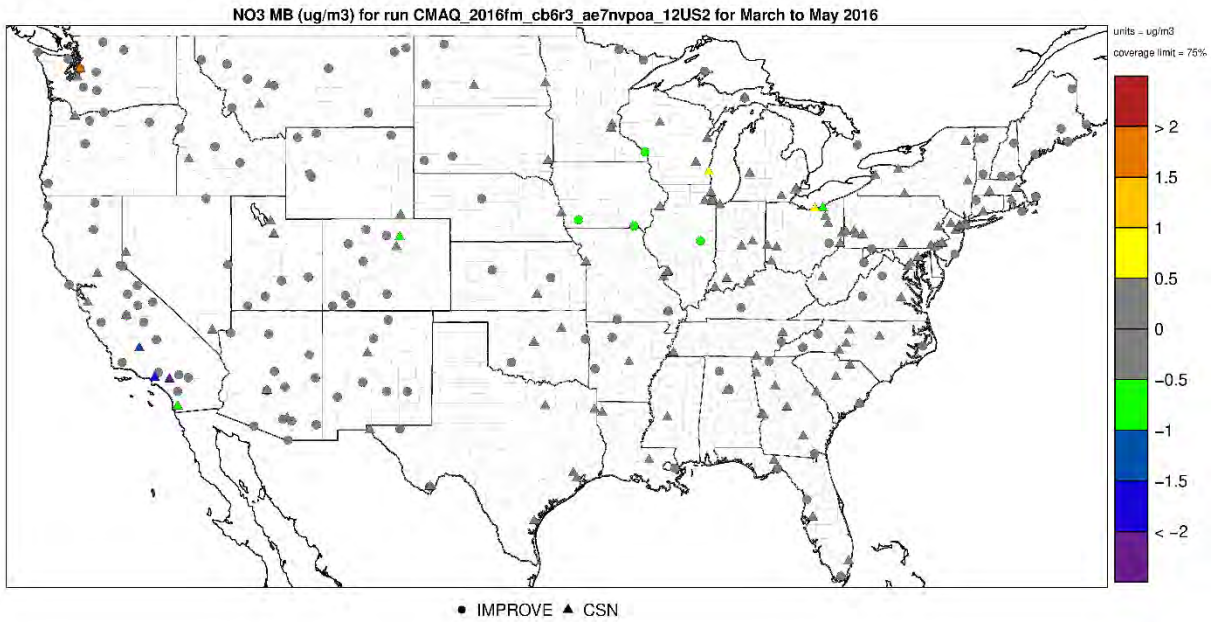


Figure 7-31 Mean Bias (ug/m^3) for nitrate during spring 2016 at monitoring sites in the modeling domain

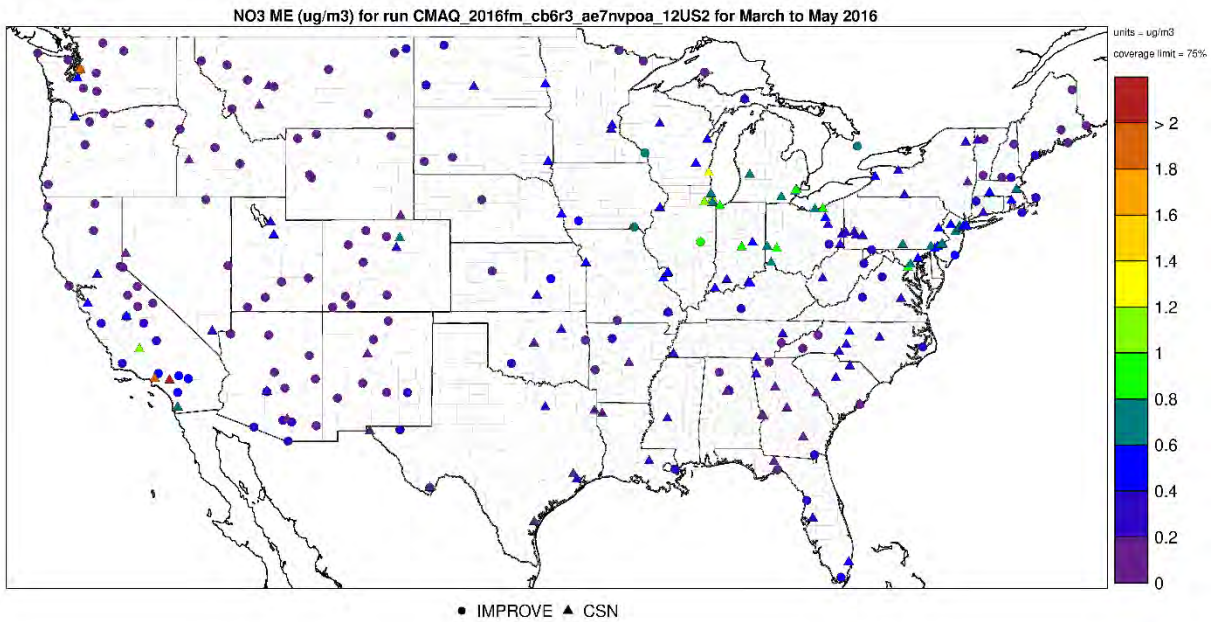


Figure 7-32 Mean Error (ug/m^3) for nitrate during spring 2016 at monitoring sites in the modeling domain

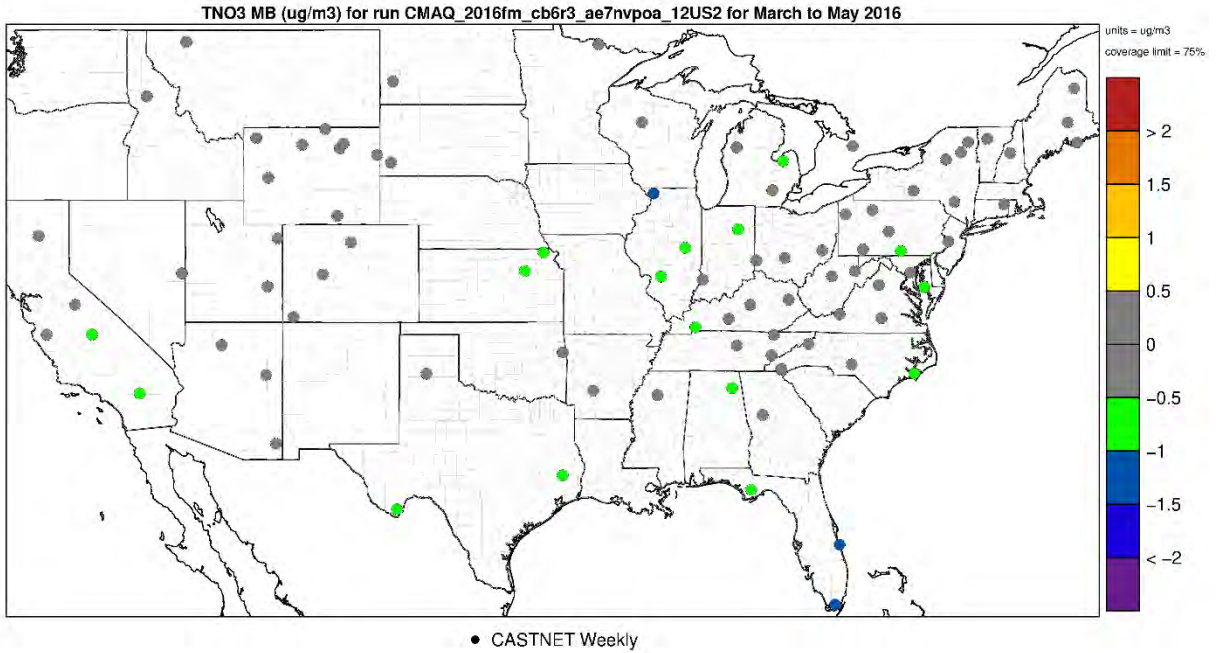


Figure 7-33 Mean Bias (ug/m^3) for total nitrate during spring 2016 at monitoring sites in the modeling domain

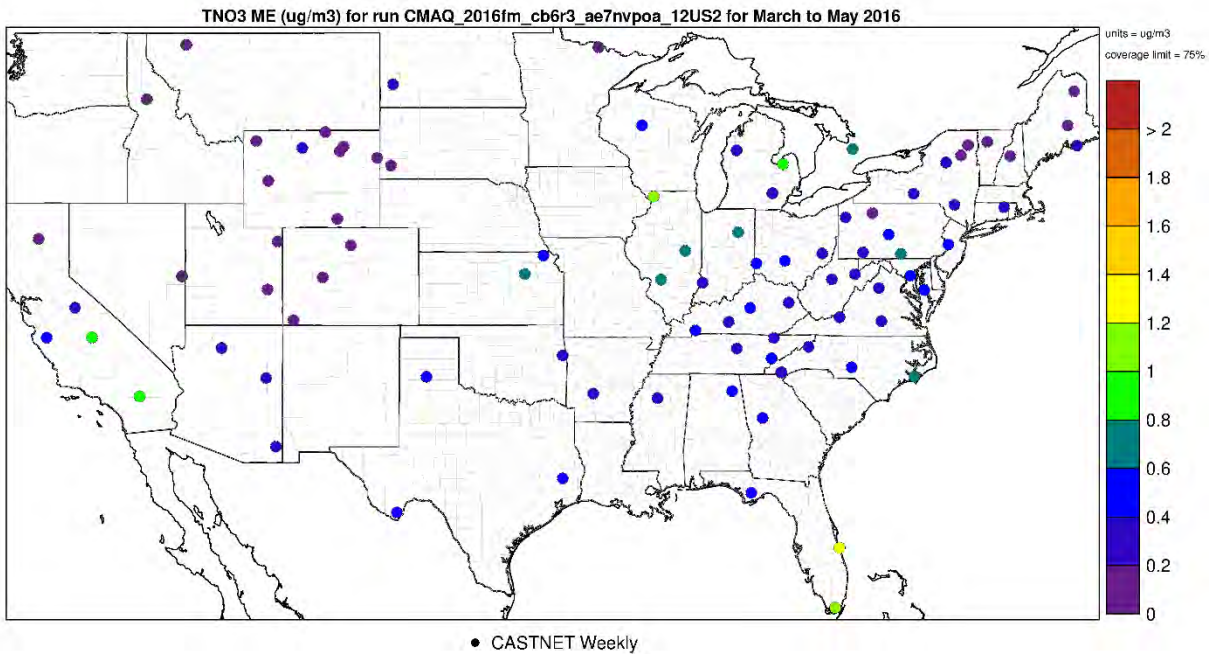


Figure 7-34 Mean Error (ug/m^3) for total nitrate during spring 2016 at monitoring sites in the modeling domain

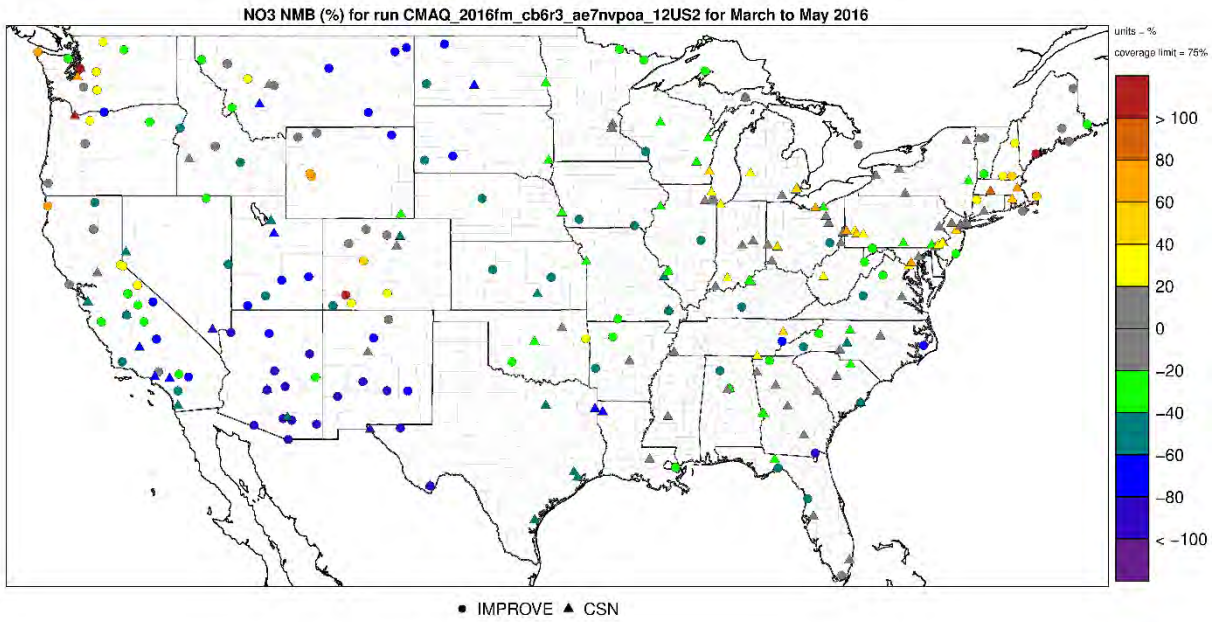


Figure 7-35 Normalized Mean Bias (%) for nitrate during spring 2016 at monitoring sites in the modeling domain

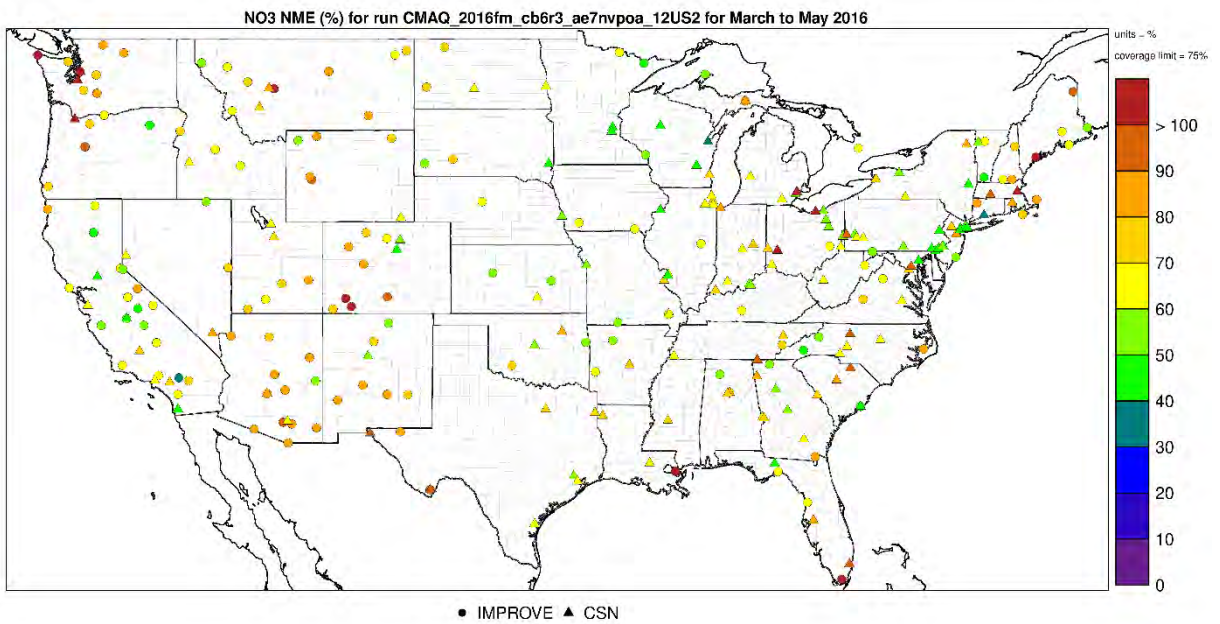


Figure 7-36 Normalized Mean Error (%) for nitrate during spring 2016 at monitoring sites in the modeling domain

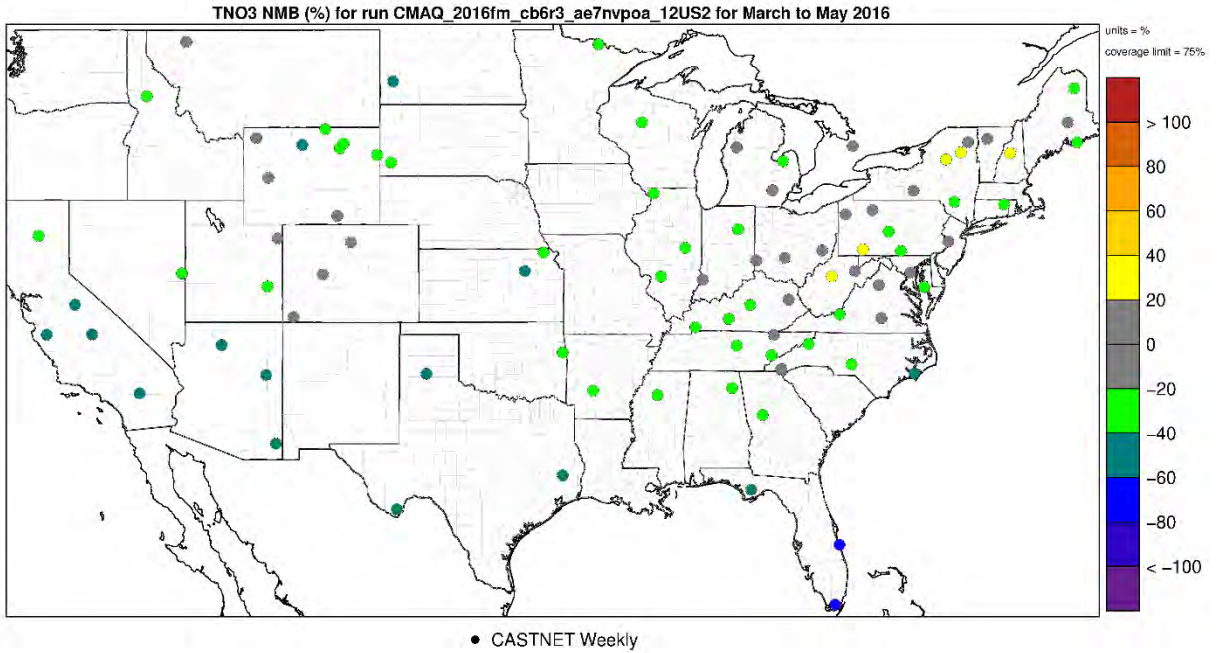


Figure 7-37 Normalized Mean Bias (%) for total nitrate during spring 2016 at monitoring sites in the modeling domain

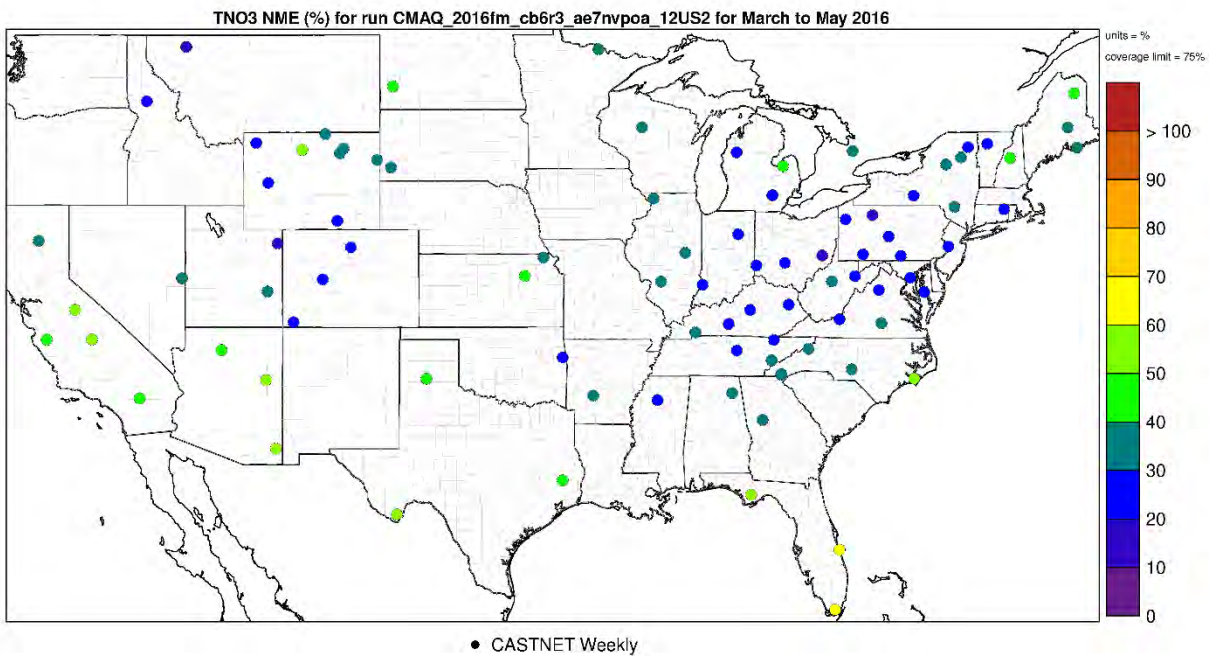


Figure 7-38 Normalized Mean Error (%) for total nitrate during spring 2016 at monitoring sites in the modeling domain

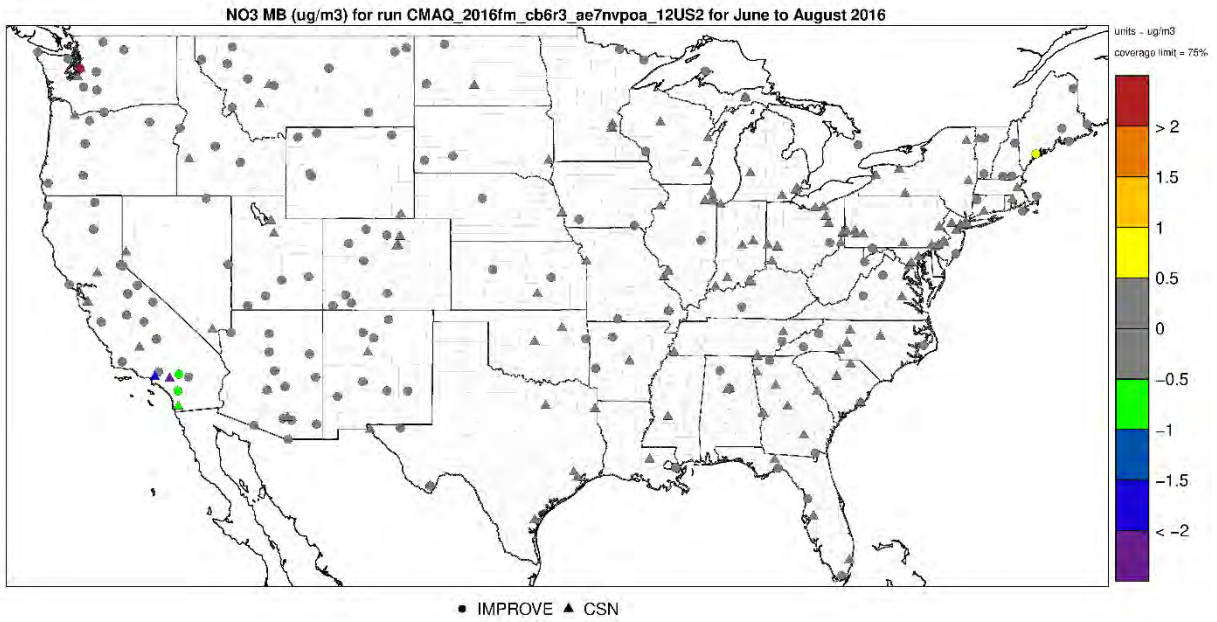


Figure 7-39 Mean Bias (ug/m^3) for nitrate during summer 2016 at monitoring sites in the modeling domain

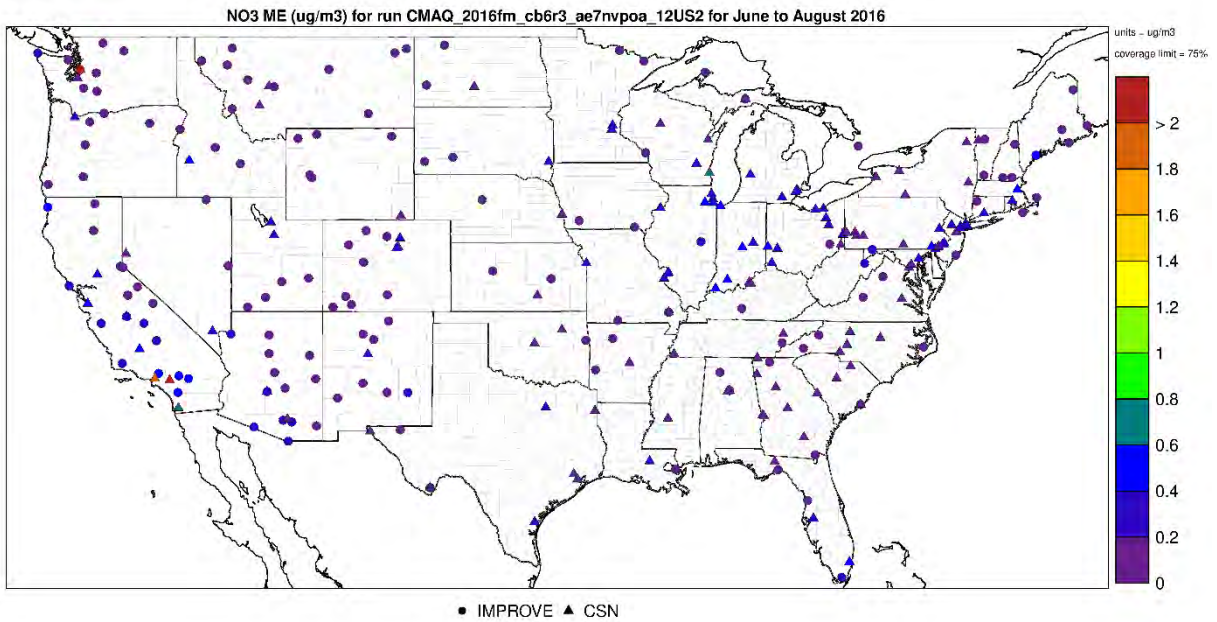


Figure 7-40 Mean Error (ug/m^3) for nitrate during summer 2016 at monitoring sites in the modeling domain

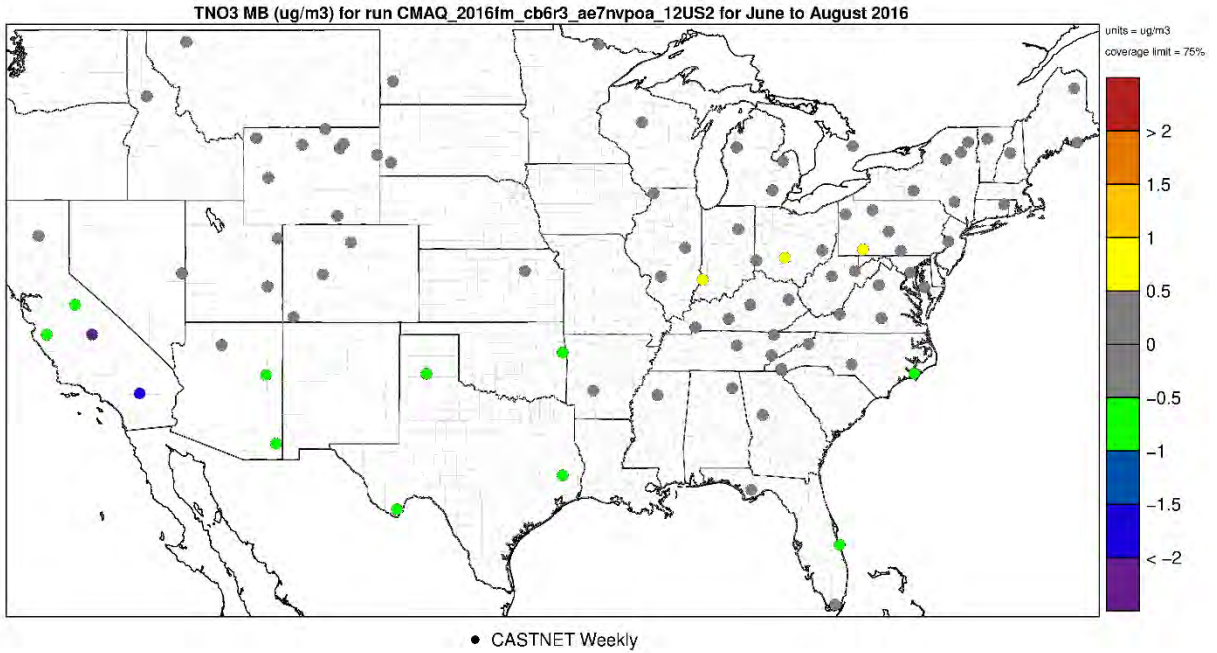


Figure 7-41 Mean Bias (ug/m3) for total nitrate during summer 2016 at monitoring sites in the modeling domain

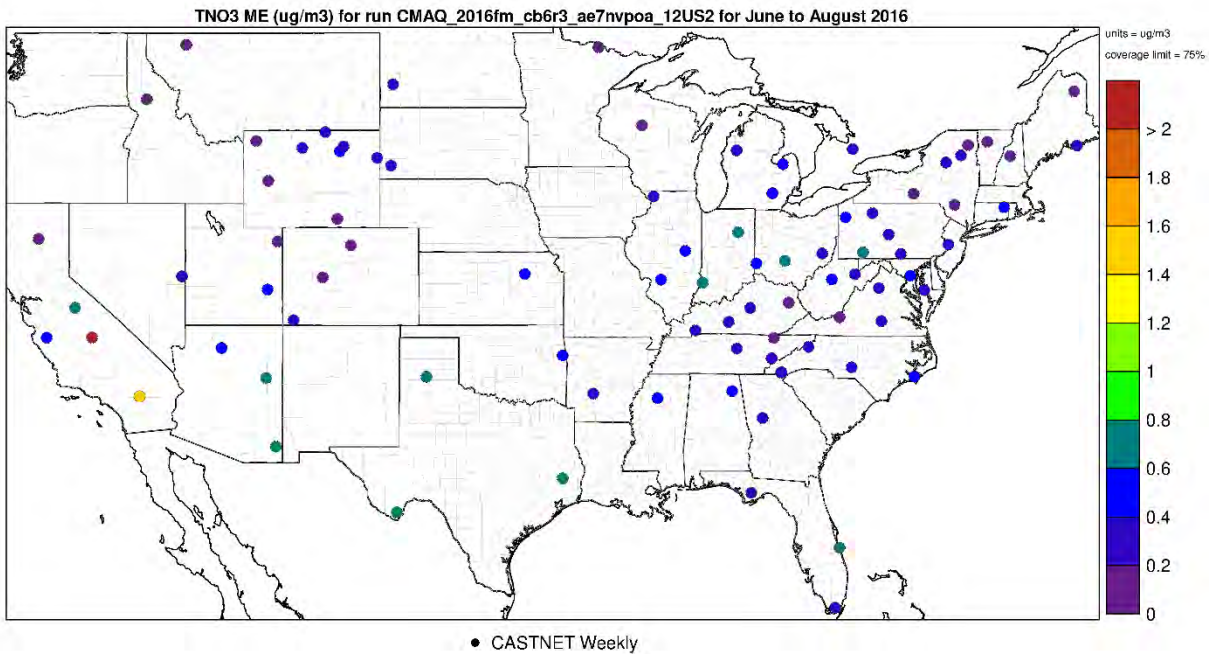


Figure 7-42 Mean Error (ug/m3) for total nitrate during summer 2016 at monitoring sites in the modeling domain

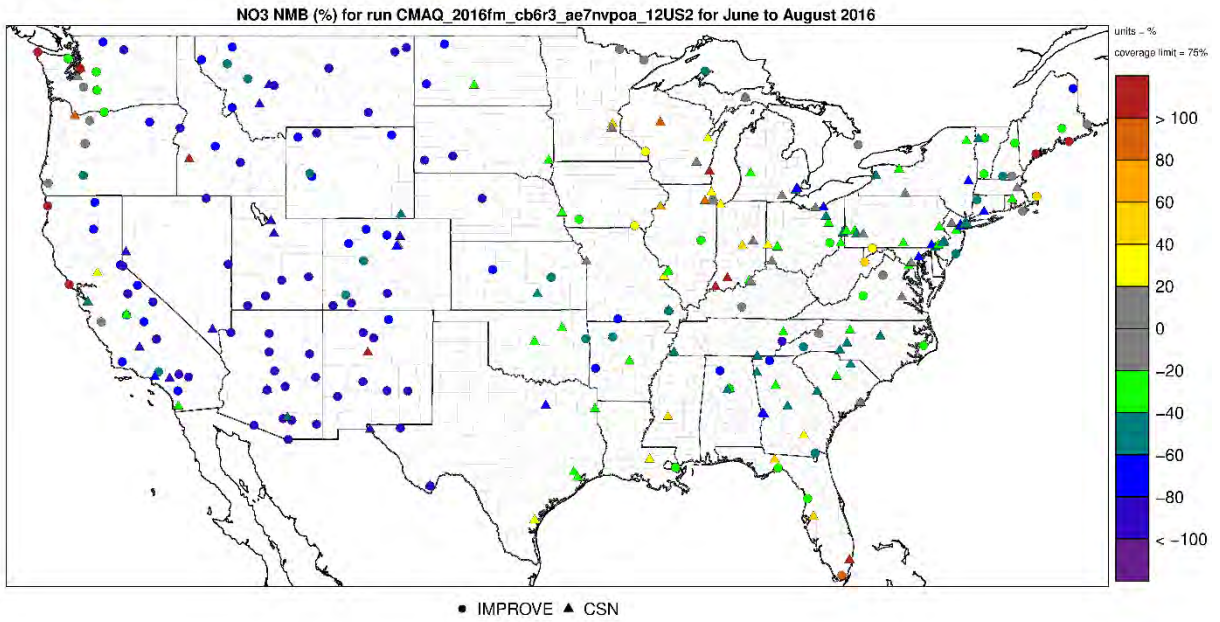


Figure 7-43 Normalized Mean Bias (%) for nitrate during summer 2016 at monitoring sites in the modeling domain

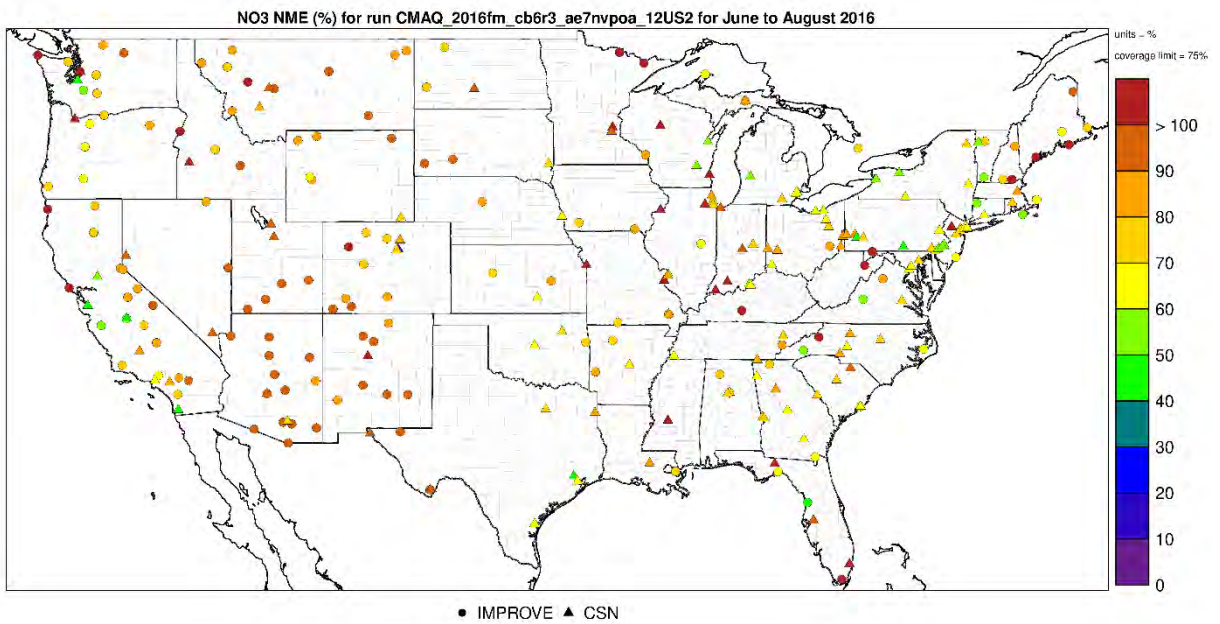


Figure 7-44 Normalized Mean Error (%) for nitrate during summer 2016 at monitoring sites in the modeling domain

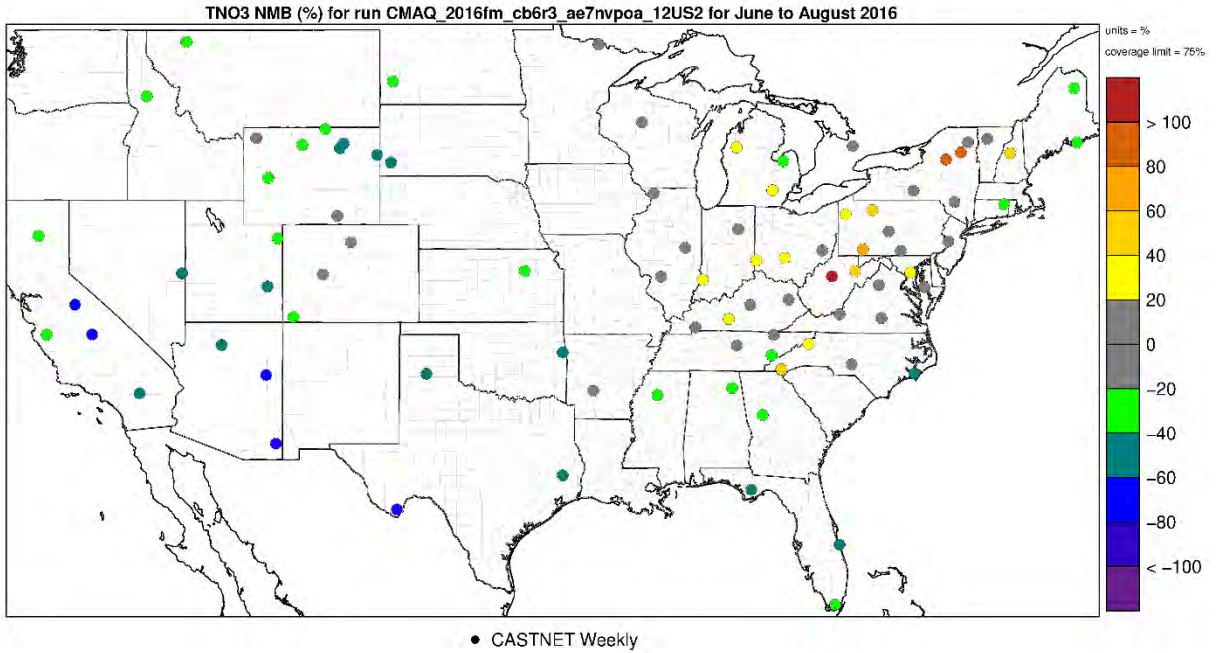


Figure 7-45 Normalized Mean Bias (%) for total nitrate during summer 2016 at monitoring sites in the modeling domain

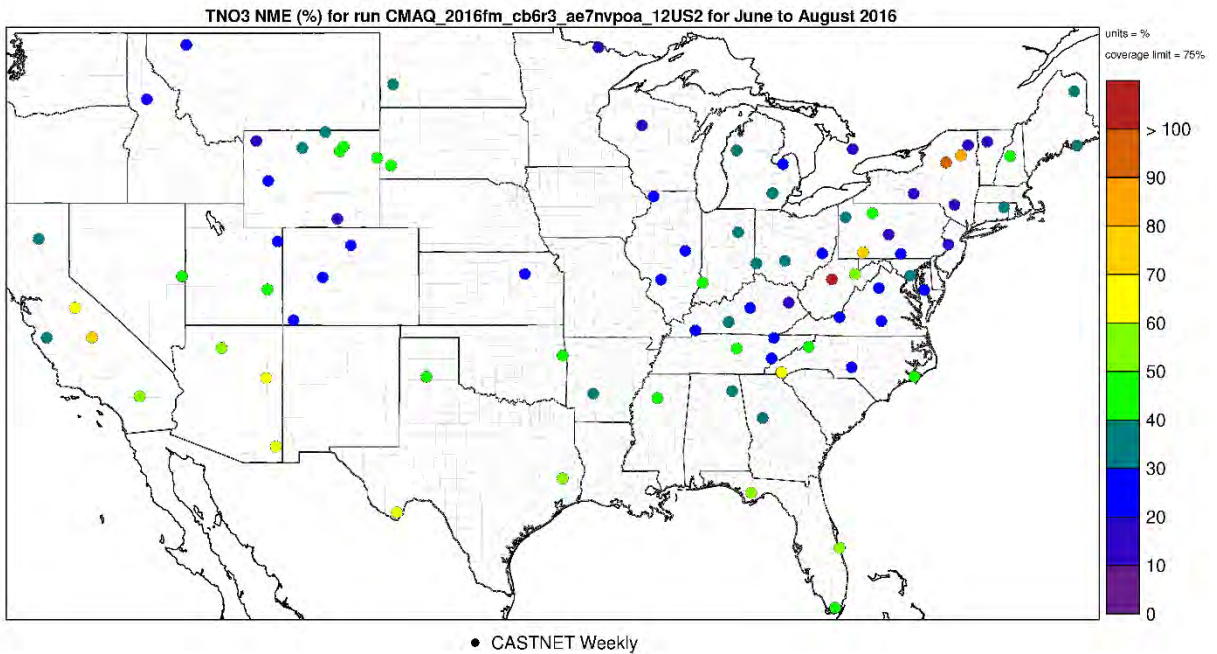


Figure 7-46 Normalized Mean Error (%) for total nitrate during summer 2016 at monitoring sites in the modeling domain

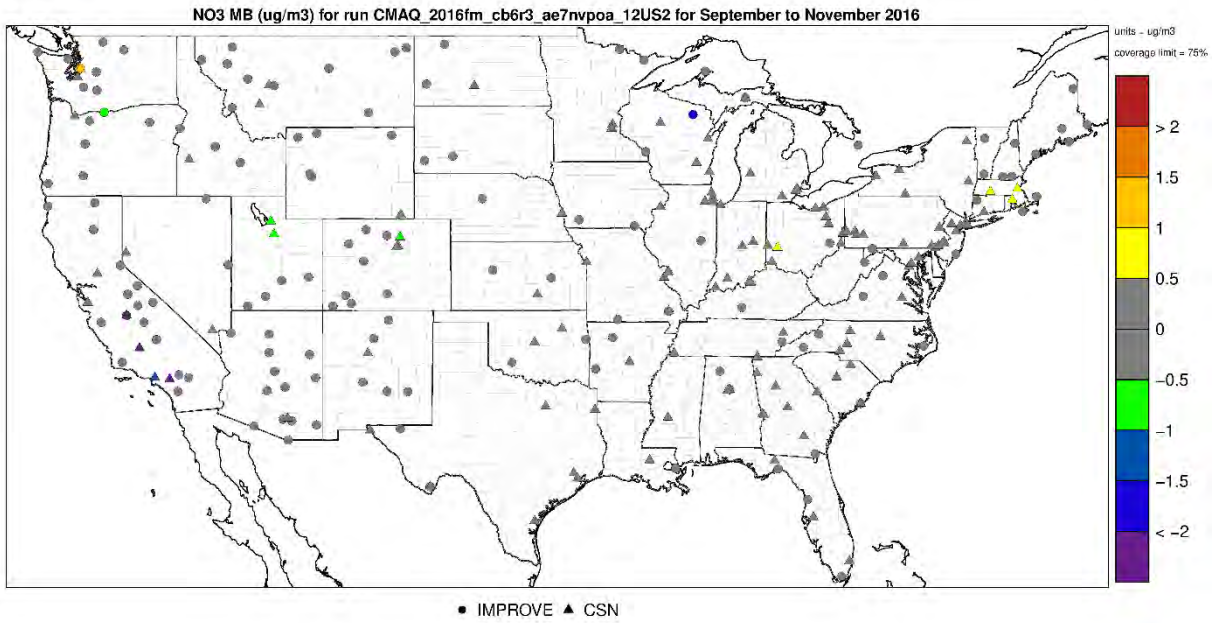


Figure 7-47 Mean Bias (ug/m^3) for nitrate during fall 2016 at monitoring sites in the modeling domain

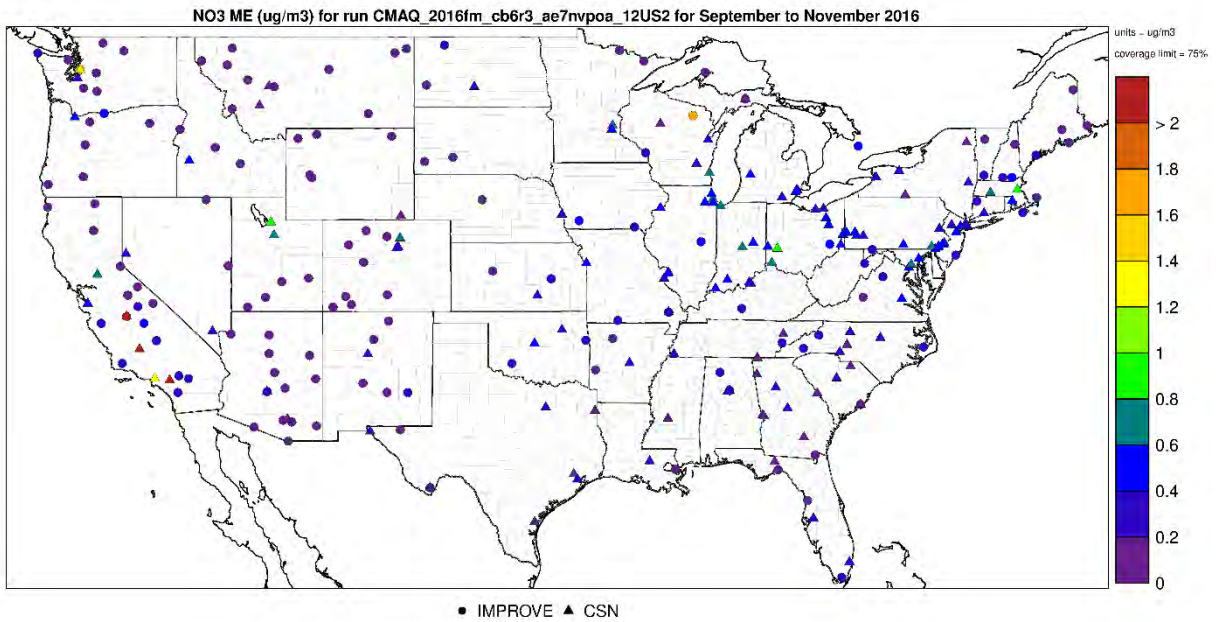


Figure 7-48 Mean Error (ug/m^3) for nitrate during fall 2016 at monitoring sites in the modeling domain

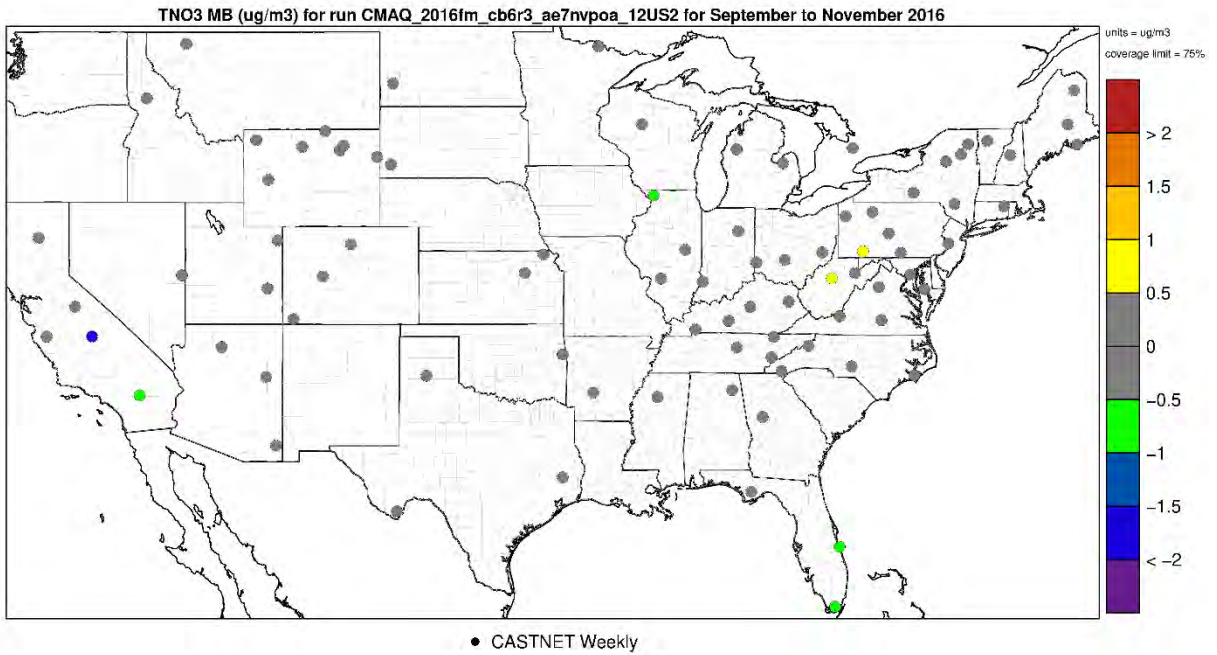


Figure 7-49 Mean Bias (ug/m^3) for total nitrate during fall 2016 at monitoring sites in the modeling domain

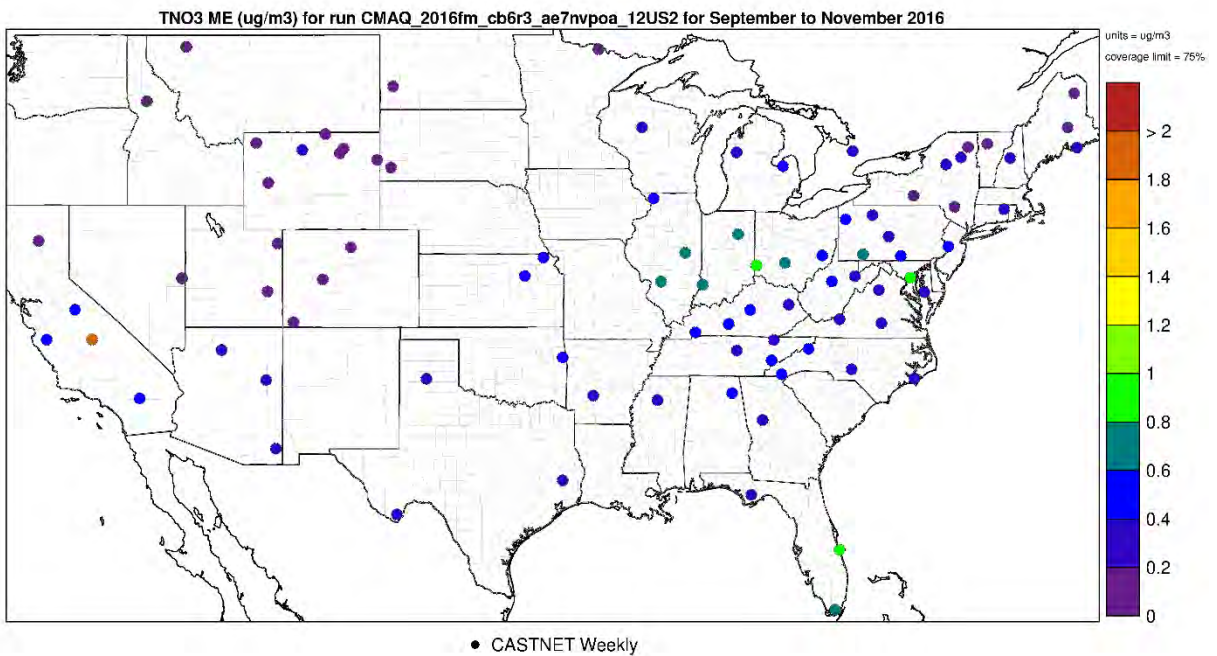


Figure 7-50 Mean Error (ug/m^3) for total nitrate during fall 2016 at monitoring sites in the modeling domain

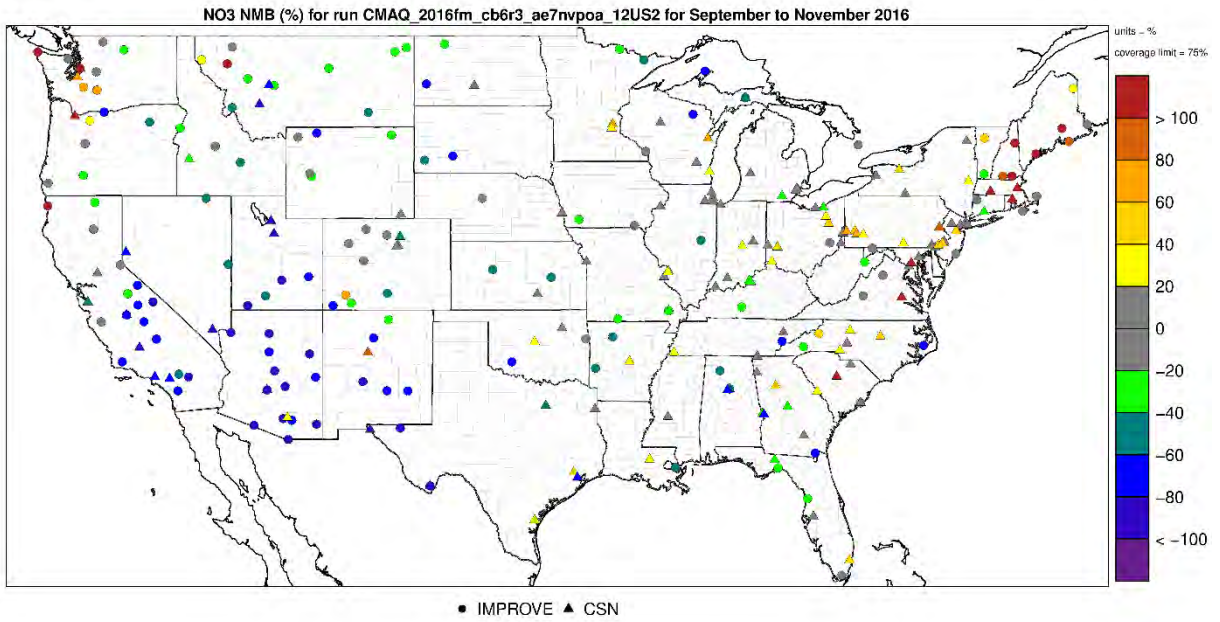


Figure 7-51 Normalized Mean Bias (%) for nitrate during fall 2016 at monitoring sites in the modeling domain

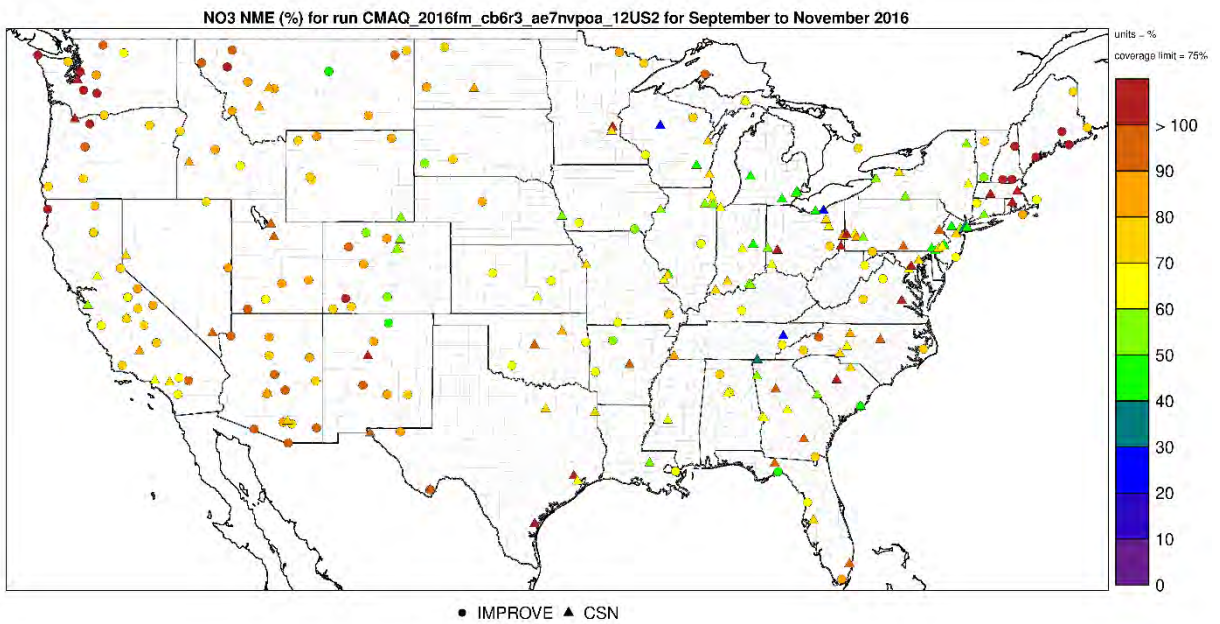


Figure 7-52 Normalized Mean Error (%) for nitrate during fall 2016 at monitoring sites in the modeling domain

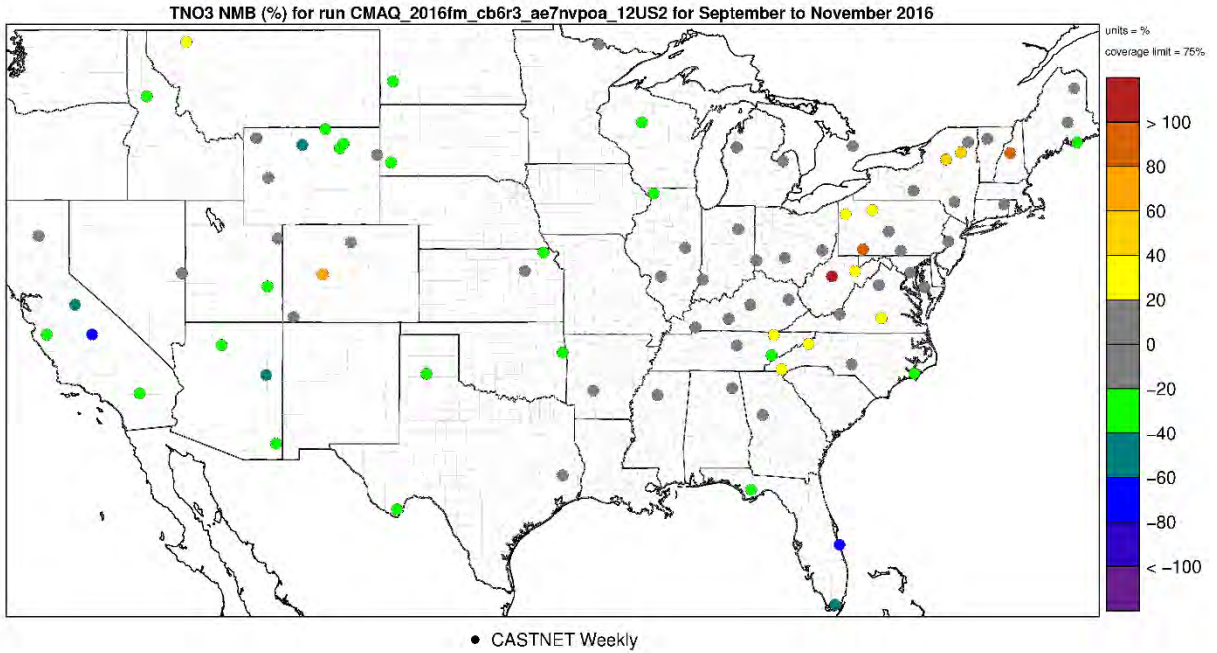


Figure 7-53 Normalized Mean Bias (%) for total nitrate during fall 2016 at monitoring sites in the modeling domain

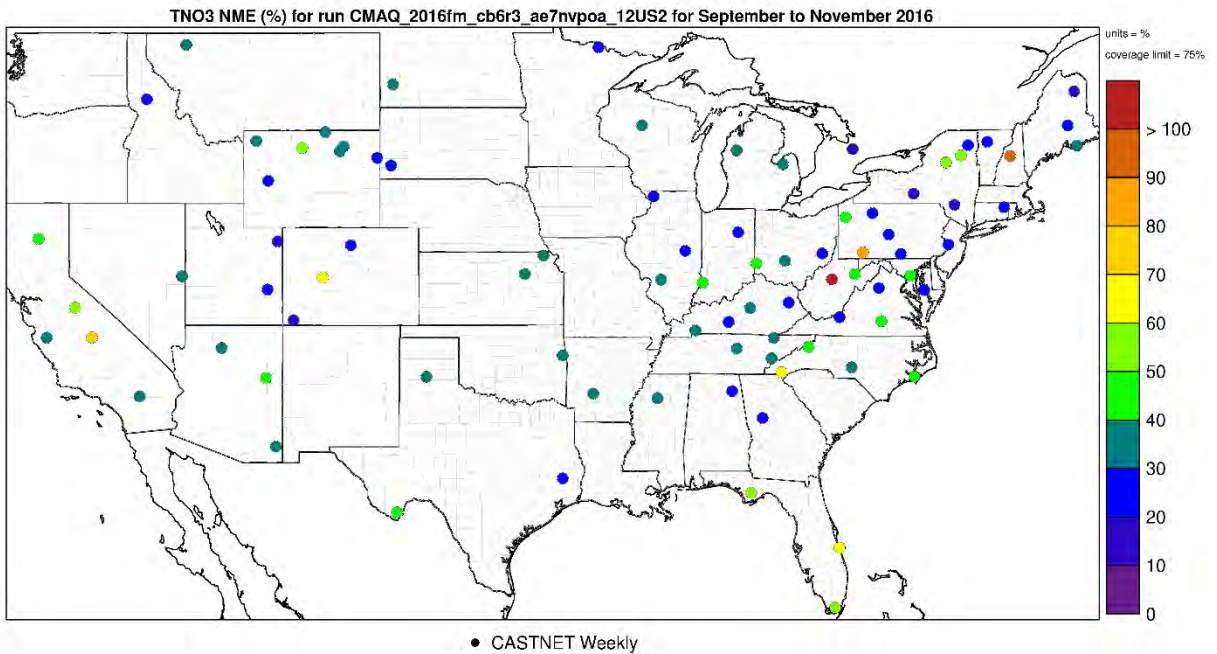


Figure 7-54 Normalized Mean Error (%) for total nitrate during fall 2016 at monitoring sites in the modeling domain

7.4.4.3 Seasonal Ammonium Performance

The model performance bias and error statistics for ammonium for each climate region and season are provided in Table 7-7. Spatial plots of the mean bias and error as well as normalized mean bias and error by season for individual monitors are shown in Figure 7-55 through Figure 7-70.

Table 7-7 Ammonium Performance Statistics by Climate Region, by Season, and by Monitoring Network for the 2016 CMAQ Model Simulation

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
Northeast	CSN	Winter	718	0.6	0.6	>100	>100
		Spring	770	0.2	0.3	81.0	>100
		Summer	782	0.0	0.1	11.6	62.0
		Fall	737	0.2	0.3	77.4	>100
	CASTNet	Winter	221	0.1	0.1	11.6	27.9
		Spring	242	-0.1	0.1	-22.1	30.4
		Summer	252	-0.1	0.1	-30.4	31.7
		Fall	242	-0.1	0.1	-20.3	32.8
Ohio Valley	CSN	Winter	547	0.2	0.5	24.6	60.1
		Spring	562	0.1	0.3	38.9	79.7
		Summer	554	0.1	0.2	21.4	64.2
		Fall	541	0.1	0.3	16.5	67.1
	CASTNet	Winter	212	-0.2	0.2	-22.0	28.5
		Spring	228	-0.2	0.2	-35.3	38.6
		Summer	224	-0.1	0.2	-25.8	31.0
		Fall	226	-0.2	0.2	-30.8	35.1
Upper Midwest	CSN	Winter	326	0.3	0.5	42.0	64.3
		Spring	354	0.2	0.3	39.0	76.9
		Summer	314	0.1	0.2	58.8	87.1
		Fall	310	0.2	0.3	82.4	>100
	CASTNet	Winter	59	-0.2	0.2	-23.3	29.0
		Spring	63	-0.1	0.2	-13.1	35.0
		Summer	63	-0.1	0.1	-24.1	27.9

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
		Fall	57	-0.2	0.1	-30.0	36.3
Southeast	CSN	Winter	513	0.3	0.4	92.7	>100
		Spring	551	-0.1	0.2	-20.6	58.1
		Summer	524	-0.1	0.2	-29.6	65.1
		Fall	503	0.0	0.2	-1.9	66.9
	CASTNet	Winter	150	0.0	0.1	-4.6	27.5
		Spring	164	-0.2	0.2	-45.7	46.6
		Summer	164	-0.2	0.2	-46.7	46.9
		Fall	154	-0.1	0.1	-34.7	38.3
South	CSN	Winter	327	0.1	0.3	38.4	82.2
		Spring	351	-0.1	0.3	-39.2	76.1
		Summer	336	-0.1	0.2	-35.3	83.3
		Fall	331	-0.1	0.2	-18.6	60.6
	CASTNet	Winter	92	-0.1	0.2	-19.4	35.3
		Spring	102	-0.2	0.2	-46.9	51.1
		Summer	96	-0.2	0.2	-50.3	52.2
		Fall	102	-0.1	0.2	-35.2	39.8
Southwest	CSN	Winter	247	-0.4	0.6	-60.9	83.7
		Spring	255	0.0	0.1	-20.3	>100
		Summer	250	-0.1	0.1	-59.3	>100
		Fall	260	-0.1	0.2	-43.8	>100
	CASTNet	Winter	101	-0.1	0.1	-43.1	57.7
		Spring	115	-0.0	0.1	-34.3	46.9
		Summer	114	-0.1	0.1	-62.1	61.2
		Fall	115	-0.1	0.1	-48.2	51.7
Northern Rockies	CSN	Winter	143	0.2	0.3	78.8	>100
		Spring	151	0.1	0.1	67.4	>100
		Summer	153	0.1	0.1	>100	>100
		Fall	139	0.1	0.1	>100	>100

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
	CASTNet	Winter	126	-0.1	0.1	-50.9	55.4
		Spring	139	-0.1	0.1	-44.9	50.4
		Summer	138	-0.1	0.1	-57.0	57.1
		Fall	129	-0.1	0.1	-46.9	51.5
Northwest	CSN	Winter	157	0.1	0.3	25.8	>100
		Spring	161	0.2	0.2	>100	>100
		Summer	166	0.2	0.3	>100	>100
		Fall	161	0.1	0.2	>100	>100
	CASTNet	Winter	-	-	-	-	-
		Spring	-	-	-	-	-
		Summer	-	-	-	-	-
		Fall	-	-	-	-	-
West	CSN	Winter	341	-0.4	0.6	-51.0	74.0
		Spring	352	-0.3	0.4	-58.8	79.1
		Summer	349	-0.3	0.3	-74.8	81.6
		Fall	332	-0.3	0.4	-64.1	82.7
	CASTNet	Winter	69	-0.1	0.1	-38.9	58.3
		Spring	73	-0.1	0.1	-59.8	61.5
		Summer	75	-0.3	0.3	-84.0	84.0
		Fall	76	-0.1	0.1	-60.9	63.3

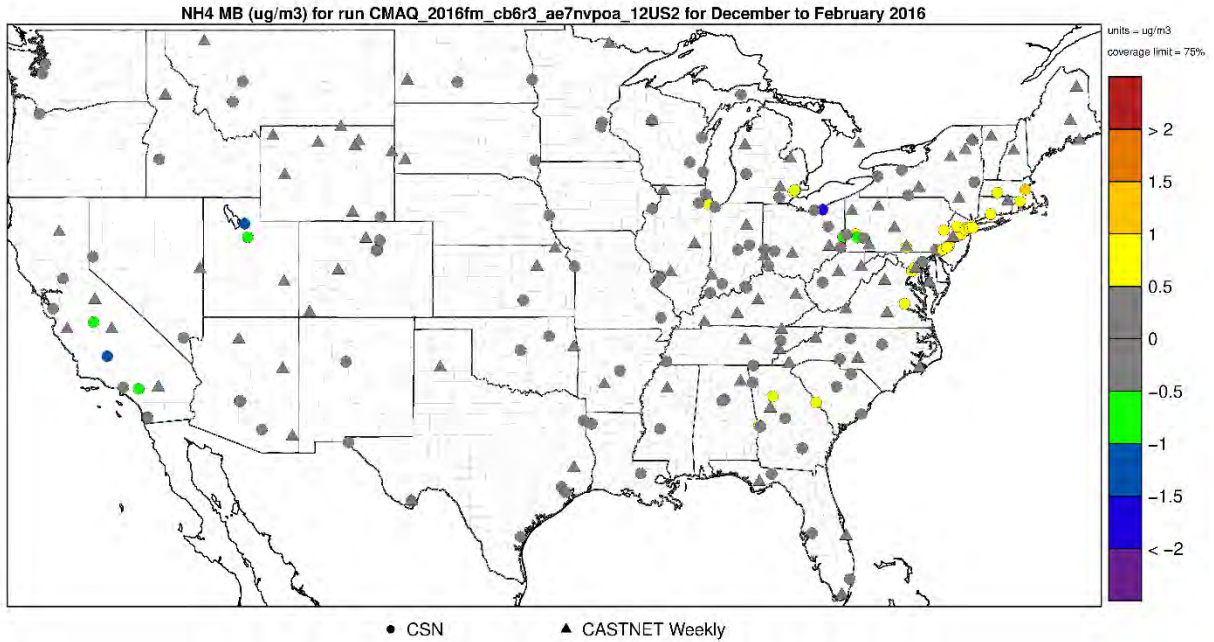


Figure 7-55 Mean Bias (ug/m3) of ammonium during winter 2016 at monitoring sites in the modeling domain

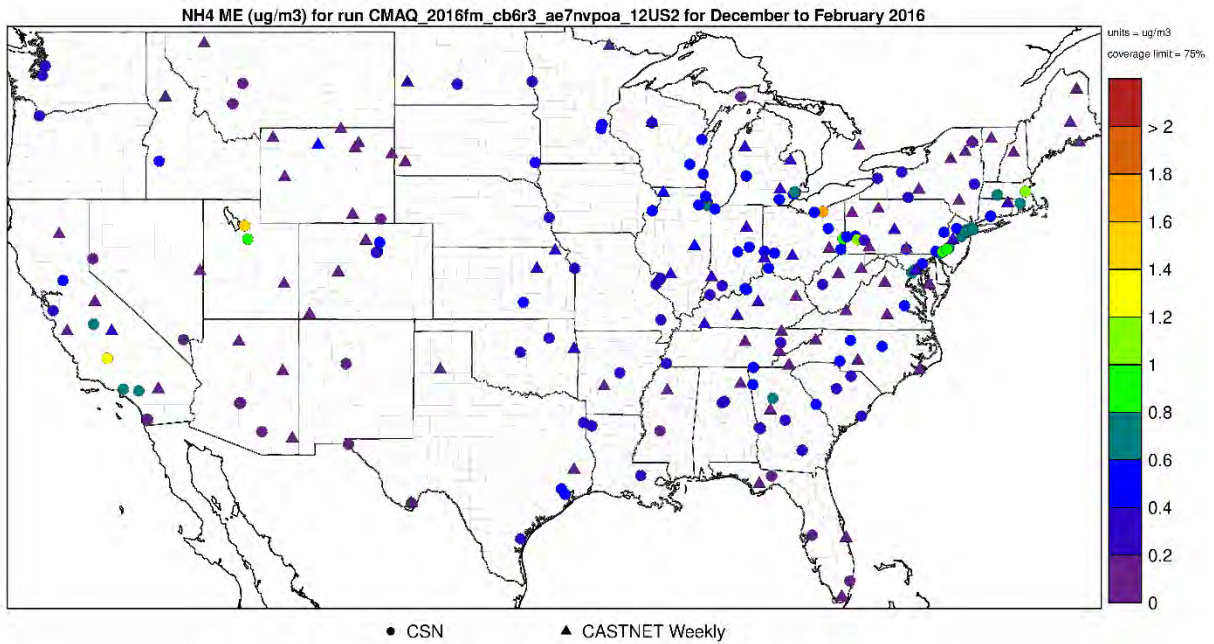


Figure 7-56 Mean Error (ug/m3) of ammonium during winter 2016 at monitoring sites in the modeling domain

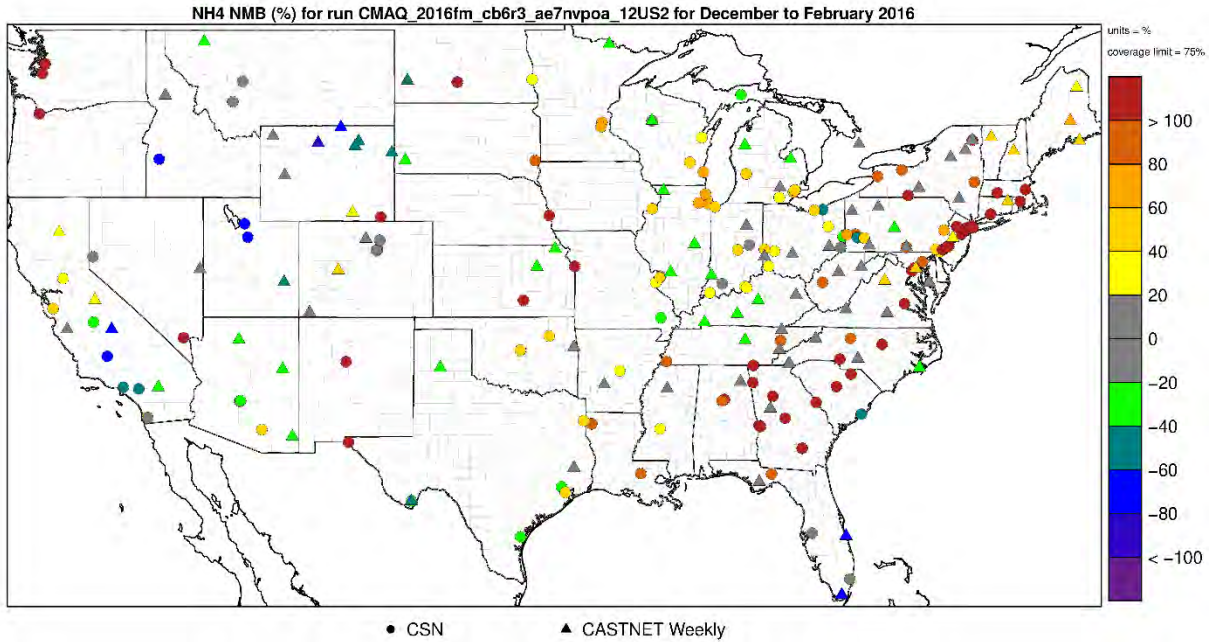


Figure 7-57 Normalized Mean Bias (%) of ammonium during winter 2016 at monitoring sites in the modeling domain

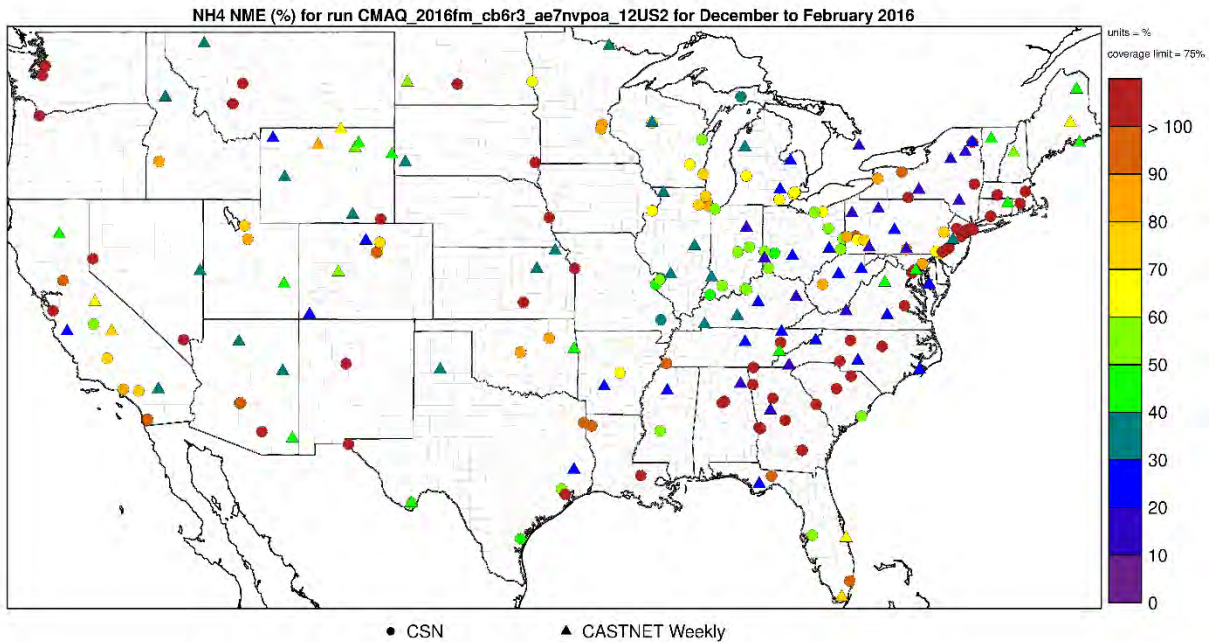


Figure 7-58 Normalized Mean Error (%) of ammonium during winter 2016 at monitoring sites in the modeling domain

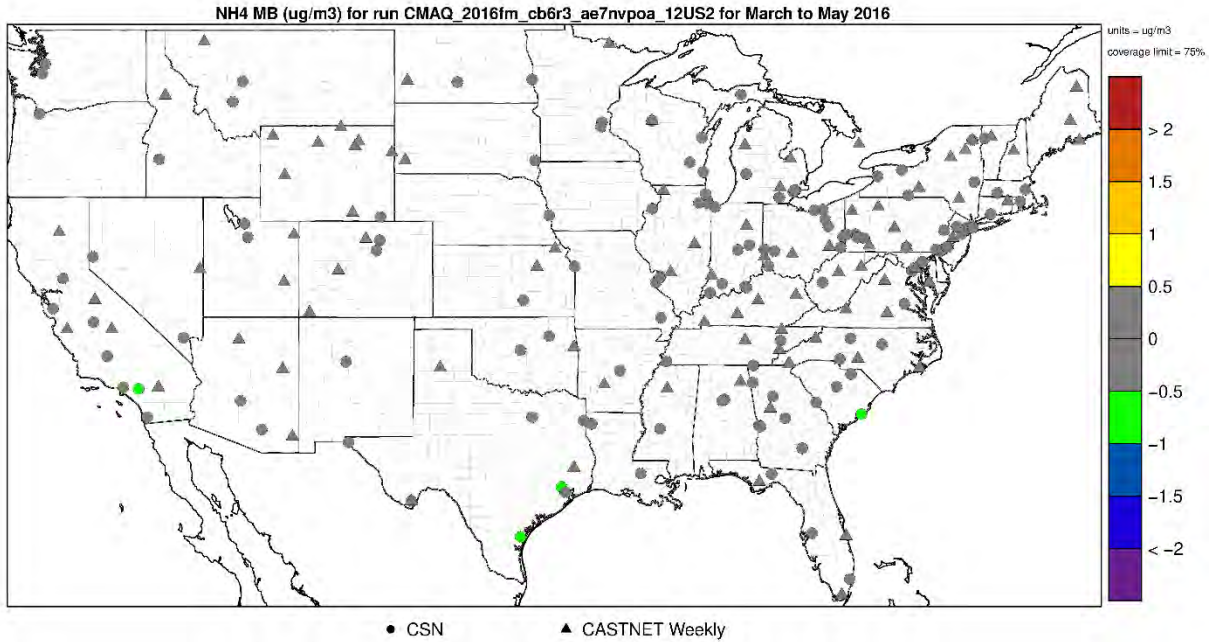


Figure 7-59 Mean Bias (ug/m^3) of ammonium during spring 2016 at monitoring sites in the modeling domain

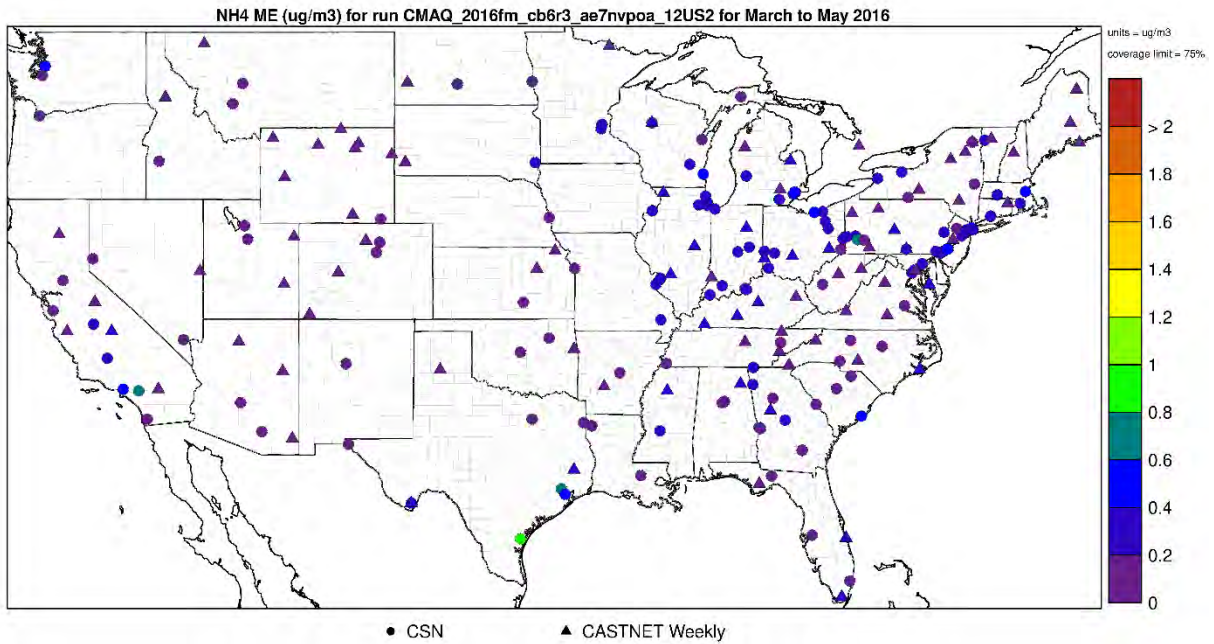


Figure 7-60 Mean Error (ug/m^3) of ammonium during spring 2016 at monitoring sites in the modeling domain

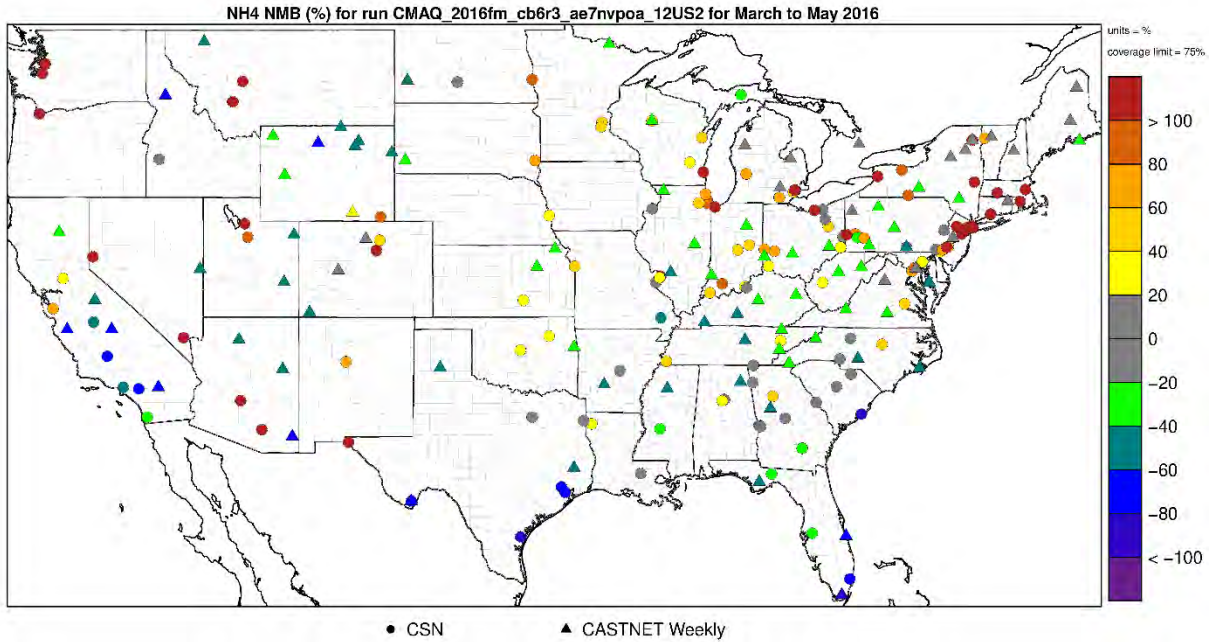


Figure 7-61 Normalized Mean Bias (%) of ammonium during spring 2016 at monitoring sites in the modeling domain

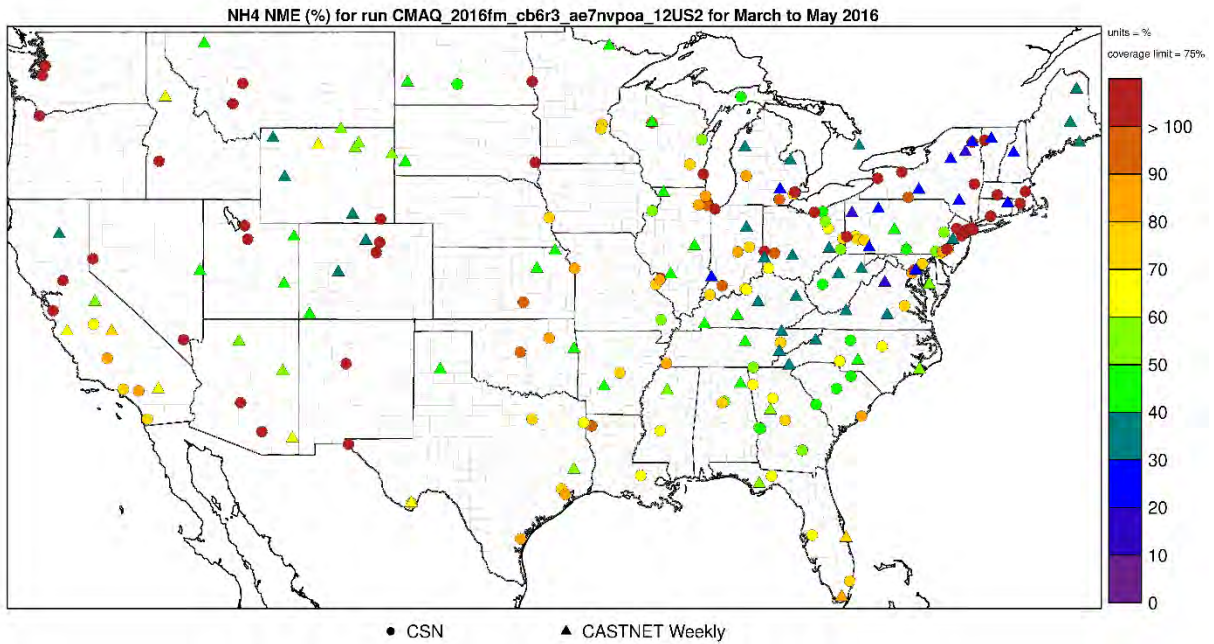


Figure 7-62 Normalized Mean Error (%) of ammonium during spring 2016 at monitoring sites in the modeling domain

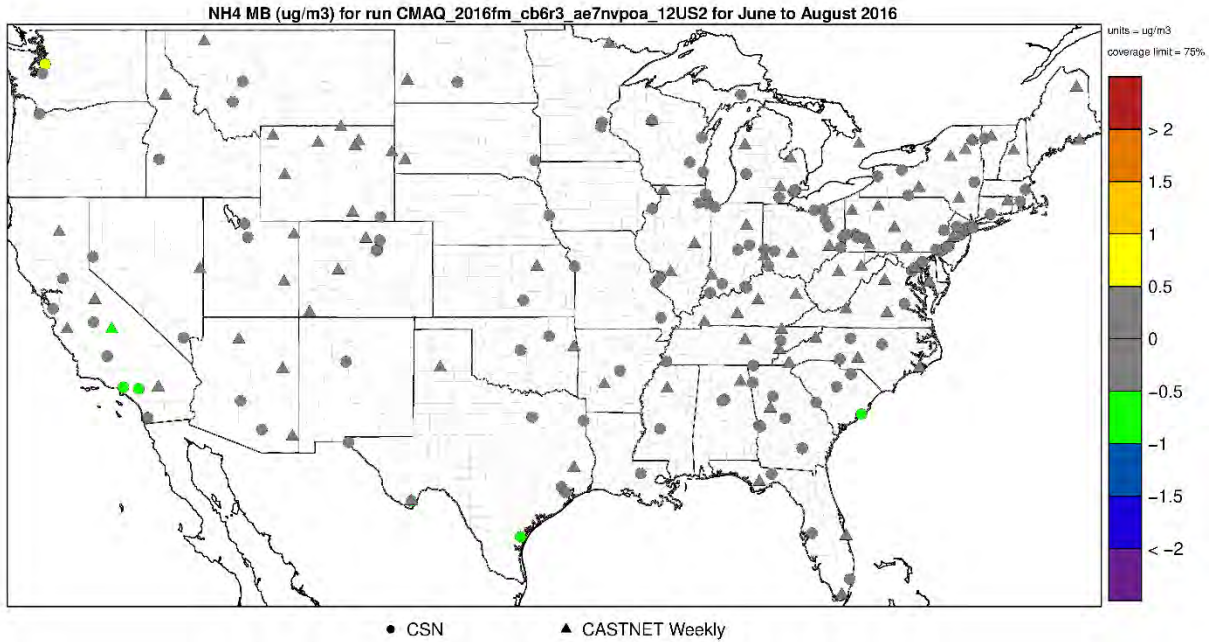


Figure 7-63 Mean Bias (ug/m3) of ammonium during summer 2016 at monitoring sites in the modeling domain

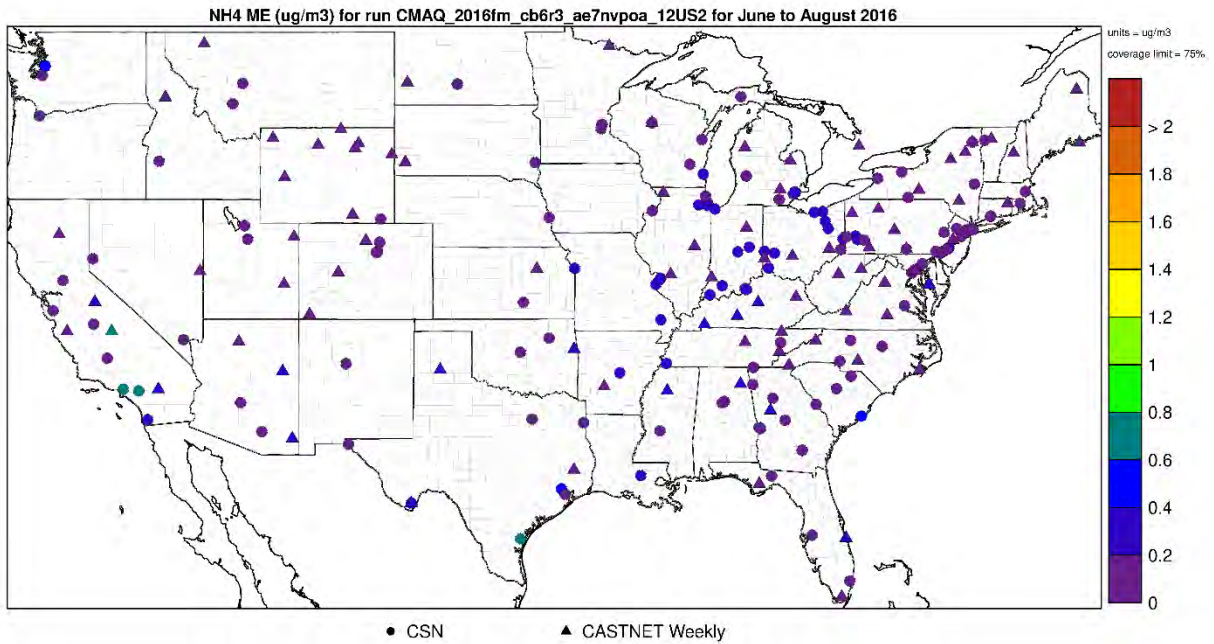


Figure 7-64 Mean Error (ug/m3) of ammonium during summer 2016 at monitoring sites in the modeling domain

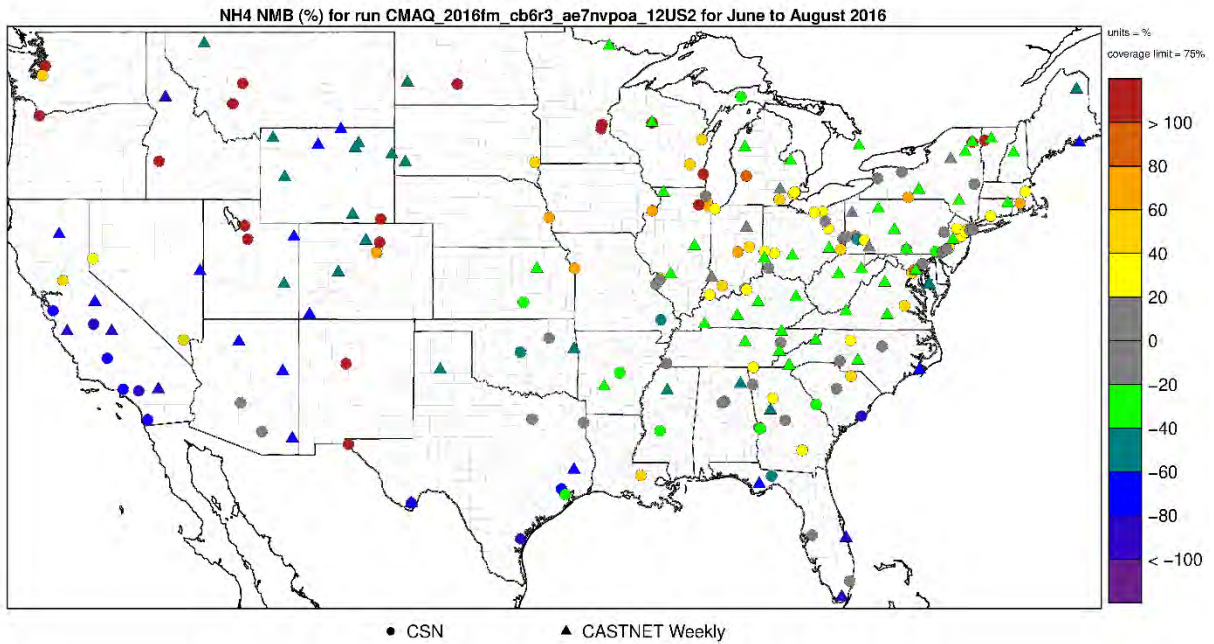


Figure 7-65 Normalized Mean Bias (%) of ammonium during summer 2016 at monitoring sites in the modeling domain

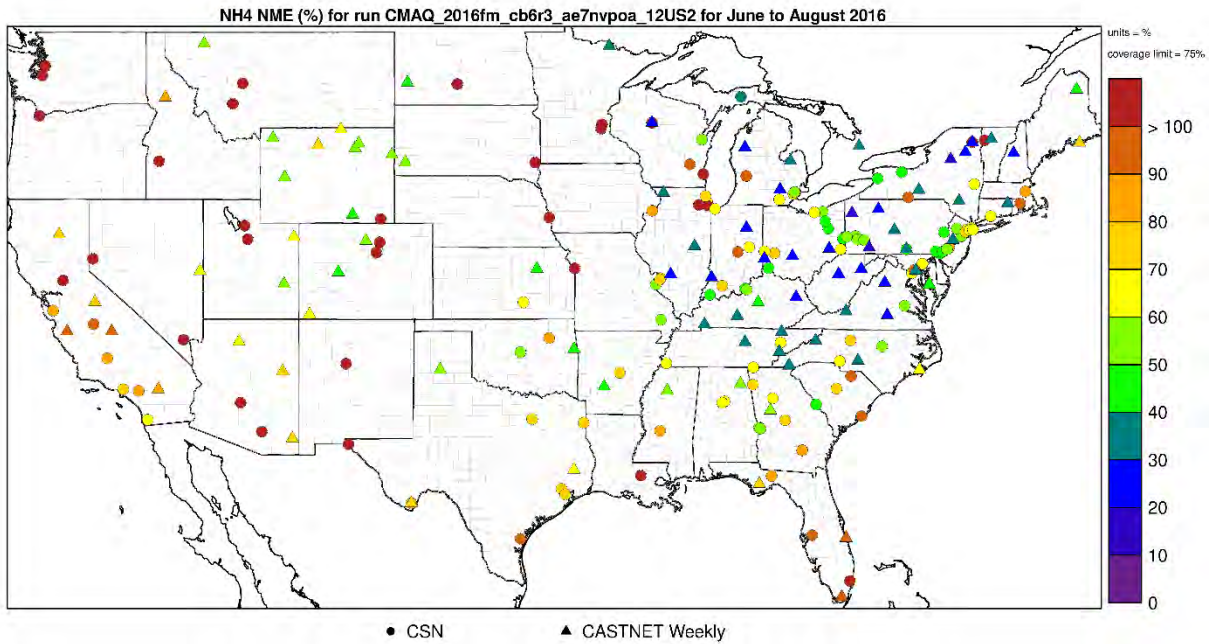


Figure 7-66 Normalized Mean Error (%) of ammonium during summer 2016 at monitoring sites in the modeling domain

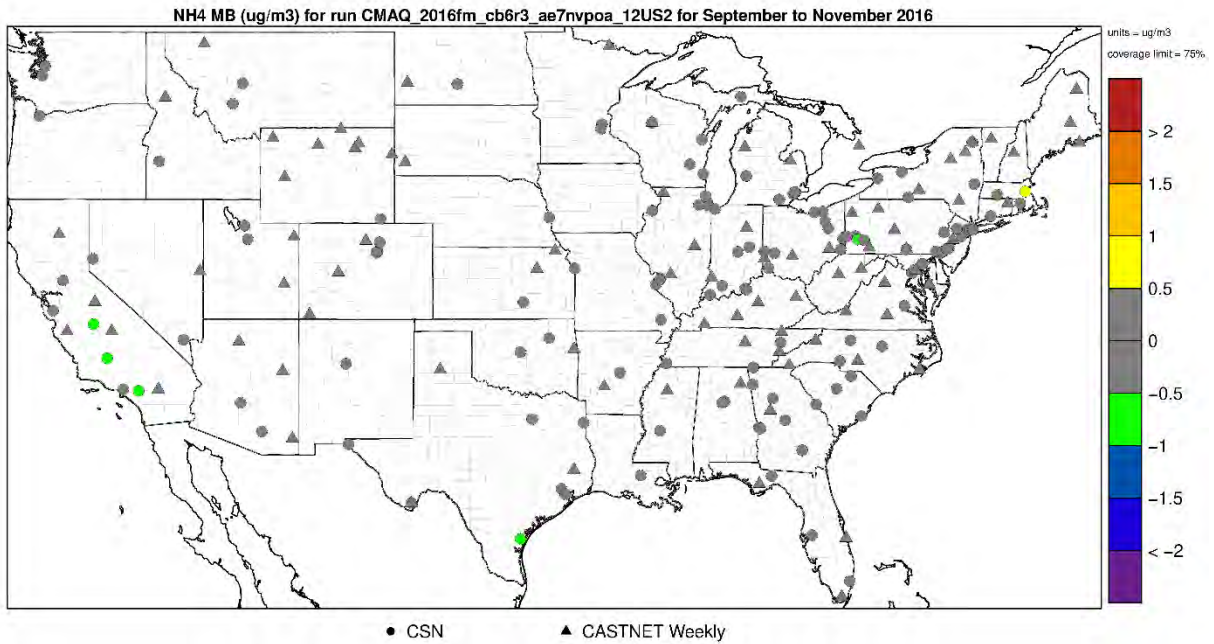


Figure 7-67 Mean Bias (ug/m^3) of ammonium during fall 2016 at monitoring sites in the modeling domain

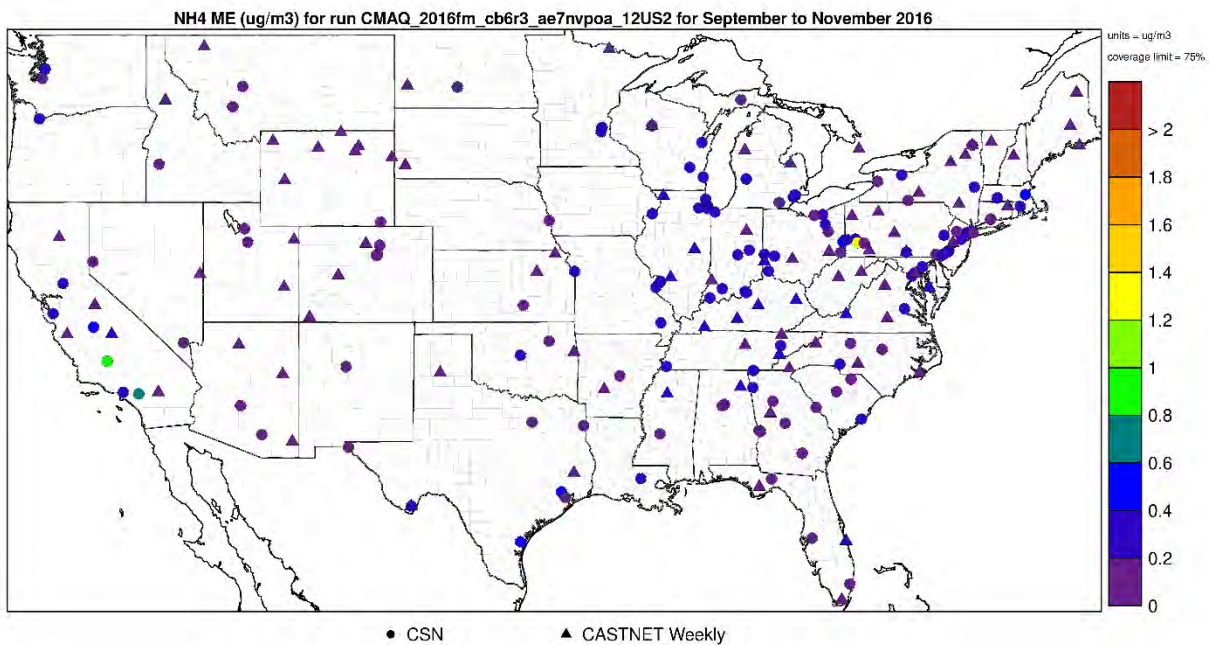


Figure 7-68 Mean Error (ug/m^3) of ammonium during fall 2016 at monitoring sites in the modeling domain

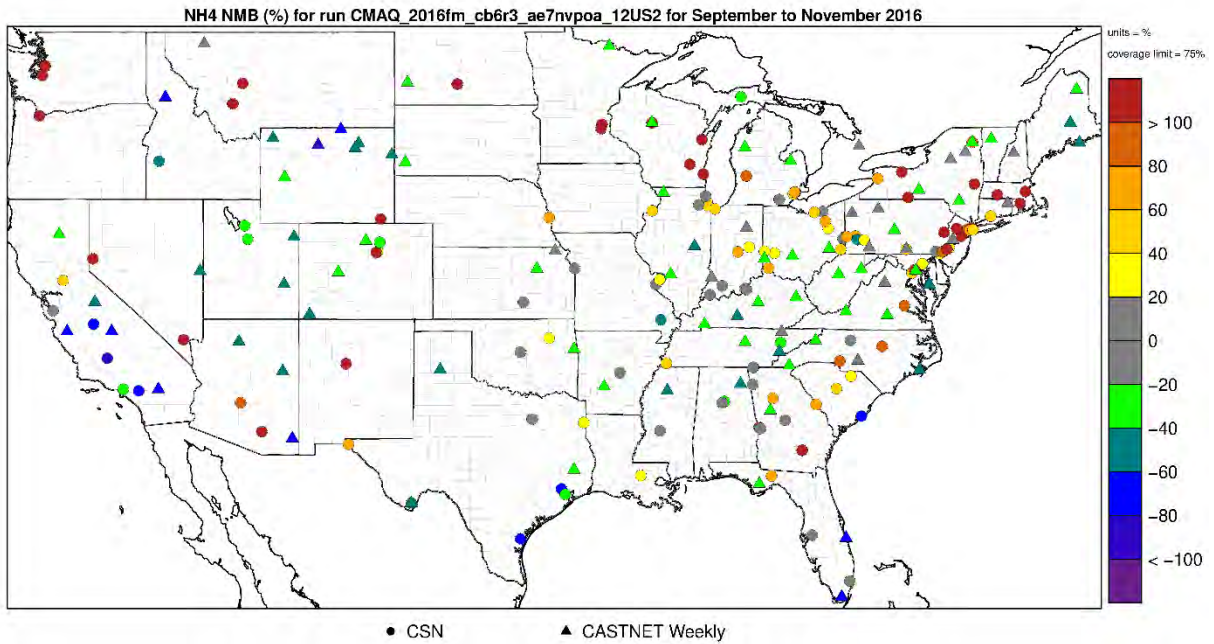


Figure 7-69 Normalized Mean Bias (%) of ammonium during fall 2016 at monitoring sites in the modeling domain

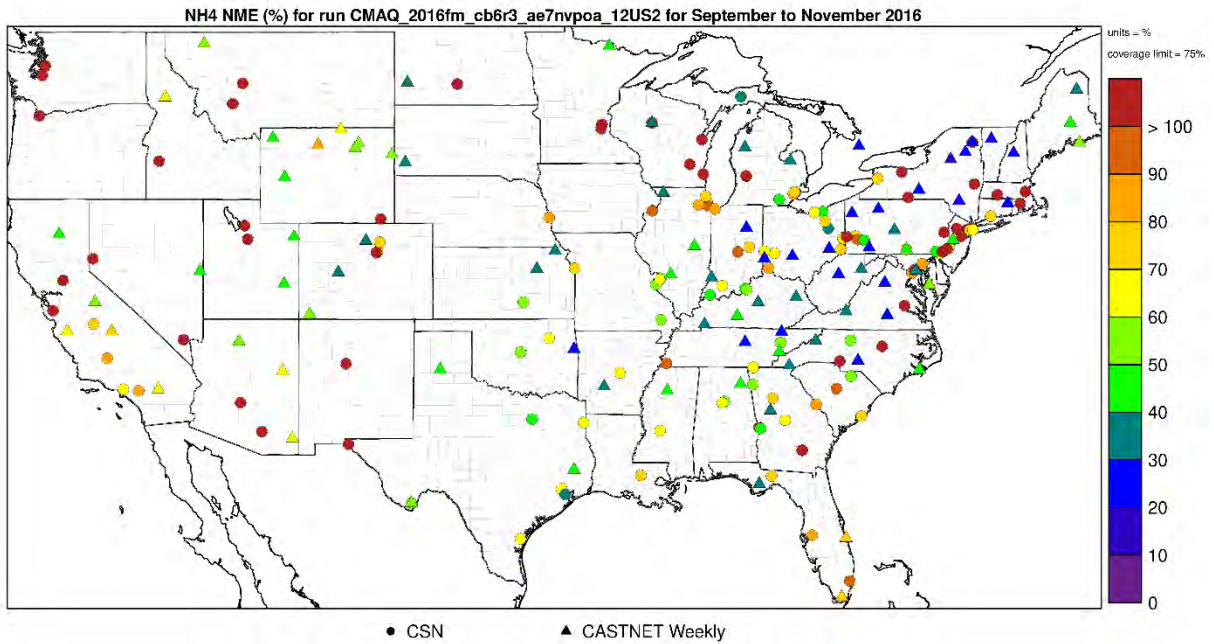


Figure 7-70 Normalized Mean Error (%) of ammonium during fall 2016 at monitoring sites in the modeling domain

7.4.4.4 Seasonal Elemental Carbon Performance

The model performance bias and error statistics for elemental carbon for each of the nine climate regions and each season are provided in Table 7-8. The statistics show clear over prediction at urban and rural sites in most climate regions. Spatial plots of the mean bias and error as well as normalized mean bias and error by season for individual monitors are shown in Figure 7-71 through Figure 7-86. In the Northwest, issues in the ambient data when compared to model predictions were found and thus removed from the performance analysis.

Table 7-8 Elemental Carbon Performance Statistics by Climate Region, by Season, and by Monitoring Network for the 2016 CMAQ Model Simulation

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
Northeast	IMPROVE	Winter	429	0.1	0.1	50.0	63.9
		Spring	478	0.0	0.1	20.4	45.0
		Summer	479	0.0	0.1	6.1	38.0
		Fall	456	0.0	0.1	14.3	43.2
	CSN	Winter	722	0.1	0.4	18.1	53.7
		Spring	785	0.0	0.2	-4.7	42.9
		Summer	788	-0.1	0.2	-13.2	38.8
		Fall	780	0.1	0.3	12.3	47.5
Ohio Valley	IMPROVE	Winter	217	0.0	0.1	67.4	10.4
		Spring	242	0.0	0.1	-15.4	44.2
		Summer	241	-0.1	0.1	-24.8	32.3
		Fall	232	-0.1	0.1	-22.5	-21.9
	CSN	Winter	535	0.1	0.2	56.5	14.9
		Spring	571	-0.1	0.2	-16.1	38.0
		Summer	532	-0.1	0.2	-20.6	37.3
		Fall	535	-0.1	0.2	-9.0	33.9
Upper Midwest	IMPROVE	Winter	222	0.1	0.1	40.3	55.3
		Spring	239	0.0	0.1	-13.8	43.9
		Summer	236	0.0	0.1	-20.6	41.7
		Fall	243	0.0	0.1	-7.7	41.5
	CSN	Winter	334	0.2	0.2	52.0	71.9
		Spring	347	0.0	0.2	-1.3	47.0

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
		Summer	332	0.0	0.2	-8.2	44.5
		Fall	338	0.0	0.2	6.1	46.4
Southeast	IMPROVE	Winter	398	0.0	0.1	-5.7	48.5
		Spring	446	-0.2	0.2	-42.2	55.7
		Summer	442	-0.1	0.1	-24.1	45.2
		Fall	422	-0.1	0.1	-27.5	38.5
	CSN	Winter	436	0.0	0.2	-4.1	40.9
		Spring	478	-0.1	0.2	-24.3	41.7
		Summer	445	0.0	0.2	-9.4	47.6
		Fall	430	-0.1	0.3	-19.4	40.4
South	IMPROVE	Winter	240	0.0	0.1	-1.5	40.5
		Spring	272	0.0	0.1	-7.9	50.1
		Summer	242	0.0	0.0	-21.5	38.9
		Fall	262	-0.1	0.1	-27.0	38.3
	CSN	Winter	272	0.0	0.2	-6.5	40.1
		Spring	297	-0.1	0.2	-15.5	37.6
		Summer	251	0.0	0.2	-4.3	50.7
		Fall	238	0.0	0.2	-2.8	44.0
Southwest	IMPROVE	Winter	890	-0.1	0.1	-34.1	58.2
		Spring	981	0.0	0.1	5.4	67.4
		Summer	962	0.0	0.1	-16.9	55.3
		Fall	945	0.0	0.1	-22.5	57.7
	CSN	Winter	228	0.0	0.4	-1.5	41.0
		Spring	254	0.1	0.1	43.9	58.5
		Summer	237	0.1	0.1	22.2	46.7
		Fall	240	0.1	0.3	13.7	47.4
Northern Rockies	IMPROVE	Winter	557	0.0	0.0	12.8	70.3
		Spring	594	0.0	0.0	-24.7	63.0
		Summer	616	0.0	0.1	30.8	79.4

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
	CSN	Fall	585	0.0	0.1	-13.9	60.0
		Winter	124	0.0	0.3	0.6	100.0
		Spring	145	0.0	0.1	-15.7	54.8
		Summer	161	0.0	0.1	-18.2	43.1
		Fall	146	0.0	0.2	-18.6	65.9
Northwest	IMPROVE	Winter	-	-	-	-	-
		Spring	-	-	-	-	-
		Summer	-	-	-	-	-
		Fall	-	-	-	-	-
	CSN	Winter	-	-	-	-	-
		Spring	-	-	-	-	-
		Summer	-	-	-	-	-
		Fall	-	-	-	-	-
West	IMPROVE	Winter	540	0.0	0.1	-14.3	62.2
		Spring	600	0.0	0.1	26.5	69.0
		Summer	601	0.0	0.1	-24.5	61.5
		Fall	565	0.0	0.1	4.9	59.7
	CSN	Winter	294	0.2	0.2	45.5	58.4
		Spring	293	0.2	0.2	42.9	56.2
		Summer	267	0.1	0.2	29.0	46.3
		Fall	277	0.2	0.3	51.3	32.6

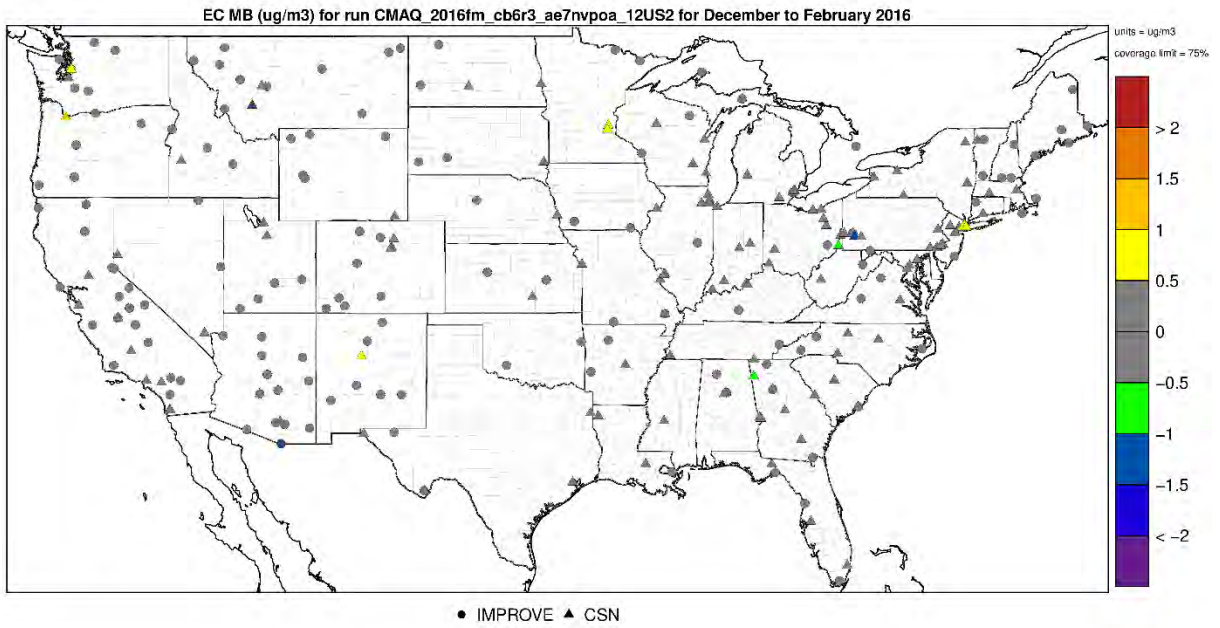


Figure 7-71 Mean Bias (ug/m3) of elemental carbon during winter 2016 at monitoring sites in the modeling domain

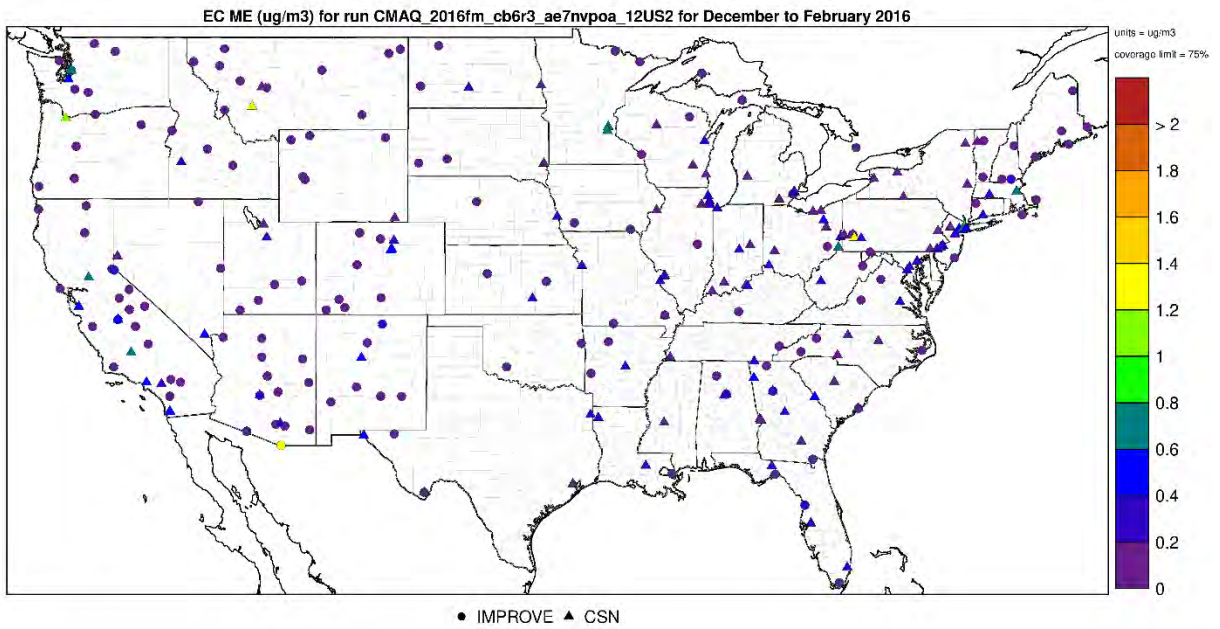


Figure 7-72 Mean Error (ug/m3) of elemental carbon during winter 2016 at monitoring sites in the modeling domain

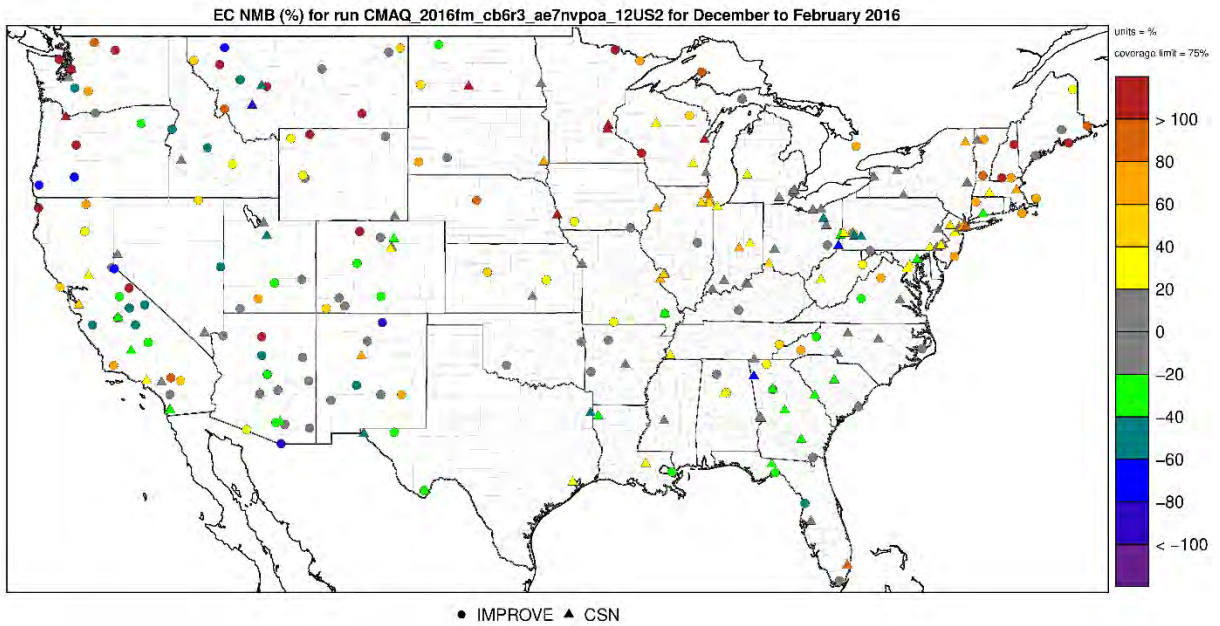


Figure 7-73 Normalized Mean Bias (%) of elemental carbon during winter 2016 at monitoring sites in the modeling domain

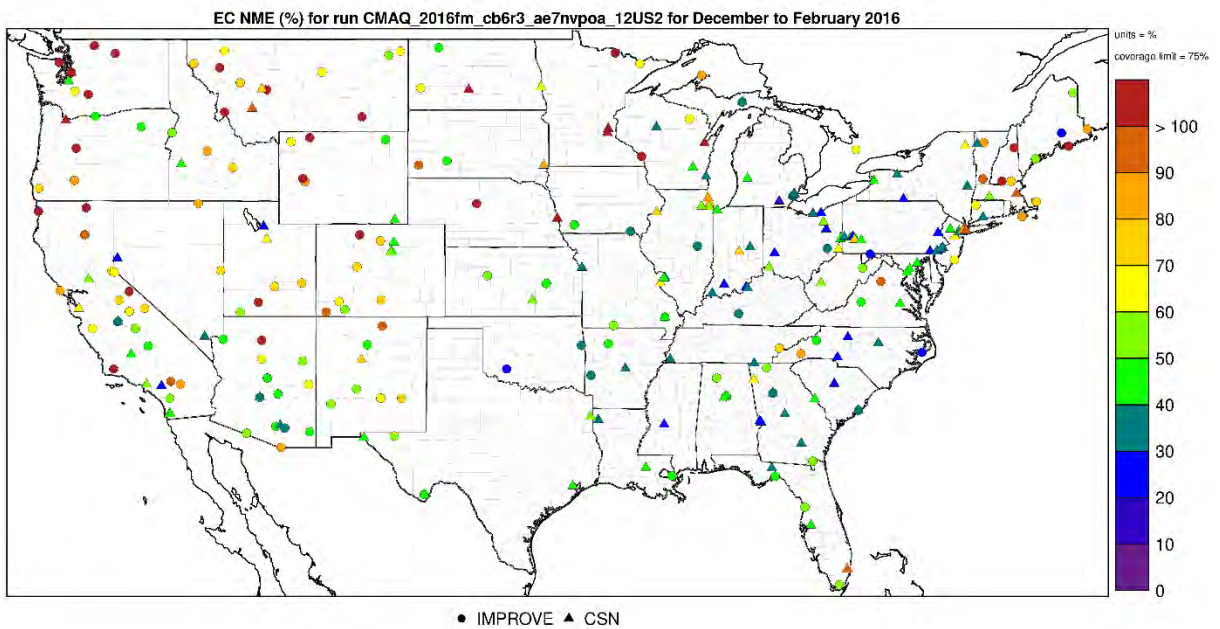


Figure 7-74 Normalized Mean Error (%) of elemental carbon during winter 2016 at monitoring sites in the modeling domain

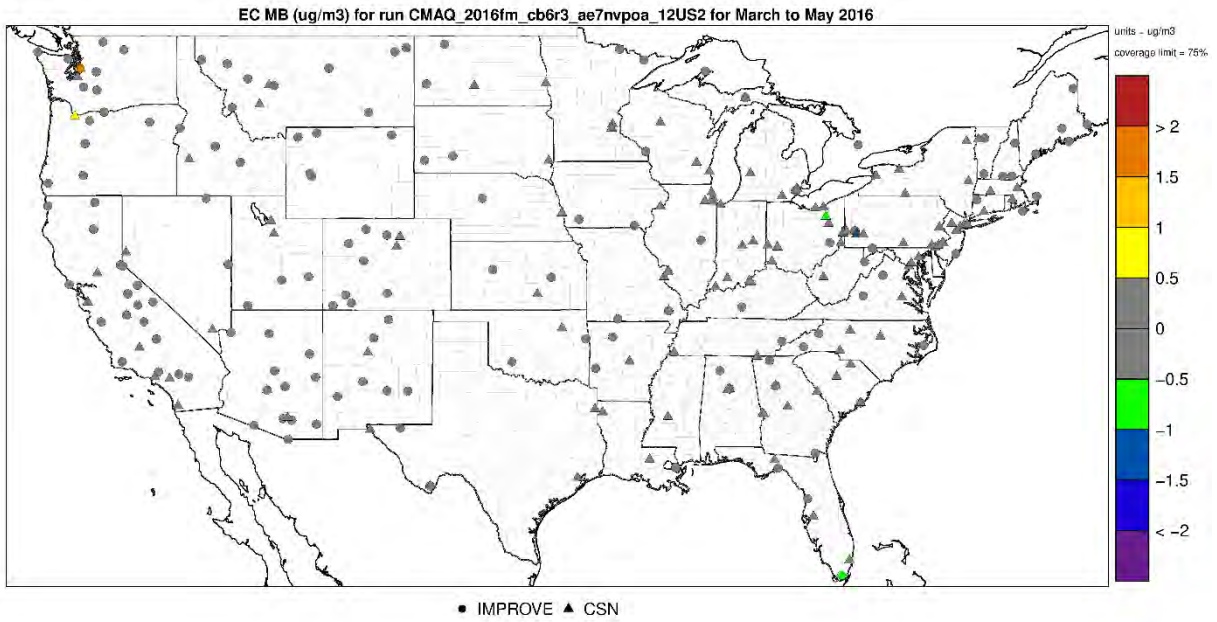


Figure 7-75 Mean Bias (ug/m^3) of elemental carbon during spring 2016 at monitoring sites in the modeling domain

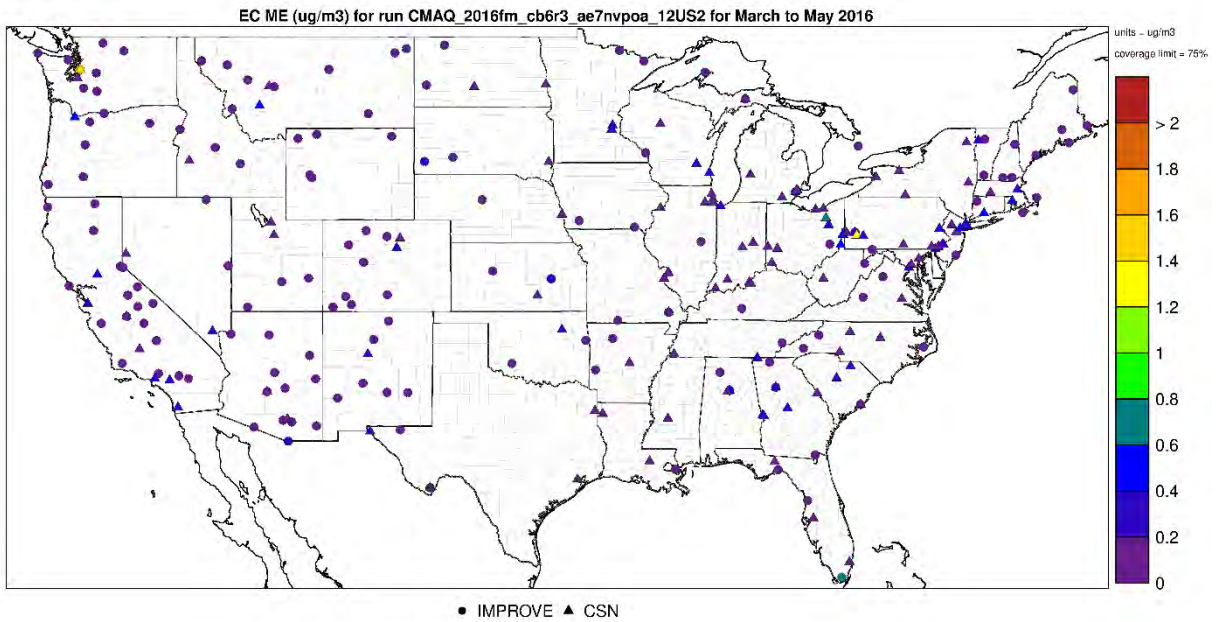


Figure 7-76 Mean Error (ug/m^3) of elemental carbon during spring 2016 at monitoring sites in the modeling domain

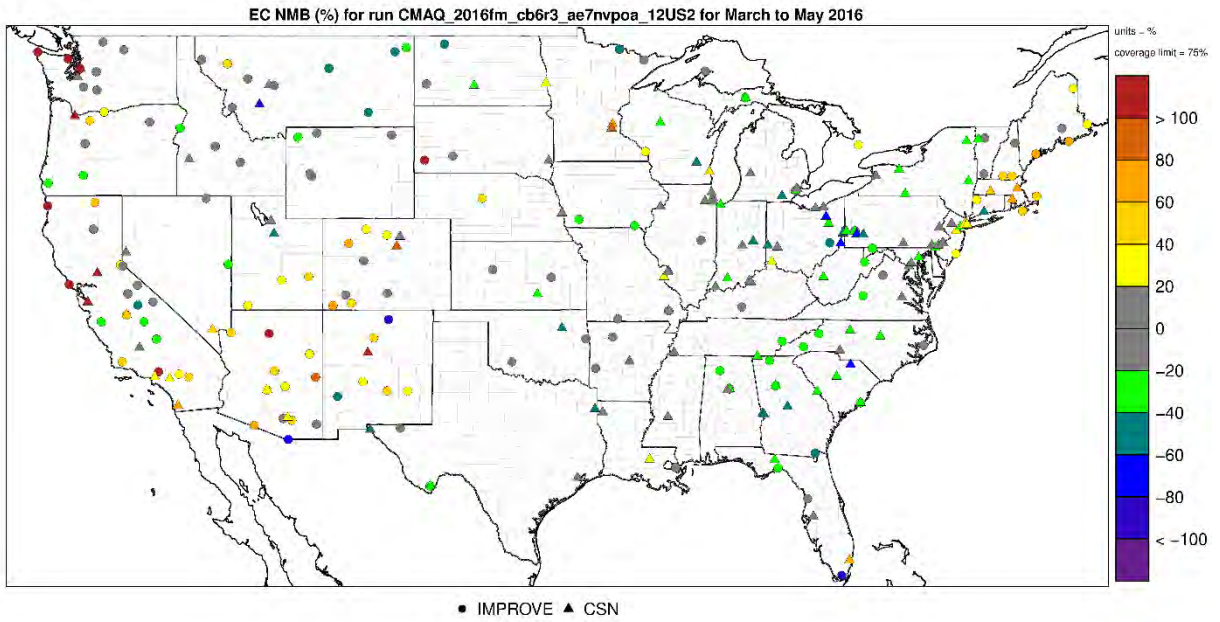


Figure 7-77 Normalized Mean Bias (%) of elemental carbon during spring 2016 at monitoring sites in the modeling domain

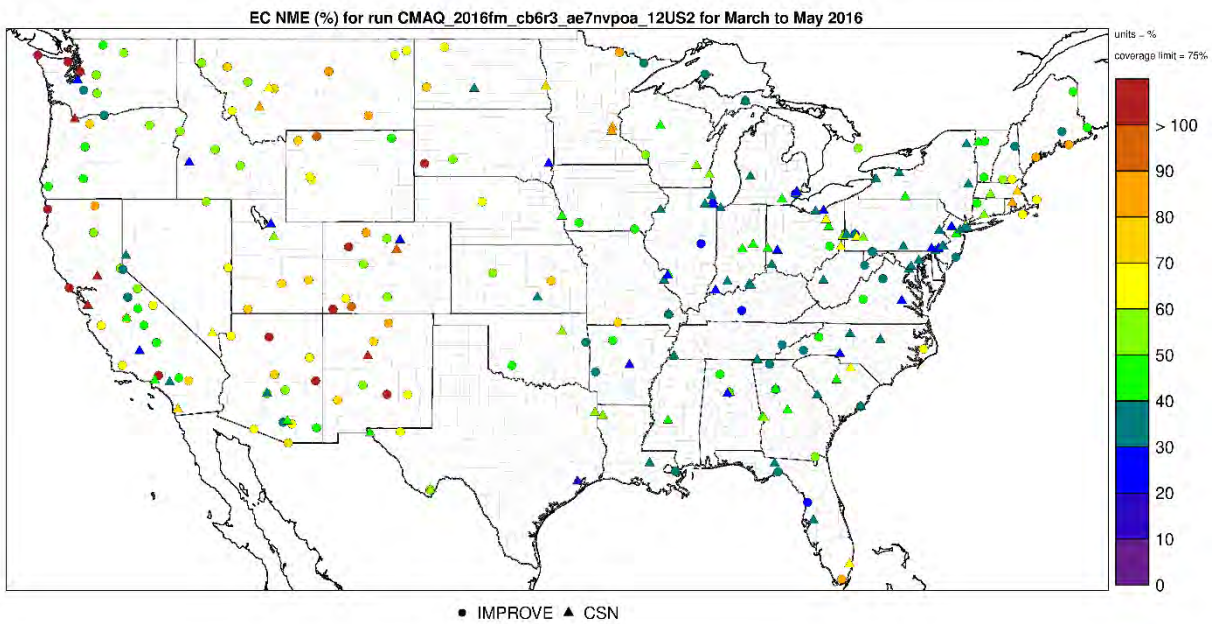


Figure 7-78 Normalized Mean Error (%) of elemental carbon during spring 2016 at monitoring sites in the modeling domain

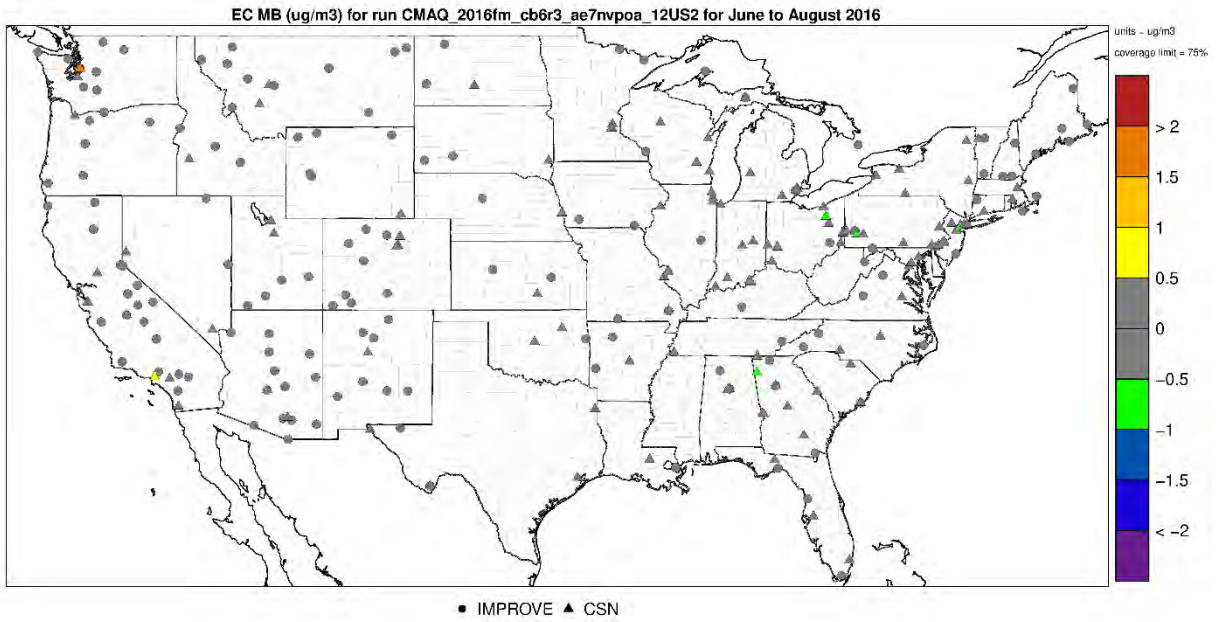


Figure 7-79 Mean Bias (ug/m3) of elemental carbon during summer 2016 at monitoring sites in the modeling domain

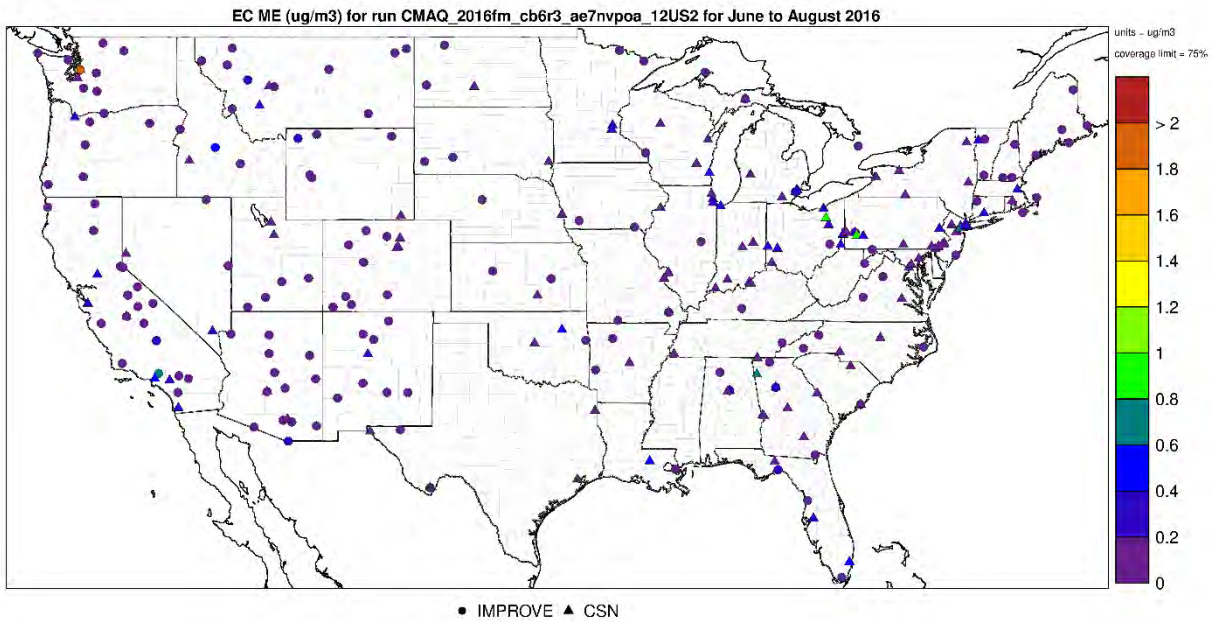


Figure 7-80 Mean Error (ug/m3) of elemental carbon during summer 2016 at monitoring sites in the modeling domain

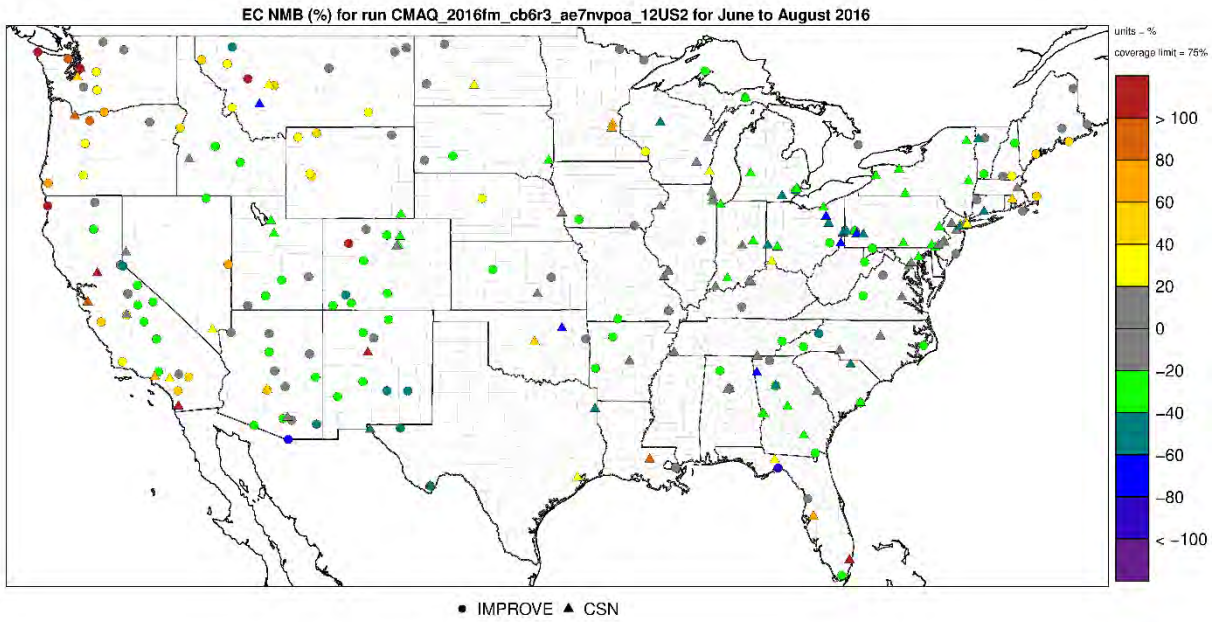


Figure 7-81 Normalized Mean Bias (%) of elemental carbon during summer 2016 at monitoring sites in the modeling domain

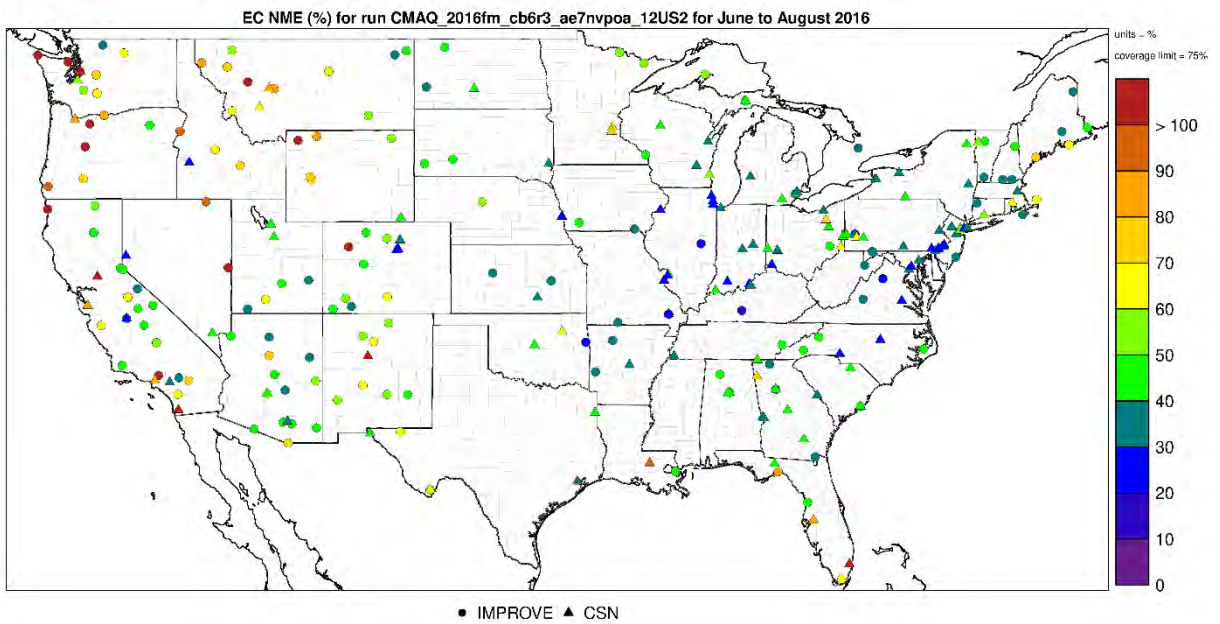


Figure 7-82 Normalized Mean Error (%) of elemental carbon during summer 2016 at monitoring sites in the modeling domain

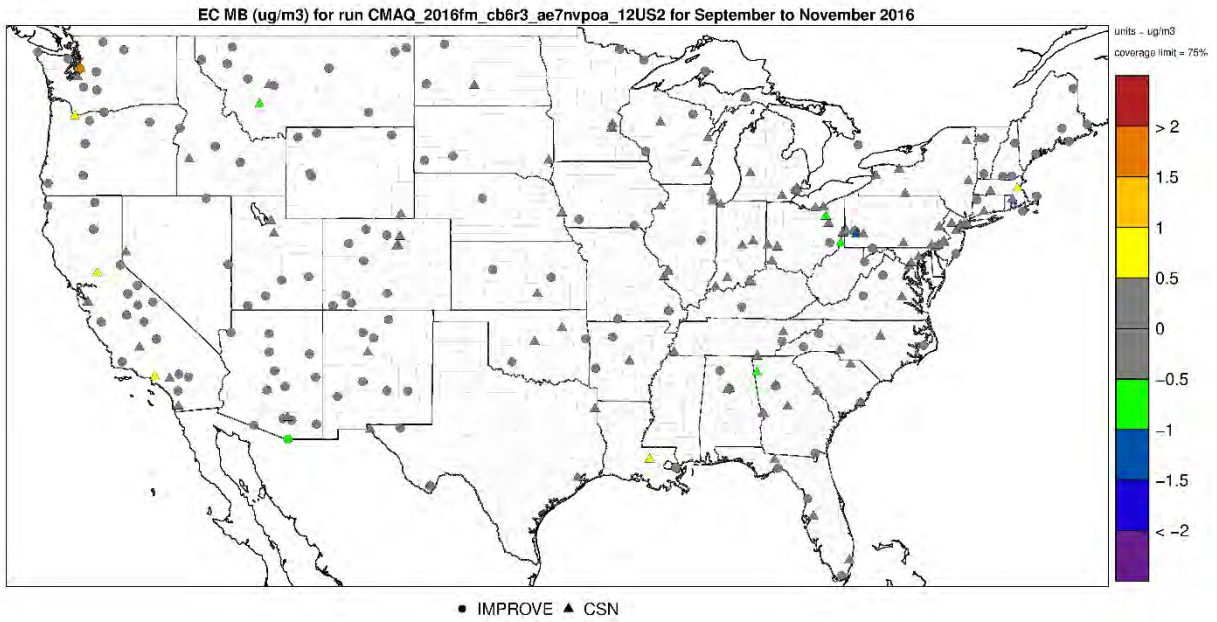


Figure 7-83 Mean Bias (ug/m^3) of elemental carbon during fall 2016 at monitoring sites in the modeling domain

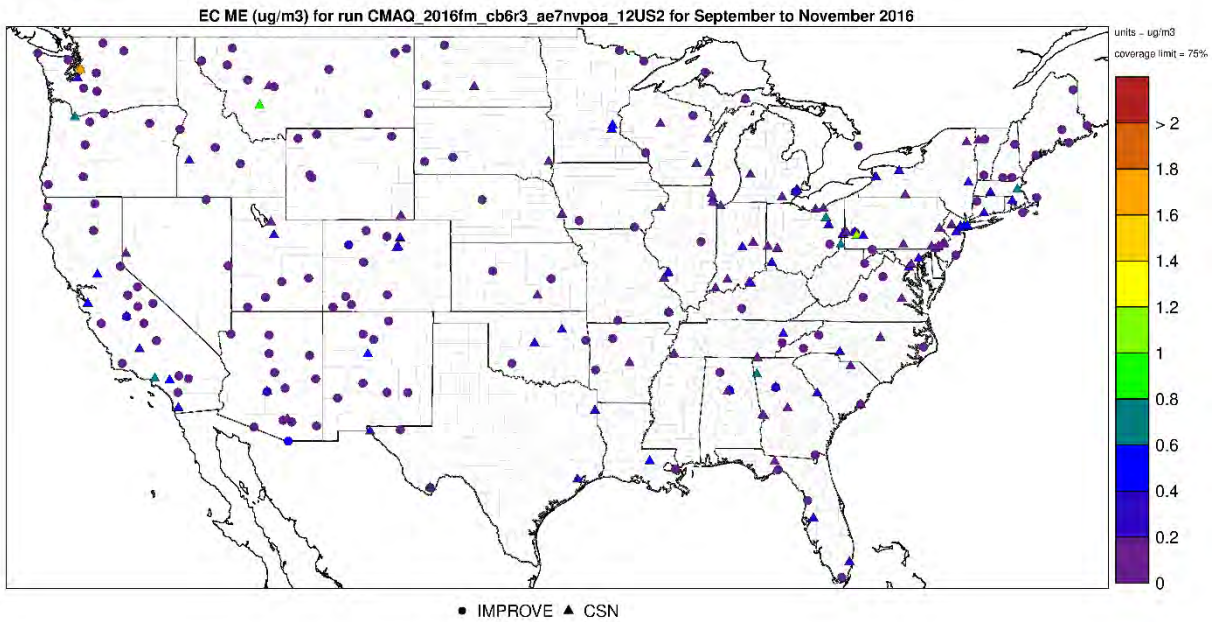


Figure 7-84 Mean Error (ug/m^3) of elemental carbon during fall 2016 at monitoring sites in the modeling domain

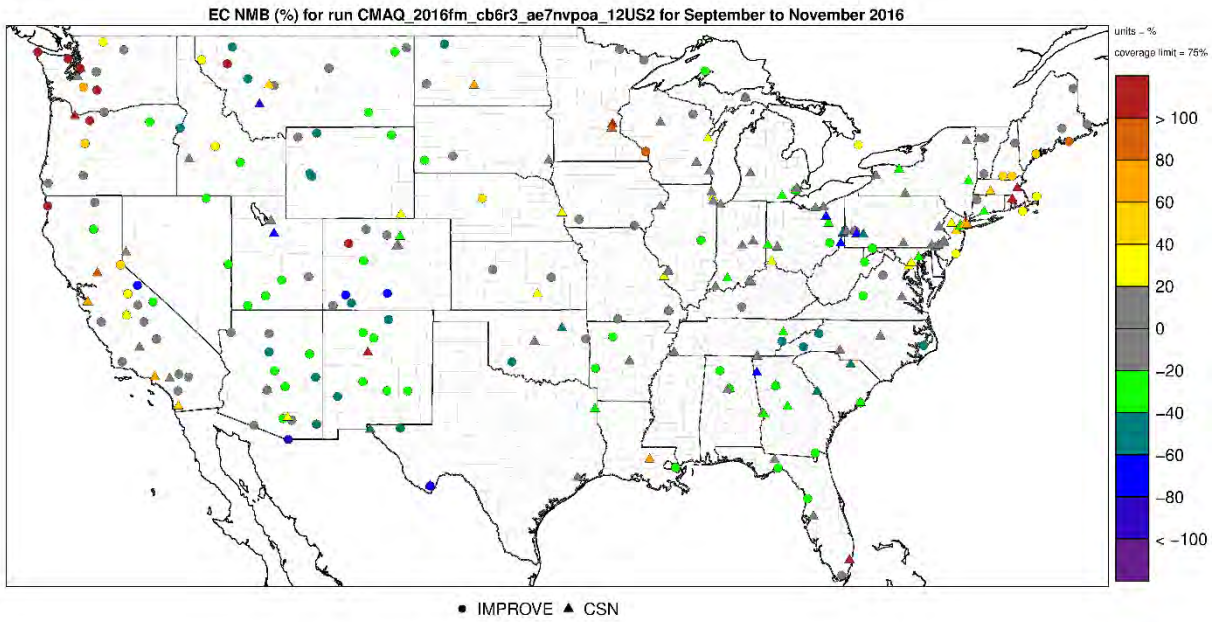


Figure 7-85 Normalized Mean Bias (%) of elemental carbon during fall 2016 at monitoring sites in the modeling domain

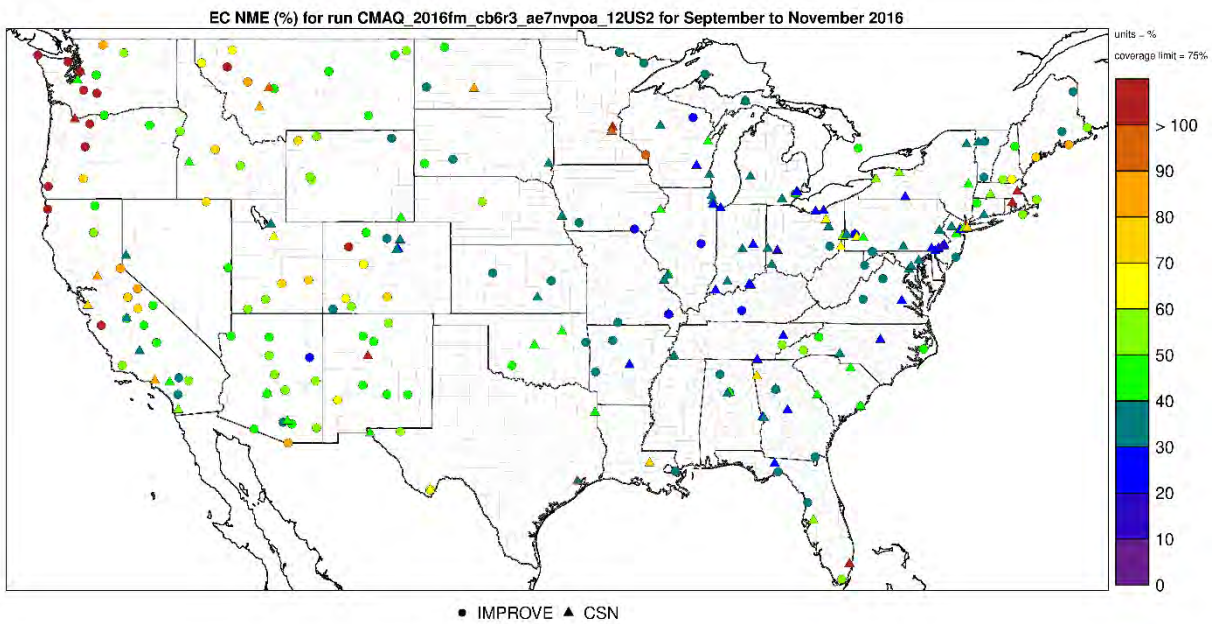


Figure 7-86 Normalized Mean Error (%) of elemental carbon during fall 2016 at monitoring sites in the modeling domain

7.4.4.5 Seasonal Organic Carbon Performance

The model performance bias and error statistics for organic carbon for each climate region and season are provided in Table 7-9. The statistics in this table indicate a tendency for the modeling platform to over predict observed organic carbon concentrations during most seasons and climate regions except in the Northern Rockies and the Western U.S. Spatial plots of the mean bias and error as well as normalized mean bias and error by season for individual monitors are shown in Figure 7-87 through Figure 7-102.

Table 7-9 Organic Carbon Performance Statistics by Climate Region, by Season, and by Monitoring Network for the 2016 CMAQ Model Simulation

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
Northeast	IMPROVE	Winter	427	1.0	1.0	>100	>100
		Spring	477	0.4	0.5	54.2	68.7
		Summer	482	0.0	0.5	3.1	37.6
		Fall	459	0.5	0.6	52.5	70.5
	CSN	Winter	722	1.5	1.7	84.4	95.2
		Spring	785	0.7	0.9	43.7	58.8
		Summer	788	0.1	0.7	5.5	33.9
		Fall	780	0.9	1.1	46.6	60.9
Ohio Valley	IMPROVE	Winter	217	0.8	1.1	87.4	>100
		Spring	242	0.6	0.9	50.7	82.6
		Summer	242	0.0	0.5	-0.1	34.4
		Fall	232	0.2	0.9	13.5	51.5
	CSN	Winter	535	0.9	1.1	56.5	70.2
		Spring	571	0.3	0.7	19.9	46.2
		Summer	531	0.0	0.6	1.8	32.7
		Fall	532	0.2	0.9	8.4	37.0
Upper Midwest	IMPROVE	Winter	226	0.6	0.7	>100	>100
		Spring	238	0.2	0.6	21.2	70.8
		Summer	237	-0.2	0.4	-20.0	37.7
		Fall	243	0.1	0.4	15.3	46.6
	CSN	Winter	333	1.4	1.5	>100	>100
		Spring	347	0.6	1.0	38.9	68.8

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
		Summer	331	0.1	0.6	5.9	36.9
		Fall	337	0.5	0.8	35.9	52.2
Southeast	IMPROVE	Winter	398	0.6	1.0	47.3	82.1
		Spring	447	-4.5	5.5	-72.7	87.9
		Summer	455	-0.1	0.7	-7.5	43.5
		Fall	423	0.0	0.9	-1.6	45.8
	CSN	Winter	436	0.8	1.1	39.9	56.2
		Spring	478	0.4	0.8	19.3	41.4
		Summer	445	0.4	0.7	21.6	38.9
		Fall	430	0.2	1.2	6.0	42.4
South	IMPROVE	Winter	239	0.4	0.6	51.8	71.7
		Spring	272	0.1	0.7	9.4	62.2
		Summer	250	-0.1	0.5	-12.3	44.6
		Fall	264	0.0	0.5	-1.0	45.2
	CSN	Winter	272	0.6	1.2	29.6	62.3
		Spring	297	0.3	0.8	22.5	52.9
		Summer	251	0.4	0.8	21.4	56.0
		Fall	237	0.6	1.1	27.4	55.3
Southwest	IMPROVE	Winter	881	-0.2	0.4	-25.3	58.0
		Spring	981	0.0	0.2	3.1	55.0
		Summer	978	-0.2	0.5	-24.6	55.2
		Fall	964	-0.1	0.4	-11.0	58.8
	CSN	Winter	228	0.6	1.6	23.3	63.3
		Spring	254	0.4	0.7	42.3	66.3
		Summer	237	0.0	0.5	-2.9	37.6
		Fall	240	0.4	1.0	23.0	60.4
Northern Rockies	IMPROVE	Winter	549	0.1	0.2	16.9	68.8
		Spring	590	-0.1	0.4	-22.7	63.0
		Summer	631	-0.2	0.7	-16.7	57.5

Climate Region	Monitor Network	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
	CSN	Fall	600	-0.1	0.4	-22.0	60.4
		Winter	140	0.1	0.9	5.6	93.9
		Spring	145	-0.1	0.5	-12.8	54.8
		Summer	161	-0.6	0.7	-39.8	47.0
		Fall	146	-0.2	0.5	-23.4	51.9
Northwest	IMPROVE	Winter	-	-	-	-	-
		Spring	-	-	-	-	-
		Summer	-	-	-	-	-
		Fall	-	-	-	-	-
	CSN	Winter	-	-	-	-	-
		Spring	-	-	-	-	-
		Summer	-	-	-	-	-
		Fall	-	-	-	-	-
West	IMPROVE	Winter	552	-0.1	0.3	-13.8	50.6
		Spring	599	-0.1	0.3	-14.6	45.9
		Summer	608	-0.4	0.9	-21.1	52.2
		Fall	574	-0.1	0.5	-8.5	49.6
	CSN	Winter	285	0.4	1.7	9.7	46.7
		Spring	294	0.3	0.7	20.2	42.9
		Summer	289	-0.2	0.9	-9.7	35.7
		Fall	277	0.3	1.2	10.9	42.5

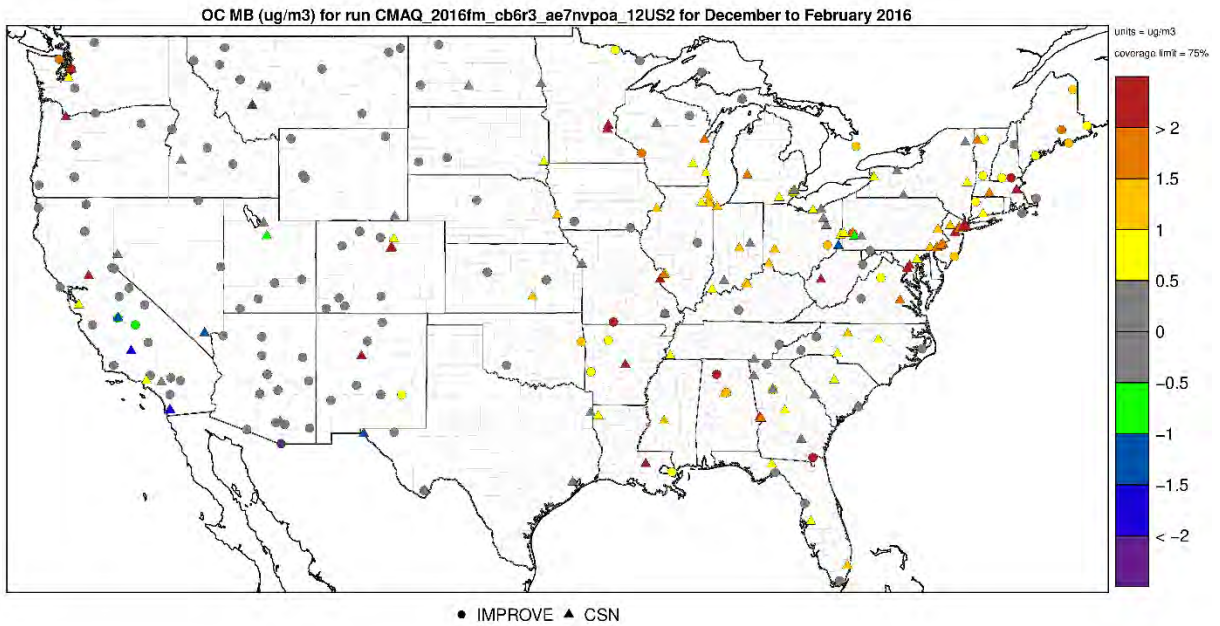


Figure 7-87 Mean Bias (ug/m3) of organic carbon during winter 2016 at monitoring sites in the modeling domain

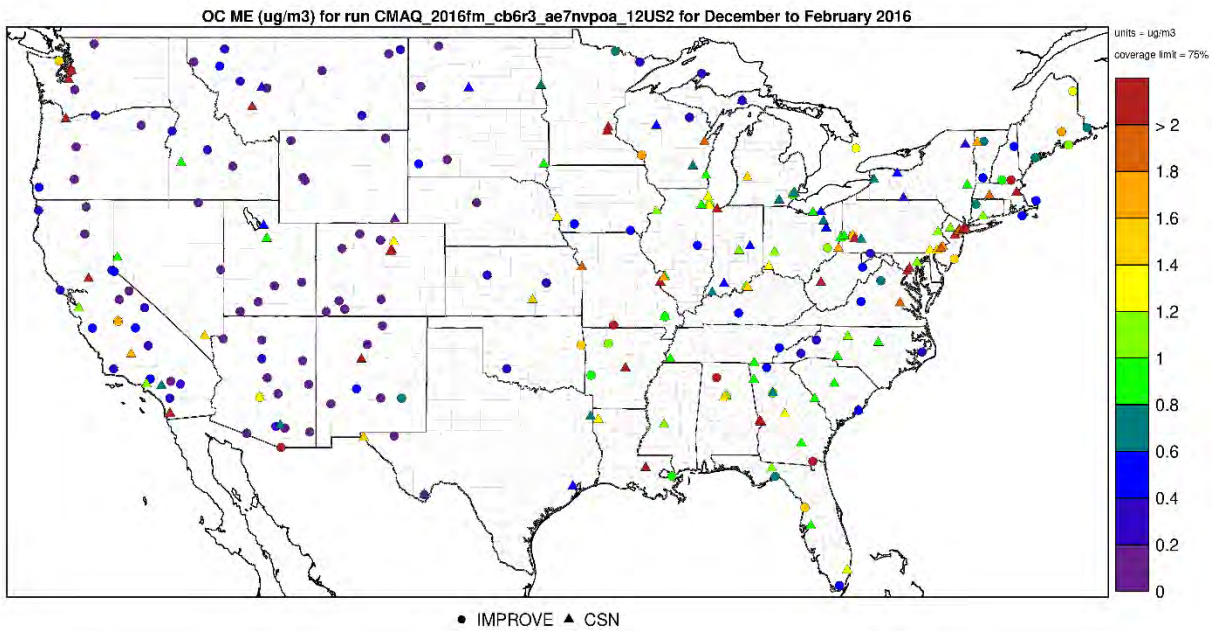


Figure 7-88 Mean Error (ug/m3) of organic carbon during winter 2016 at monitoring sites in the modeling domain

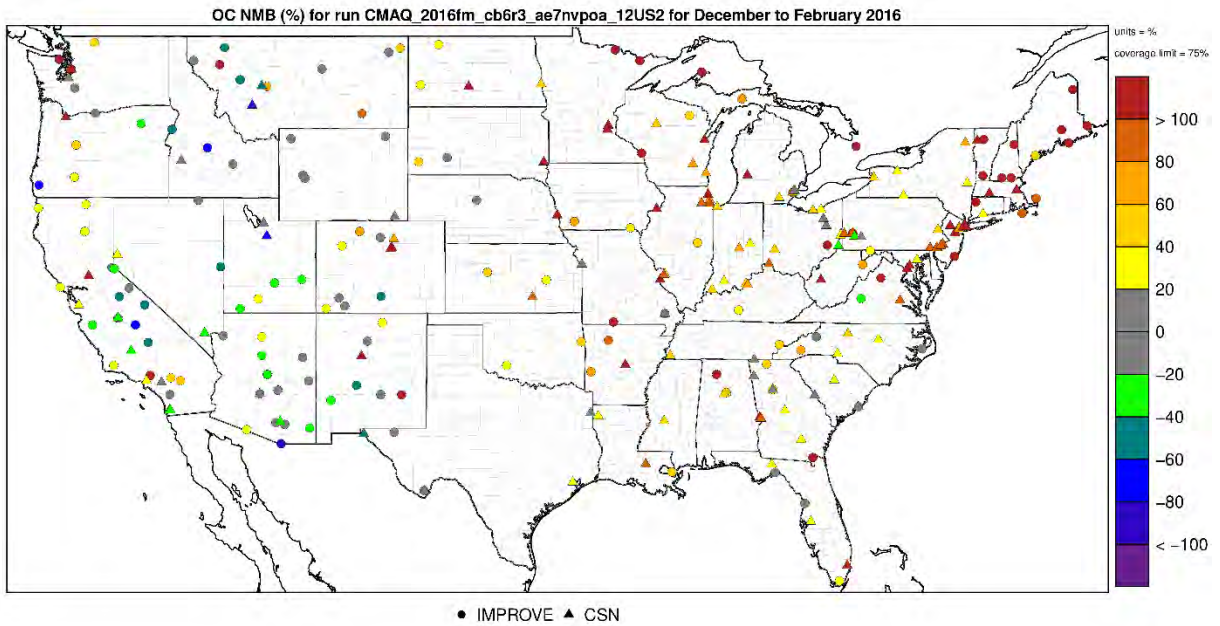


Figure 7-89 Normalized Mean Bias (%) of organic carbon during winter 2016 at monitoring sites in the modeling domain

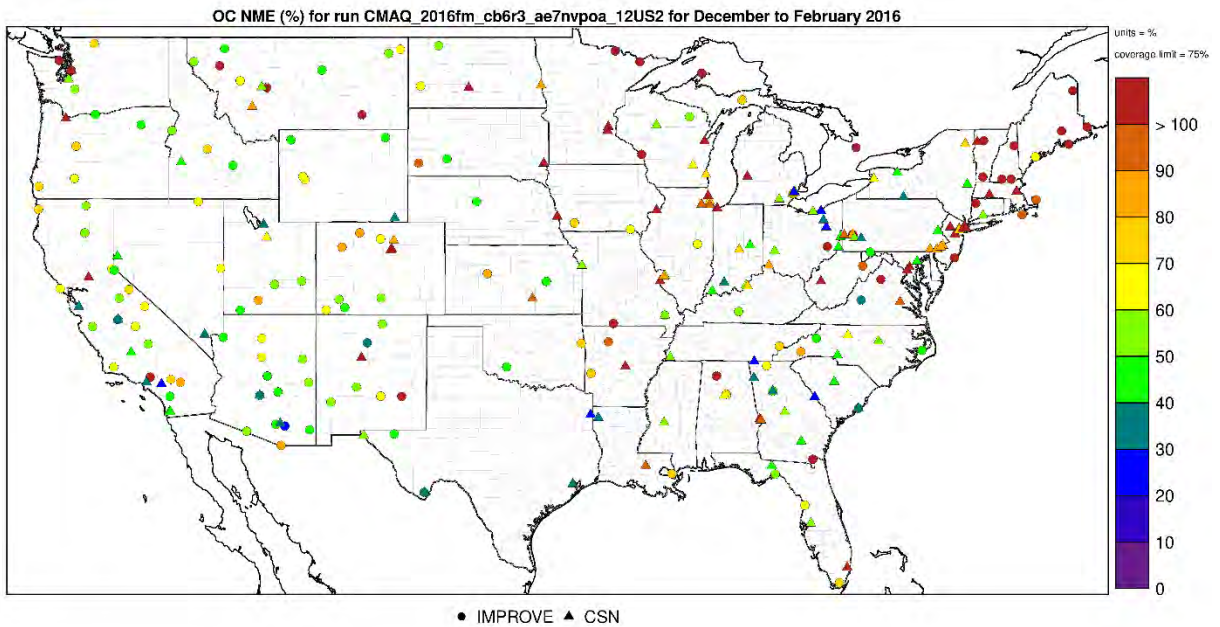


Figure 7-90 Normalized Mean Error (%) of organic carbon during winter 2016 at monitoring sites in the modeling domain

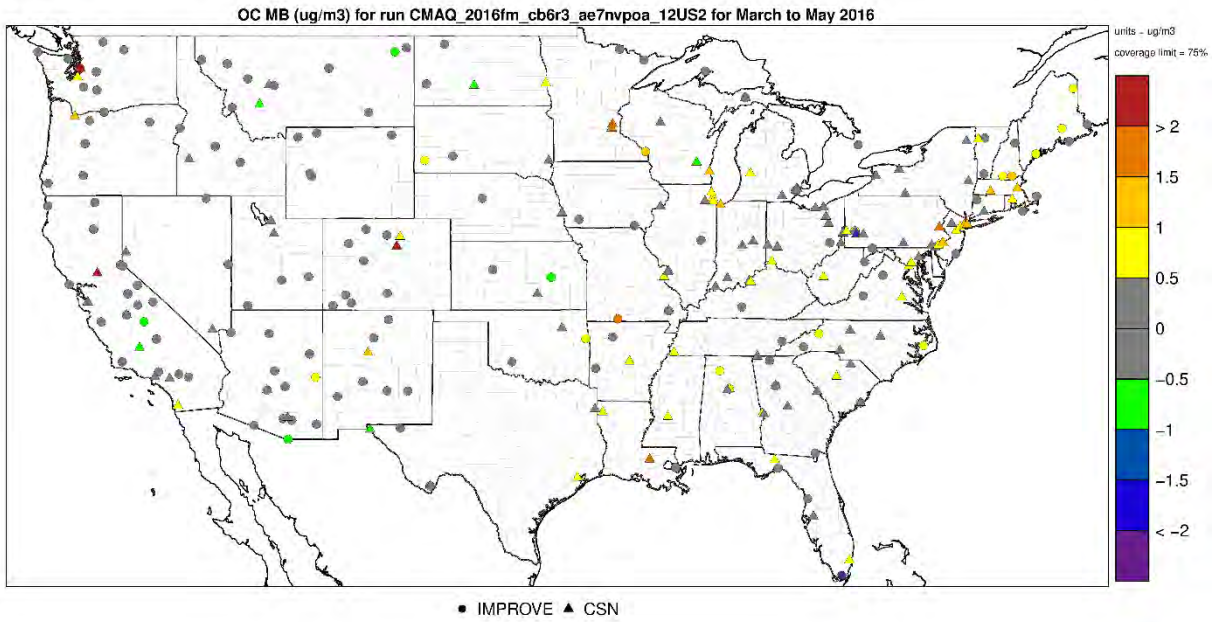


Figure 7-91 Mean Bias (ug/m^3) of organic carbon during spring 2016 at monitoring sites in the modeling domain

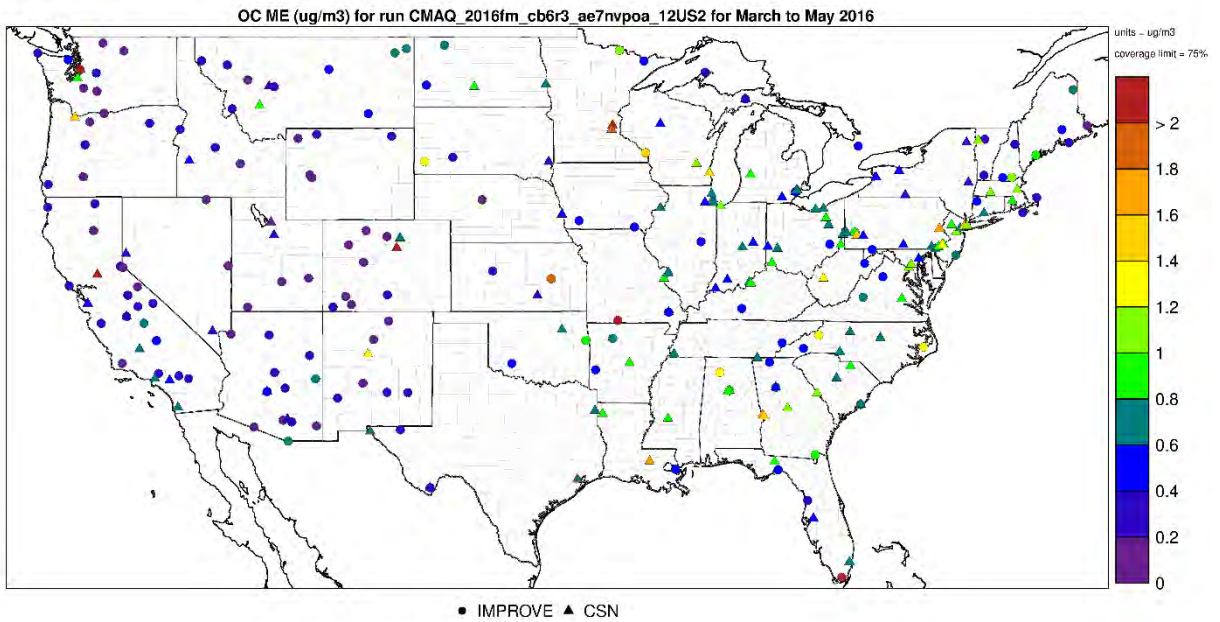


Figure 7-92 Mean Error (ug/m^3) of organic carbon during spring 2016 at monitoring sites in the modeling domain

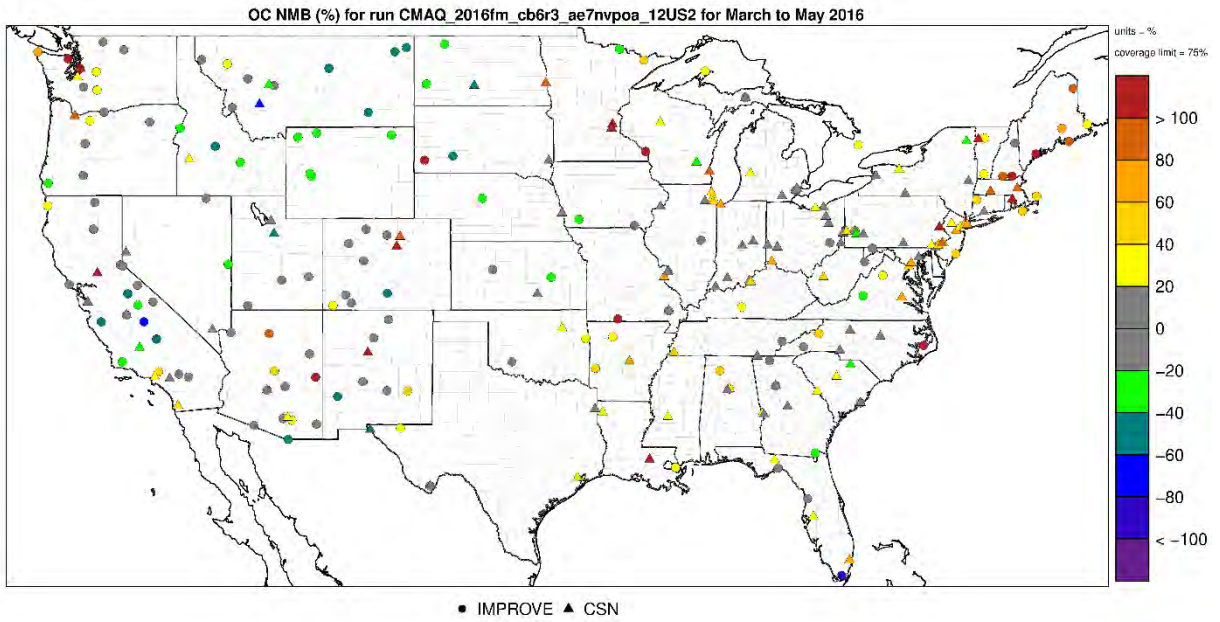


Figure 7-93 Normalized Mean Bias (%) of organic carbon during spring 2016 at monitoring sites in the modeling domain

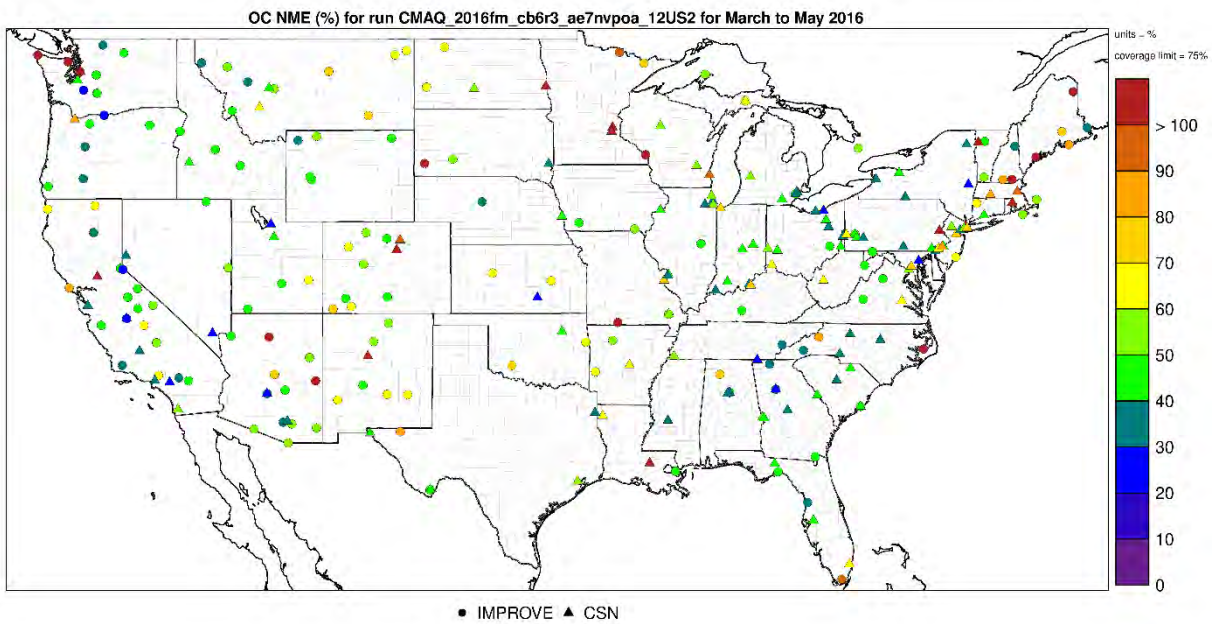


Figure 7-94 Normalized Mean Error (%) of organic carbon during spring 2016 at monitoring sites in the modeling domain

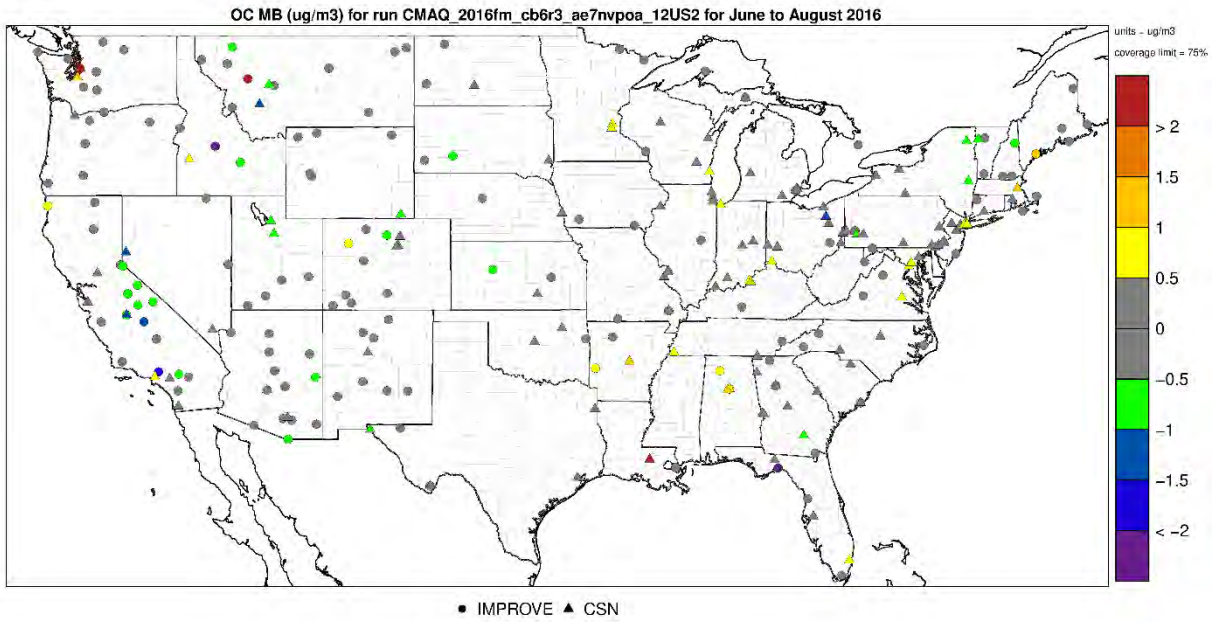


Figure 7-95 Mean Bias (ug/m3) of organic carbon during summer 2016 at monitoring sites in the modeling domain

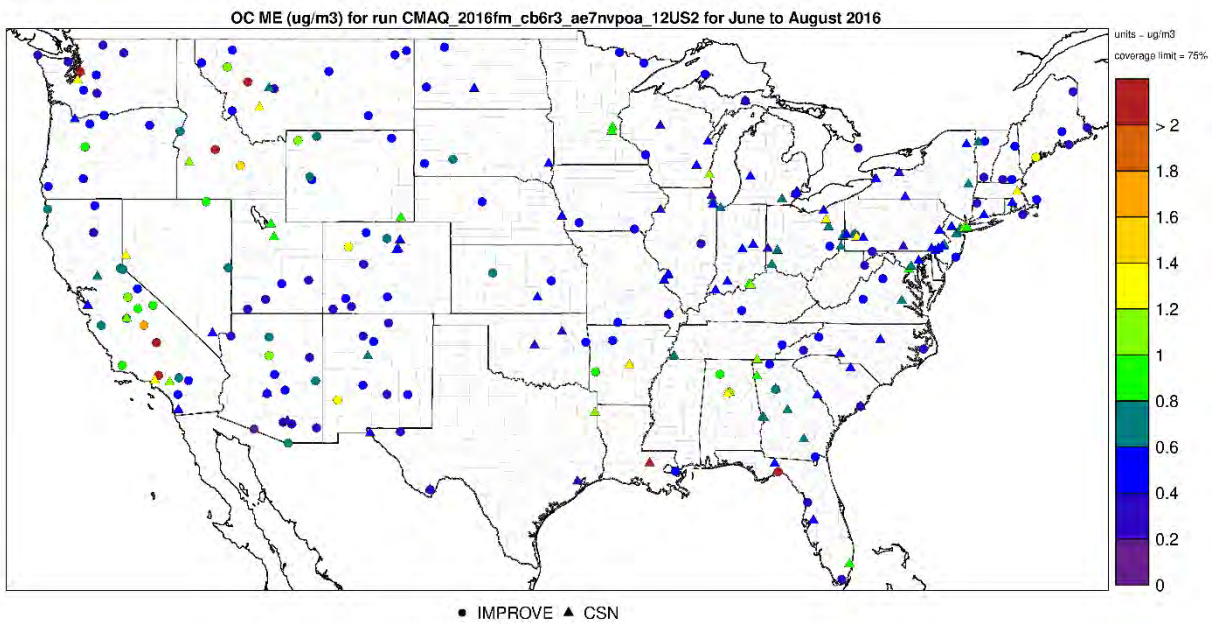


Figure 7-96 Mean Error (ug/m3) of organic carbon during summer 2016 at monitoring sites in the modeling domain

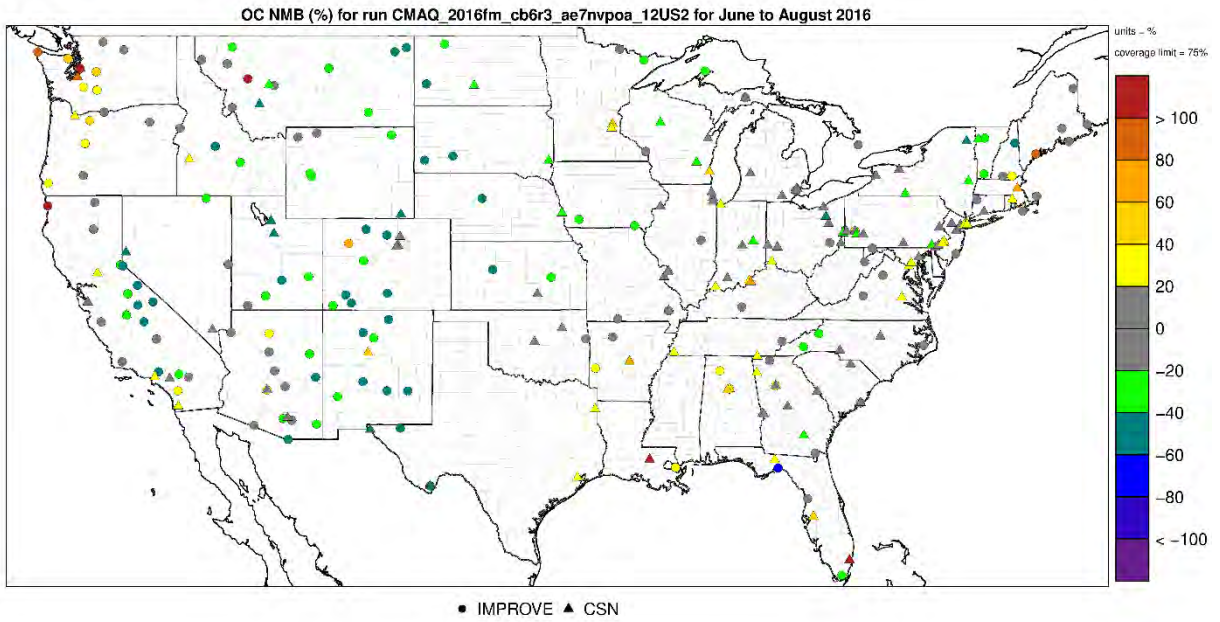


Figure 7-97 Normalized Mean Bias (%) of organic carbon during summer 2016 at monitoring sites in the modeling domain

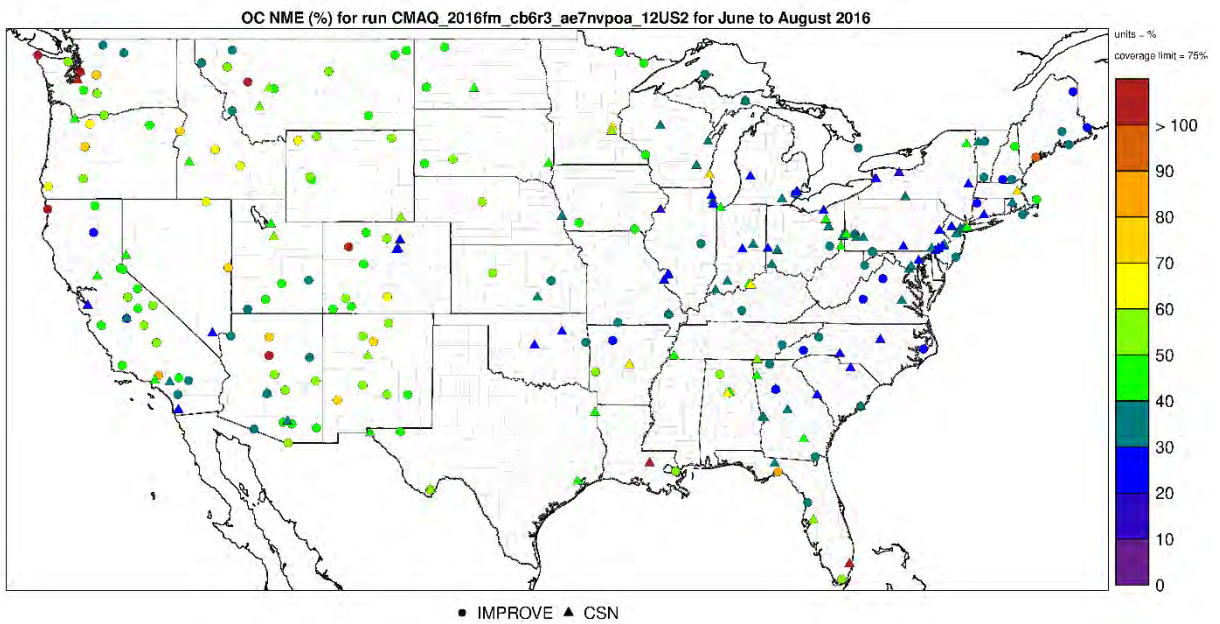


Figure 7-98 Normalized Mean Error (%) of organic carbon during summer 2016 at monitoring sites in the modeling domain

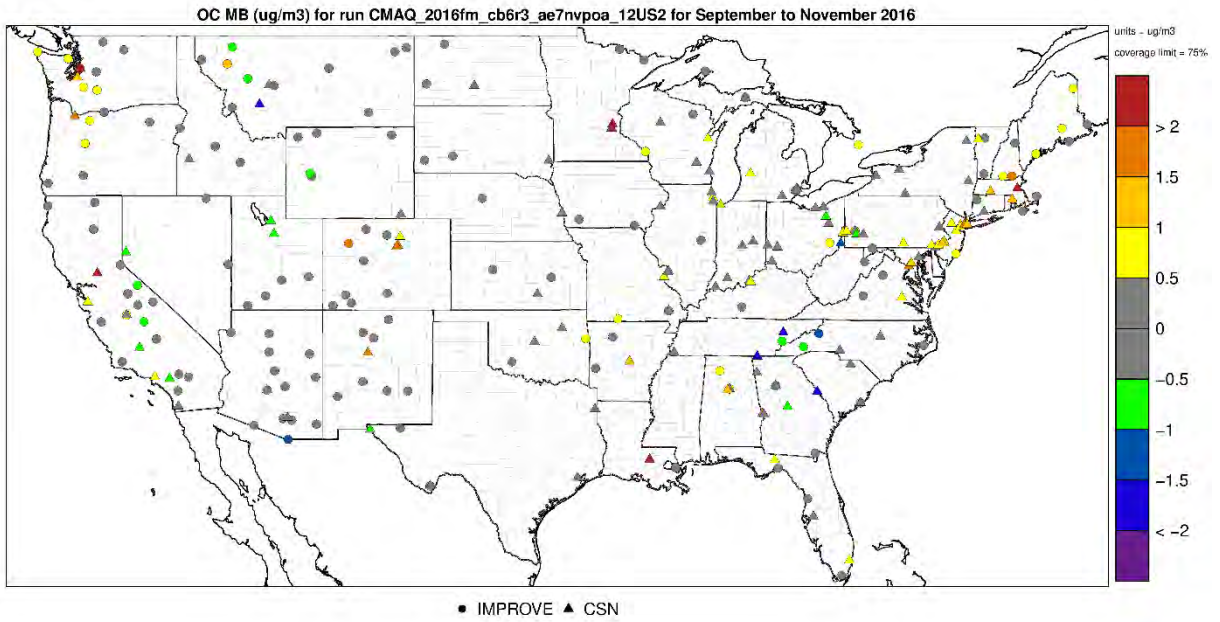


Figure 7-99 Mean Bias (ug/m^3) of organic carbon during fall 2016 at monitoring sites in the modeling domain

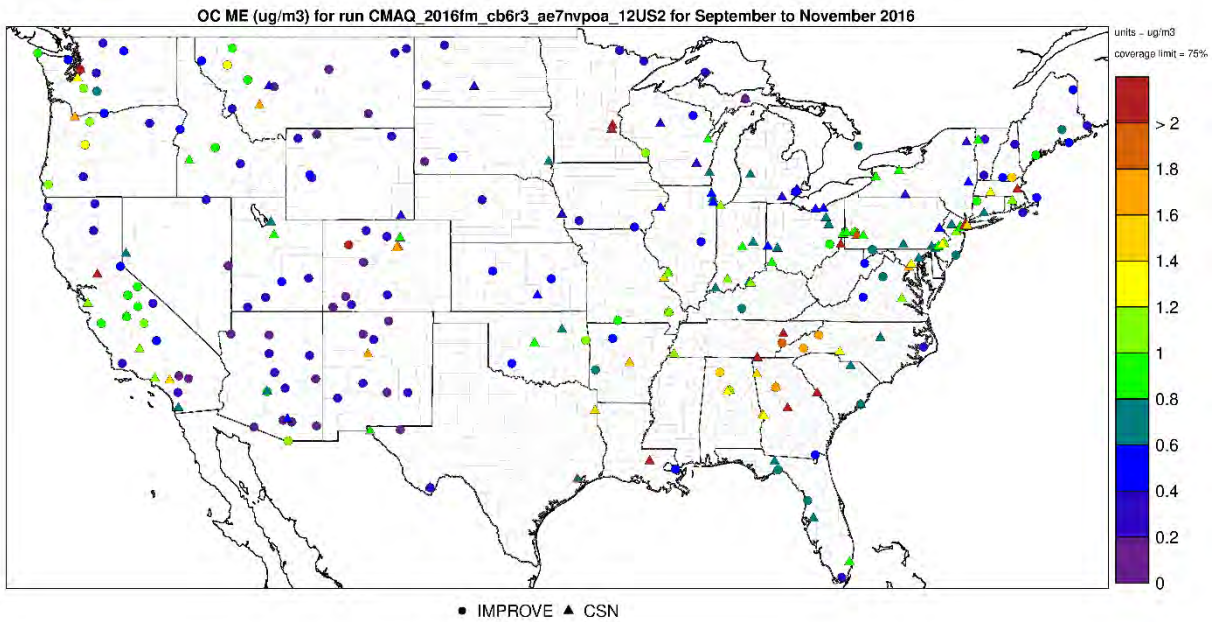


Figure 7-100 Mean Error (ug/m^3) of organic carbon during fall 2016 at monitoring sites in the modeling domain

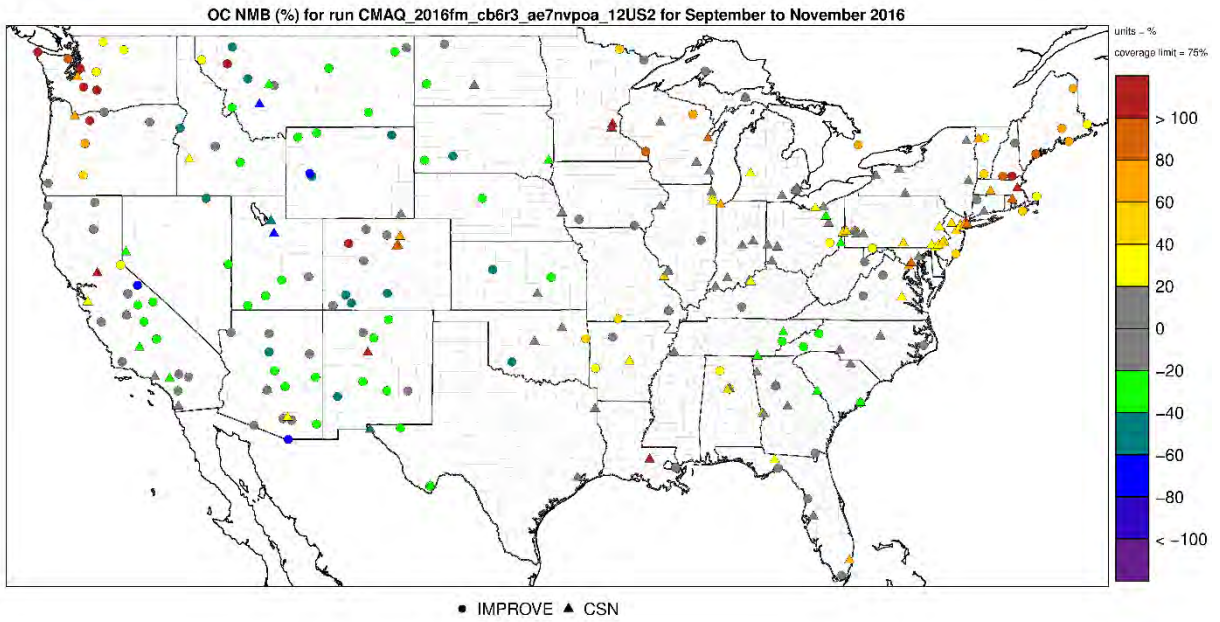


Figure 7-101 Normalized Mean Bias (%) of organic carbon during fall 2016 at monitoring sites in the modeling domain

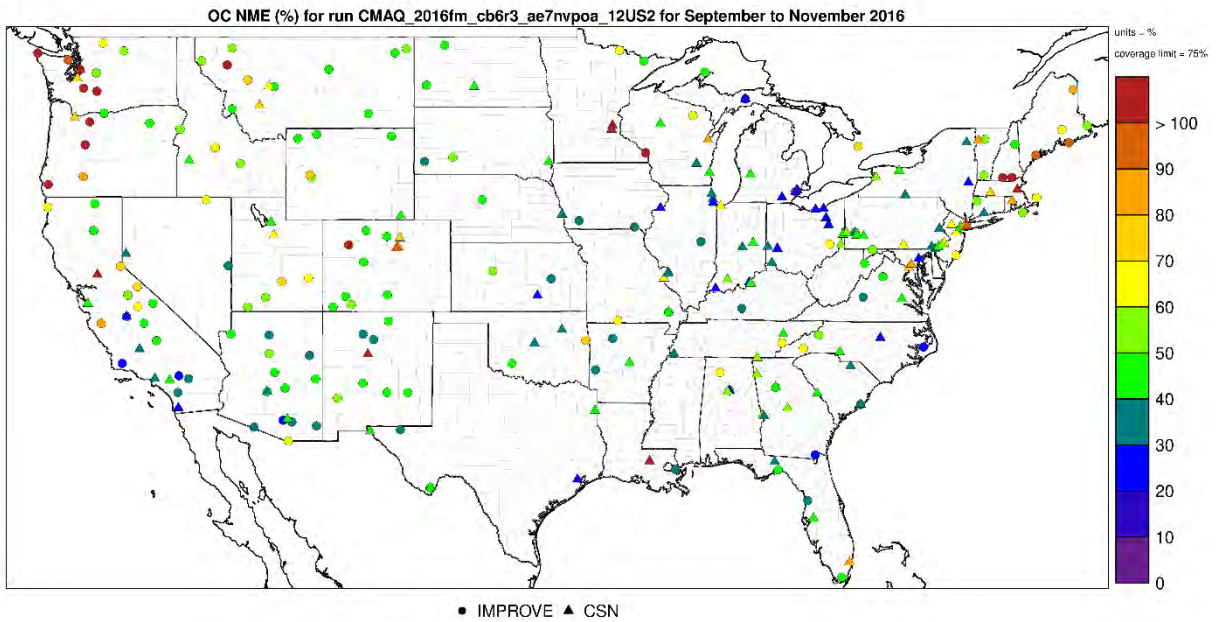


Figure 7-102 Normalized Mean Error (%) of organic carbon during fall 2016 at monitoring sites in the modeling domain

7.4.5 Seasonal Hazardous Air Pollutants Performance

A seasonal operational model performance evaluation for specific hazardous air pollutants (i.e., formaldehyde, acetaldehyde, benzene, and 1,3-butadiene) was conducted in order to estimate the ability of the CMAQ modeling system to replicate the base year concentrations for the 12 km Continental United States domain. The seasonal model performance results for the 12 km modeling domain are presented below in Table 7-10. Toxic measurements included in the evaluation were taken from the 2016 air toxics archive, <https://www.epa.gov/amtic/amtic-air-toxics-data-ambient-monitoring-archive>. While most of the data in the archive are from the AQS database including the National Air Toxics Trends Stations (NATTS), additional data (e.g., special studies) are included in the archive but not reported in the AQS. Similar to PM_{2.5} and ozone, the evaluation principally consists of statistical assessments of model versus observed pairs that were paired in time and space on daily basis.

Model predictions of annual formaldehyde, acetaldehyde, benzene, and 1,3 butadiene showed relatively small to moderate bias and error percentages when compared to observations. Model performance for HAPs is not as good as model performance for ozone and PM_{2.5}. Technical issues in the HAPs data consist of (1) uncertainties in monitoring methods; (2) limited measurements in time/space to characterize ambient concentrations (“local in nature”); (3) ambient data below method detection limit (MDL); (4) commensurability issues between measurements and model predictions; (5) emissions and science uncertainty issues may also affect model performance; and (6) limited data for estimating intercontinental transport that effects the estimation of boundary conditions (i.e., boundary estimates for some species are much higher than predicted values inside the domain).

As with the national, annual PM_{2.5} and ozone CMAQ modeling, the “acceptability” of model performance was judged by comparing our CMAQ 2016 performance results to the limited performance found in recent regional multi-pollutant model applications.^{82,83} Overall, the mean bias and error (MB and ME), as well as the normalized mean bias and error (NMB and NME) statistics shown below in Table 7-10 indicate that CMAQ-predicted 2016 toxics (i.e., observation vs. model predictions) are within the range of recent regional modeling applications.

Table 7-10 Hazardous Air Toxics Performance Statistics by Season for the 2016 CMAQ Model Simulation

Air Toxic Species	Season	No. of Obs.	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
Formaldehyde	Winter	1,814	-1.0	1.1	-58.4	63.1
	Spring	1,914	-1.3	1.3	-59.4	61.8

⁸² Phillips, S., K. Wang, C. Jang, N. Possiel, M. Strum, T. Fox, 2007: Evaluation of 2002 Multi-pollutant Platform: Air Toxics, Ozone, and Particulate Matter, 7th Annual CMAS Conference, Chapel Hill, NC, October 6-8, 2008.

⁸³ Wesson, K., N. Fann, M. Morris, T. Fox, and B. Hubbell 2010: A Multi-pollutant, Risk-based Approach to the Air Quality Management: Case Study for Detroit, Atmospheric Pollution Research, 1 (4) (2010), pp. 296-304, 10.5094/APR.2010.037.

	Summer	2,318	-1.5	1.6	-47.0	50.4
	Fall	1,886	-1.1	1.2	-48.0	54.4
Acetaldehyde	Winter	1,818	-0.4	0.4	-51.1	57.4
	Spring	1,920	-0.5	0.5	-54.1	58.4
	Summer	2,316	-0.2	0.5	-27.8	47.9
	Fall	1,870	-0.4	0.5	-39.1	51.4
Benzene	Winter	3,406	-0.1	0.4	-11.9	42.6
	Spring	3,968	-0.2	0.3	-25.8	47.2
	Summer	5,249	0.0	0.2	-11.2	54.9
	Fall	3,858	-0.2	0.4	-21.9	47.9
1,3-Butadiene	Winter	2,791	-0.1	0.2	-71.5	87.4
	Spring	2,926	-0.1	0.1	-72.9	89.5
	Summer	2,785	-0.1	0.1	-70.5	88.8
	Fall	2,629	-0.1	0.1	-73.0	88.7

7.4.6 Seasonal Nitrate and Sulfate Deposition Performance

Seasonal nitrate and sulfate wet deposition performance statistics for the 12 km Continental U.S. domain are provided in Table 7-11 and Table 7-12. The model predictions for seasonal nitrate deposition generally show under predictions for the continental U.S. NADP sites (NMB values range from -1.4% to -78.0%). Sulfate deposition performance shows similar under predictions (NMB values range from -10.3% to 78.3%). The errors for both annual nitrate and sulfate are relatively moderate with most values ranging from 33% to 88% which reflect scatter in the model predictions versus observation comparison.

Table 7-11 Nitrate Wet Deposition Performance Statistics by Climate Region, by Season, and by Monitoring Network for the 2016 CMAQ Model Simulation

Climate Region	Season	No. of Obs	MB (ug/m³)	ME (ug/m³)	NMB (%)	NME (%)
Northeast	Winter	600	-0.1	0.1	-37.8	53.7
	Spring	649	0.0	0.1	-7.4	44.7
	Summer	681	0.0	0.1	-20.2	51.2
	Fall	679	0.0	0.1	6.5	51.2
Ohio Valley	Winter	297	0.0	0.1	0.9	52.0

Climate Region	Season	No. of Obs	MB (ug/m³)	ME (ug/m³)	NMB (%)	NME (%)
	Spring	300	0.0	0.1	-0.8	33.5
	Summer	309	-0.1	0.1	-25.9	50.1
	Fall	288	0.0	0.1	11.9	53.8
Upper Midwest	Winter	275	0.0	0.1	-36.9	63.5
	Spring	277	0.0	0.1	-23.4	46.1
	Summer	292	-0.1	0.1	-28.7	45.5
	Fall	301	0.0	0.1	-12.4	47.2
Southeast	Winter	359	0.0	0.0	0.3	52.4
	Spring	376	0.0	0.1	-9.7	46.0
	Summer	413	-0.1	0.1	-30.8	50.5
	Fall	385	0.0	0.0	-11.5	61.0
South	Winter	236	0.0	0.0	15.5	57.8
	Spring	263	0.0	0.1	-9.2	45.6
	Summer	281	-0.1	0.1	-36.0	54.6
	Fall	280	0.0	0.0	-15.7	54.7
Southwest	Winter	300	0.0	0.0	-78.0	82.5
	Spring	322	0.0	0.1	-68.8	80.4
	Summer	292	0.0	0.1	-38.7	55.9
	Fall	334	0.0	0.0	-47.5	72.8
Northern Rockies	Winter	216	0.0	0.0	-66.9	87.5
	Spring	251	0.0	0.0	-47.9	57.3
	Summer	226	0.0	0.1	-37.8	50.0
	Fall	237	0.0	0.0	-35.1	63.7
Northwest	Winter	121	0.0	0.0	-1.4	51.2
	Spring	141	0.0	0.0	-6.4	58.7
	Summer	138	0.0	0.0	-4.4	71.7
	Fall	145	0.0	0.0	19.3	64.5
West	Winter	151	0.0	0.0	-28.0	57.5

Climate Region	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
	Spring	151	0.0	0.0	13.6	81.7
	Summer	161	0.0	0.0	-81.7	92.7
	Fall	160	0.0	0.0	-13.9	76.6

Table 7-12 Sulfate Wet Deposition Performance Statistics by Climate Region, by Season, and by Monitoring Network for the 2016 CMAQ Model Simulation

Climate Region	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
Northeast	Winter	600	0.0	0.1	-40.9	56.8
	Spring	649	0.0	0.0	-16.6	45.0
	Summer	681	0.0	0.1	-11.4	57.1
	Fall	679	0.0	0.1	-14.9	54.0
Ohio Valley	Winter	297	0.0	0.1	-25.8	50.3
	Spring	300	0.0	0.1	-13.3	34.9
	Summer	309	0.0	0.1	-17.8	50.2
	Fall	288	0.0	0.0	-10.3	51.6
Upper Midwest	Winter	275	0.0	0.0	-37.8	58.3
	Spring	277	0.0	0.0	-28.5	49.3
	Summer	292	0.0	0.1	-21.6	49.0
	Fall	301	0.0	0.0	-32.9	52.6
Southeast	Winter	359	0.0	0.1	-25.1	51.0
	Spring	376	0.0	0.1	-25.5	53.6
	Summer	413	0.0	0.1	-25.0	53.4
	Fall	385	0.0	0.0	-17.7	63.8
South	Winter	236	0.0	0.0	-15.3	48.4
	Spring	263	-0.1	0.1	-40.3	53.7
	Summer	281	-0.1	0.1	-41.0	63.2
	Fall	280	-0.0	0.0	-36.5	60.7
Southwest	Winter	300	0.0	0.0	-78.2	84.5
	Spring	322	0.0	0.0	-65.6	79.8

Climate Region	Season	No. of Obs	MB (ug/m ³)	ME (ug/m ³)	NMB (%)	NME (%)
	Summer	292	0.0	0.0	-31.4	59.2
	Fall	334	0.0	0.0	-63.2	75.0
Northern Rockies	Winter	216	0.0	0.0	-71.2	86.3
	Spring	251	0.0	0.0	-50.7	58.7
	Summer	226	0.0	0.0	-28.4	53.2
	Fall	237	0.0	0.0	-46.8	64.6
Northwest	Winter	121	0.0	0.0	33.8	69.7
	Spring	141	0.0	0.0	13.4	63.4
	Summer	138	0.0	0.0	32.8	95.8
	Fall	145	0.0	0.1	46.2	92.3
West	Winter	151	0.0	0.0	65.4	>100
	Spring	151	0.0	0.0	42.0	>100
	Summer	161	0.0	0.0	-78.3	92.3
	Fall	160	0.0	0.0	7.7	91.4

7.5 Model Simulation Scenarios

As part of our analysis for this rulemaking, the CMAQ modeling system was used to calculate annual PM_{2.5} concentrations, 8-hour maximum average ozone season concentrations, annual NO₂, SO₂, and CO concentrations, annual and seasonal (summer and winter) air toxics concentrations, and annual nitrogen and sulfur deposition for each of the following emissions scenarios:

- 2016 base year
- 2055 reference
- 2055 light and medium duty regulatory scenario

We use the predictions from the CMAQ model in a relative sense by combining the 2016 base-year predictions with predictions from each future-year scenario and applying these modeled ratios to ambient air quality observations to estimate 8-hour ozone concentrations during the ozone season (May - Sept), daily and annual PM_{2.5} concentrations, and visibility impairment for each of the 2055 scenarios. The ambient air quality observations are average conditions, on a site-by-site basis, for a period centered around the model base year (i.e., 2014-2018).

The projected annual PM_{2.5} concentrations were calculated using the Speciated Modeled Attainment Test (SMAT) approach that utilizes a Federal Reference Method (FRM) mass construction methodology which results in reduced nitrates (relative to the amount measured by routine speciation networks), higher mass associated with sulfates (reflecting water included in FRM measurements), and a measure of organic carbonaceous mass that is derived from the difference between measured PM_{2.5} and its non-carbon components. This characterization of PM_{2.5} mass also reflects crustal material and other minor constituents. The resulting characterization provides a complete mass balance. It does not have any unknown mass that is sometimes presented as the difference between measured PM_{2.5} mass and the characterized chemical components derived from routine speciation measurements. However, the assumption that all mass difference is organic carbon has not been validated in many areas of the U.S. The SMAT methodology uses the following PM_{2.5} species components: sulfates, nitrates, ammonium, organic carbon mass, elemental carbon, crustal, water, and blank mass (a fixed value of 0.5 µg/m³). More complete details of the SMAT procedures can be found in the report "Procedures for Estimating Future PM_{2.5} Values for the CAIR Final Rule by Application of the (Revised) Speciated Modeled Attainment Test (SMAT)." For this analysis, several datasets and techniques were updated. These changes are fully described within the technical support document for the Final Transport Rule AQM TSD.

Additionally, we conducted an analysis to compare the absolute differences between the future year reference and regulatory scenario for annual and seasonal acetaldehyde, benzene, formaldehyde, and naphthalene, as well as annual NO₂, SO₂, CO, and nitrate/sulfate deposition. These data were not compared in a relative sense due to the limited observational data available.

8 Additional Results of Illustrative Air Quality Analysis

EPA conducted an illustrative air quality modeling analysis of a regulatory scenario involving light- and medium-duty "onroad" vehicle emission reductions and corresponding changes in "upstream" emission sources like EGU (electric generating unit) emissions and refinery emissions. Decisions about the emissions and other elements used in the air quality modeling were made early in the analytical process for the proposed rulemaking. Accordingly, the air quality analysis does not represent the proposal's regulatory scenario, nor does it reflect the expected impacts of the Inflation Reduction Act (IRA). Based on updated power sector modeling that incorporated expected generation mix impacts of the IRA (presented in Chapter 5), we are projecting the IRA will lead to a significantly cleaner power grid; because the air quality analysis presented here does not account for these impacts on EGU emissions, the location and magnitude of the changes in pollutant concentrations should be considered illustrative and not viewed as Agency projections of what we expect will be the total impact of the proposed standards. Nevertheless, the analysis provides some insights into potential air quality impacts associated with emissions increases and decreases from these multiple sectors.

Given the considerable uncertainty associated with the upstream emissions inventory (see Sections 4 and 5), we also modeled a sensitivity case that examined only the air quality impacts of the onroad emissions changes from the LMDV regulatory scenario. This "onroad-only" sensitivity case assumed no change in emissions from upstream sources and is based on the onroad emission inventories described in Section 3.

The draft RIA includes maps that present the impact of the LMDV regulatory scenario on projected ozone, PM_{2.5}, NO₂, SO₂, CO, and air toxics concentrations, and projected nitrogen deposition. In this TSD we present annual reference and LMDV regulatory scenario maps for CO, NO₂, SO₂, air toxics, and nitrogen deposition as well as seasonal difference maps for air toxics and visibility levels at Mandatory Class I Federal Areas.

8.1 Annual 2055 Reference, LMDV Regulatory, and Onroad-Only Scenario Maps

The following section presents maps of ambient concentrations of PM_{2.5}, ozone, CO, NO₂, SO₂, acetaldehyde, benzene, formaldehyde and naphthalene and total nitrogen deposition in the 2055 reference case and the 2055 LMDV regulatory scenario and the 2055 onroad-only scenario.

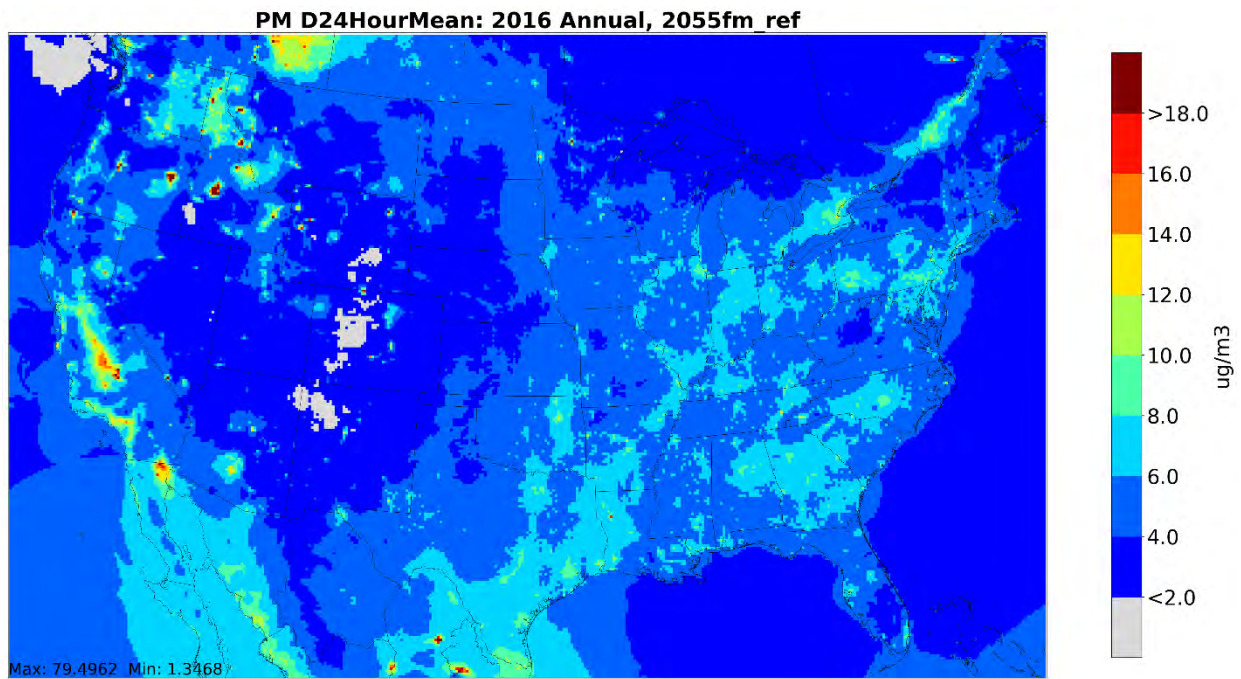


Figure 8-1 Projected Illustrative Annual Average PM_{2.5} Concentrations in 2055 Reference Case (ug/m³)

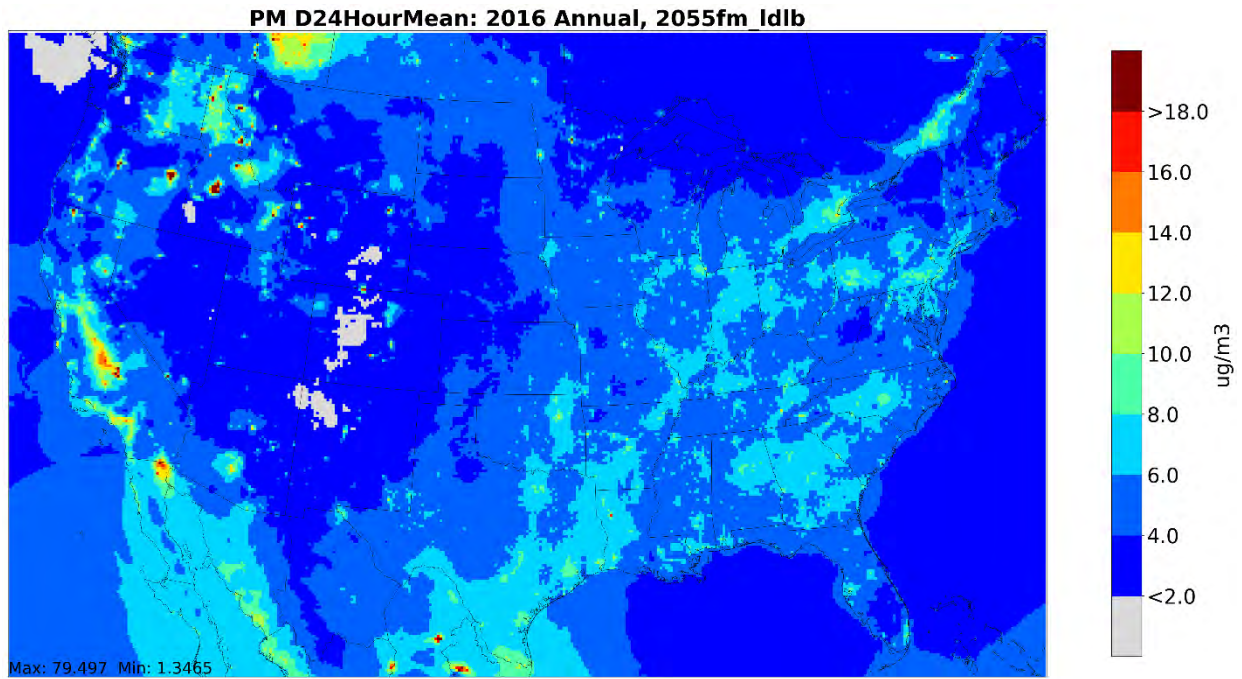


Figure 8-2 Projected Illustrative Annual Average $\text{PM}_{2.5}$ Concentrations in 2055 LMDV Regulatory Scenario ($\mu\text{g}/\text{m}^3$)

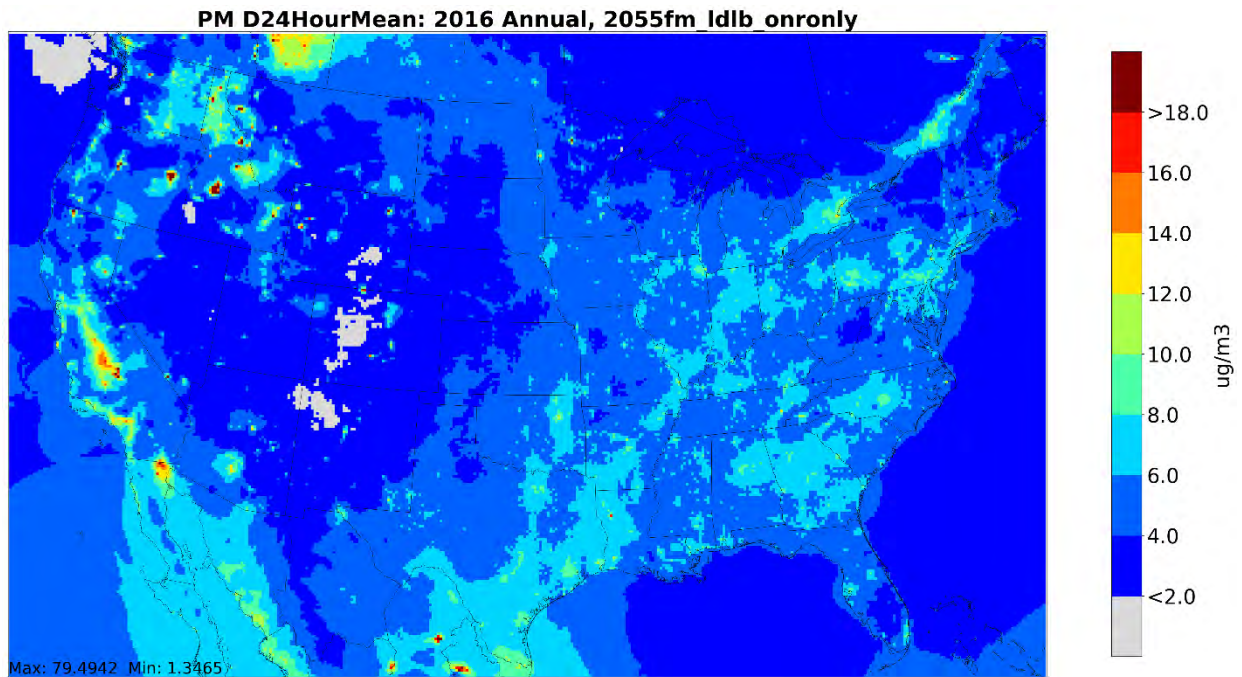


Figure 8-3 Projected Illustrative Annual Average $\text{PM}_{2.5}$ Concentrations in 2055 Onroad-Only Scenario ($\mu\text{g}/\text{m}^3$)

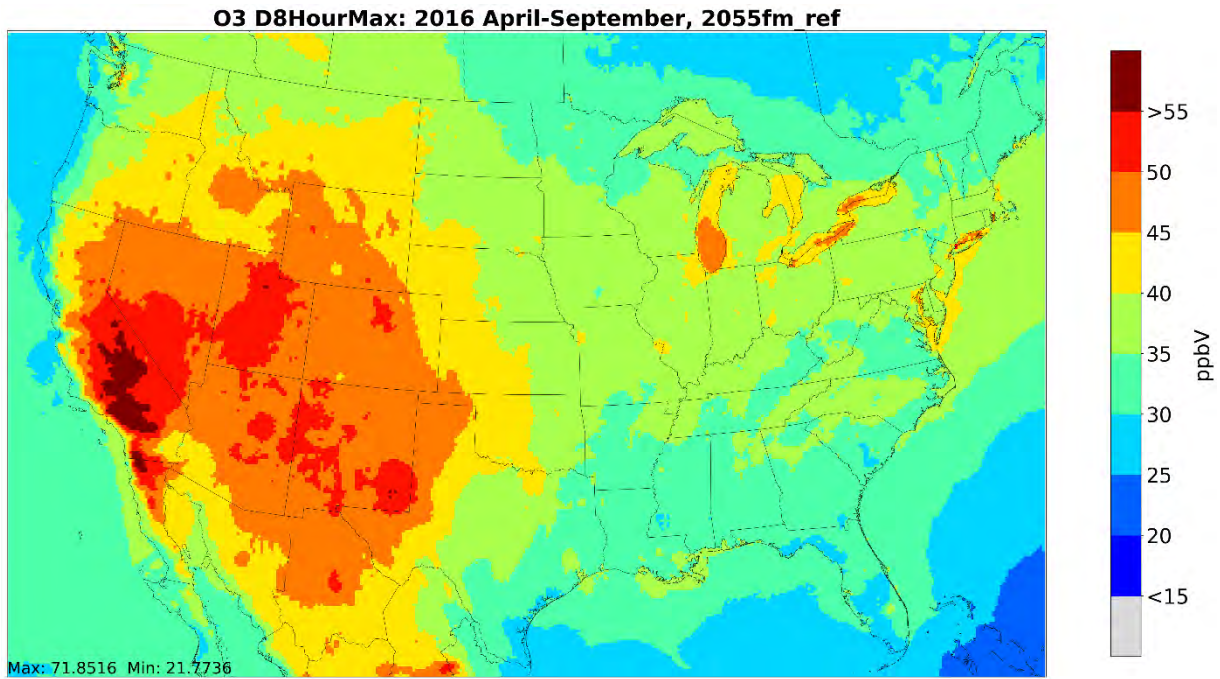


Figure 8-4 Projected Illustrative Ozone Season (Apr-Sept) 8-hour Maximum Average Ozone Concentrations in 2055 Reference case (ppb)

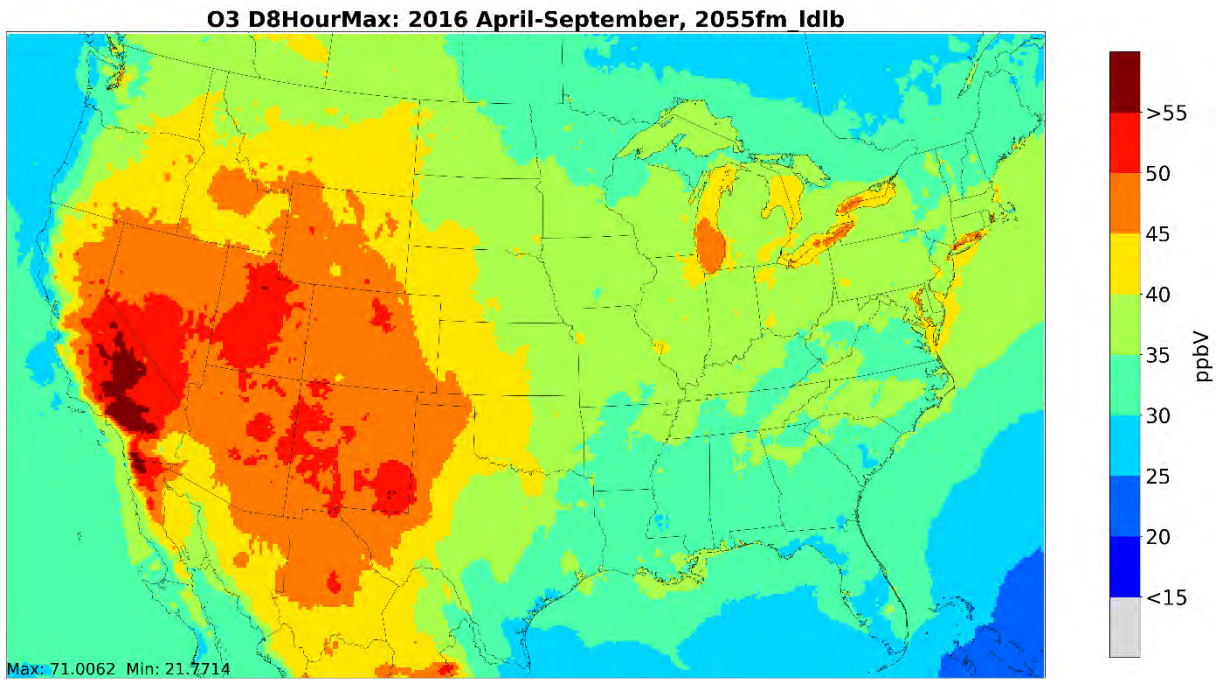


Figure 8-5 Projected Illustrative Ozone Season (Apr-Sept) 8-hour Maximum Average Ozone Concentrations in 2055 LMDV Regulatory Scenario (ppb)

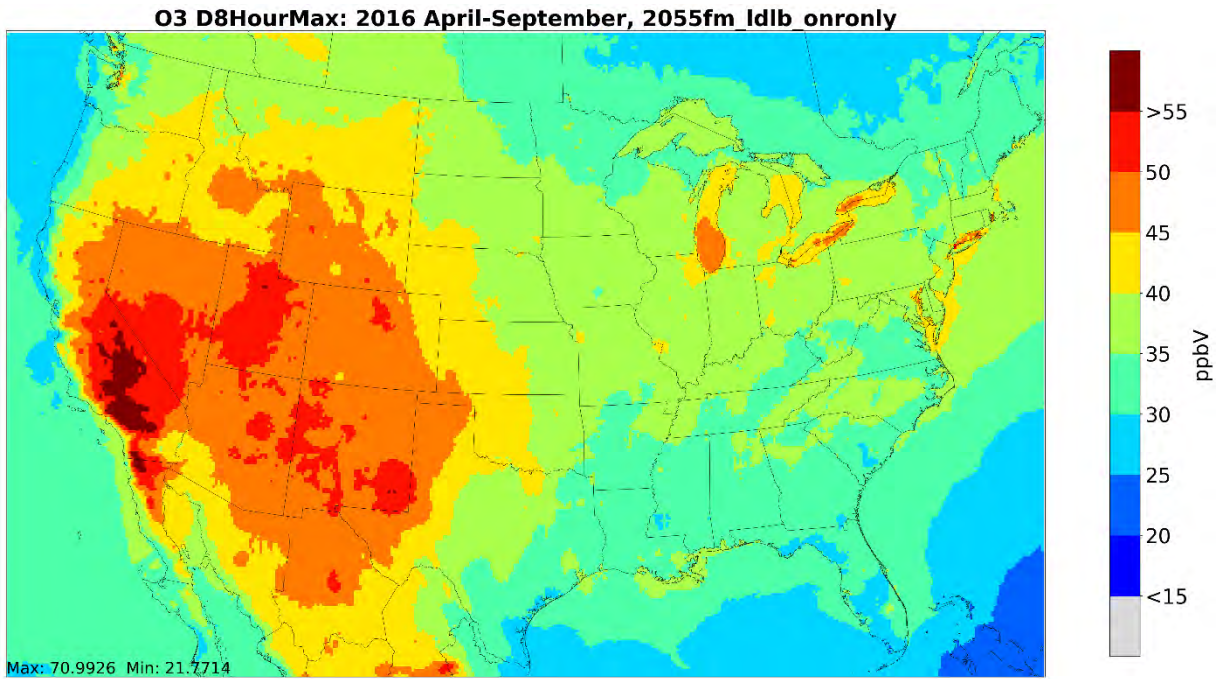


Figure 8-6 Projected Illustrative Ozone Season (Apr-Sept) 8-hour Maximum Average Ozone Concentrations in 2055 Onroad-Only Scenario (ppb)

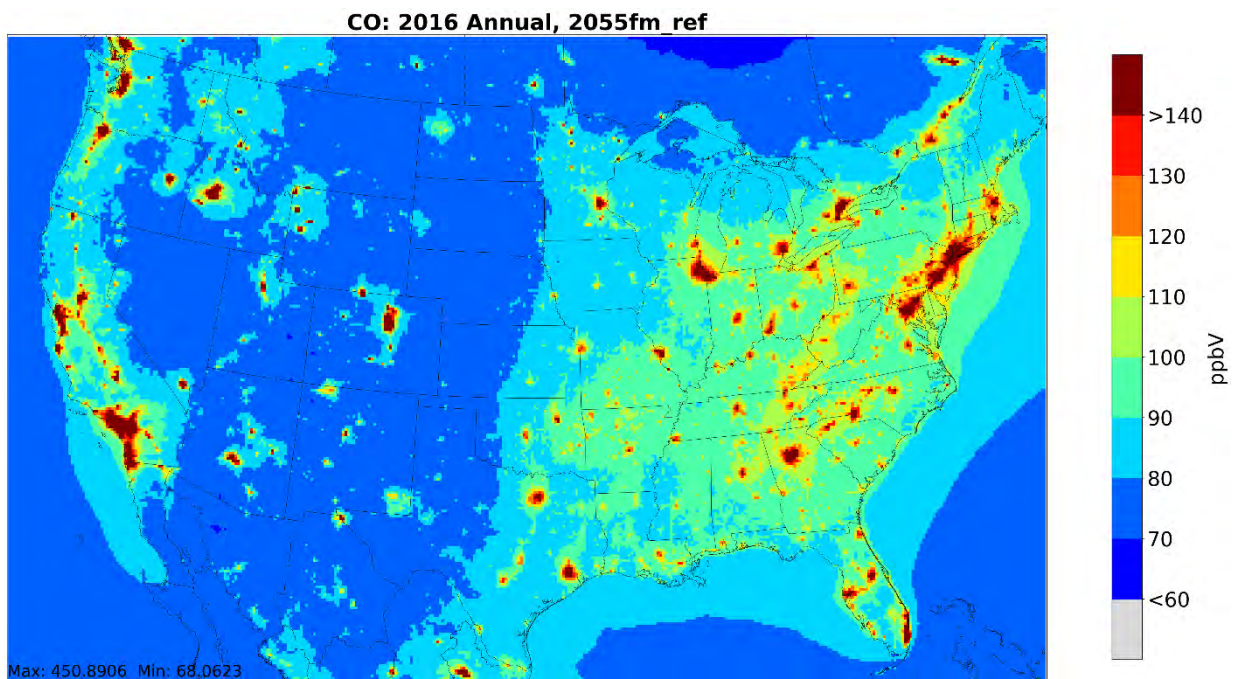


Figure 8-7 Projected Illustrative Annual Average CO Concentrations in 2055 Reference Case (ppb)

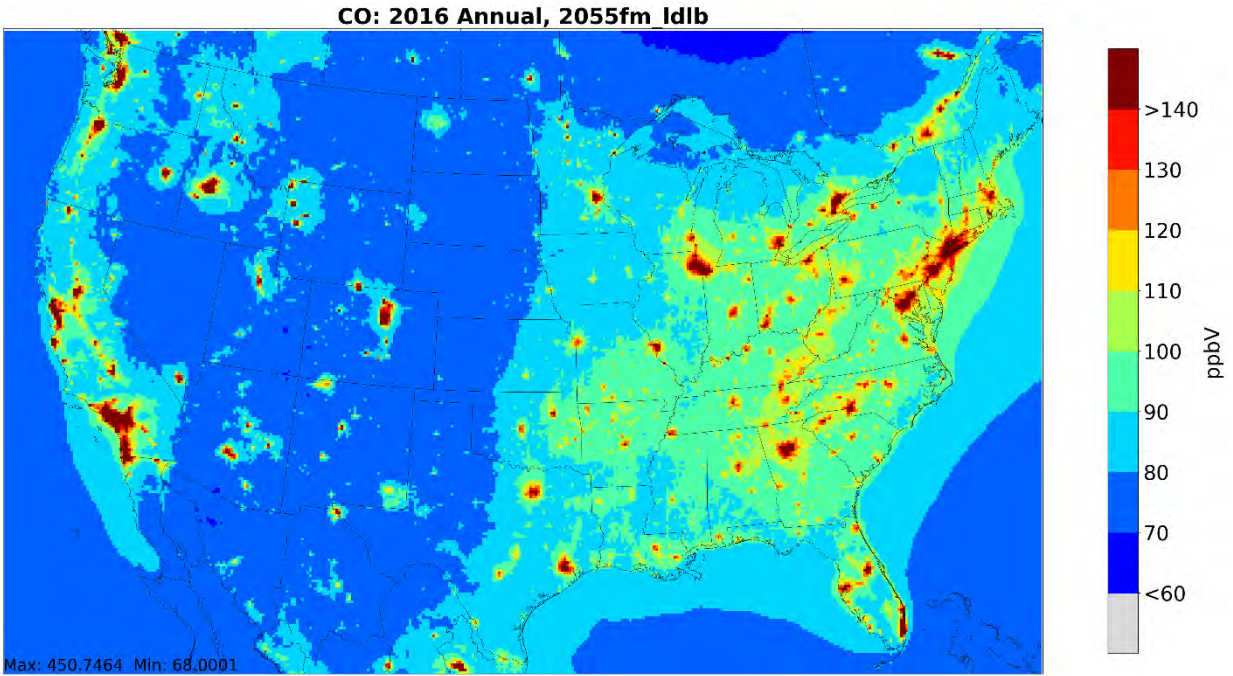


Figure 8-8 Projected Illustrative Annual Average CO Concentrations in 2055 LMDV Regulatory Scenario (ppb)

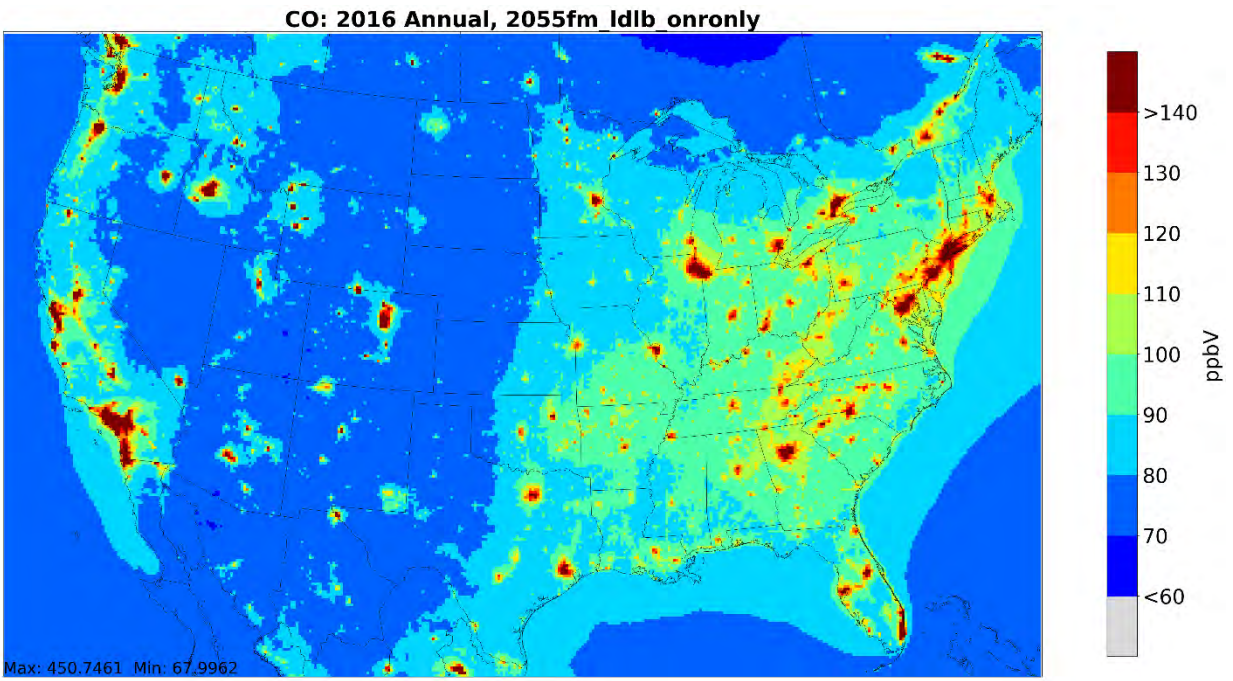


Figure 8-9 Projected Illustrative Annual Average CO Concentrations in 2055 Onroad-Only Scenario (ppb)

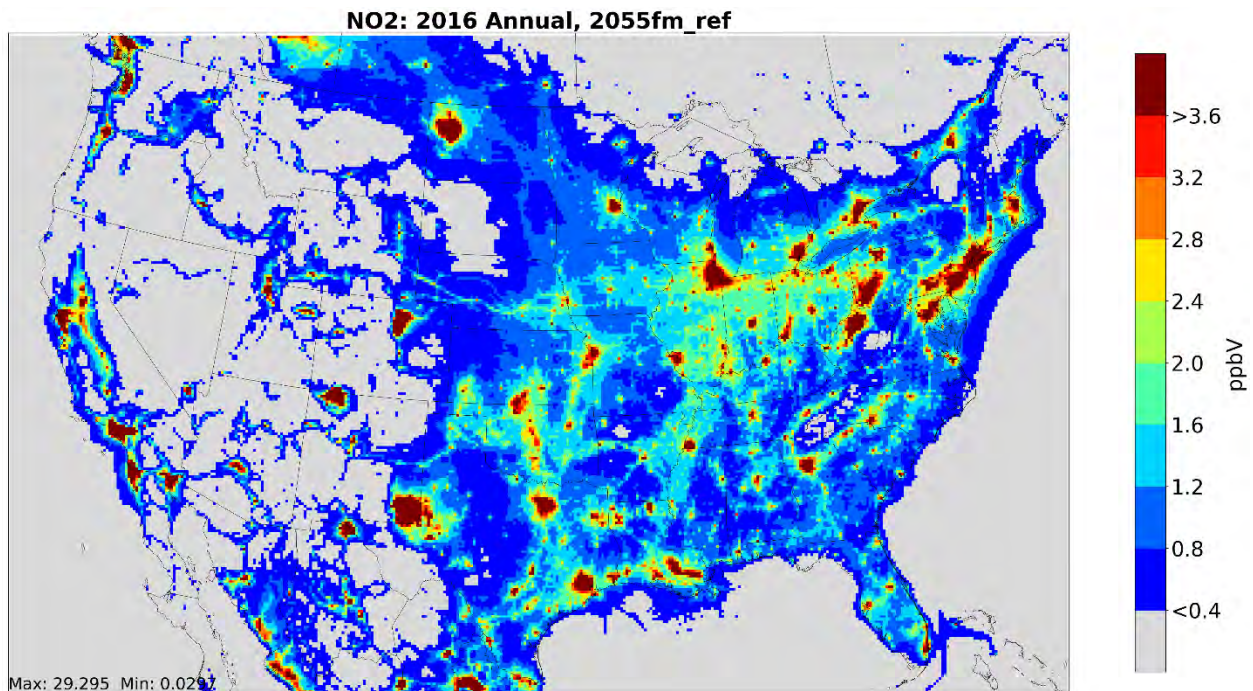


Figure 8-10 Projected Illustrative Annual Average NO₂ Concentrations in 2055 Reference Case (ppb)

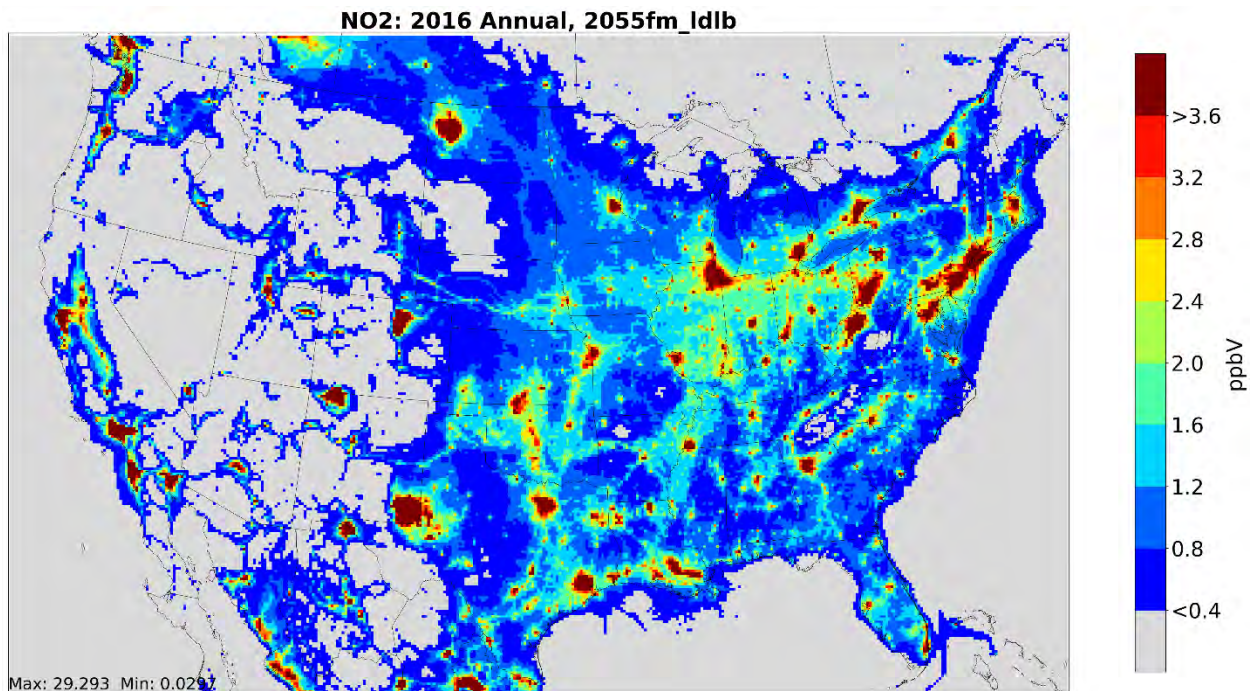


Figure 8-11 Projected Illustrative Annual Average NO₂ Concentrations in 2055 LMDV Regulatory Scenario (ppb)

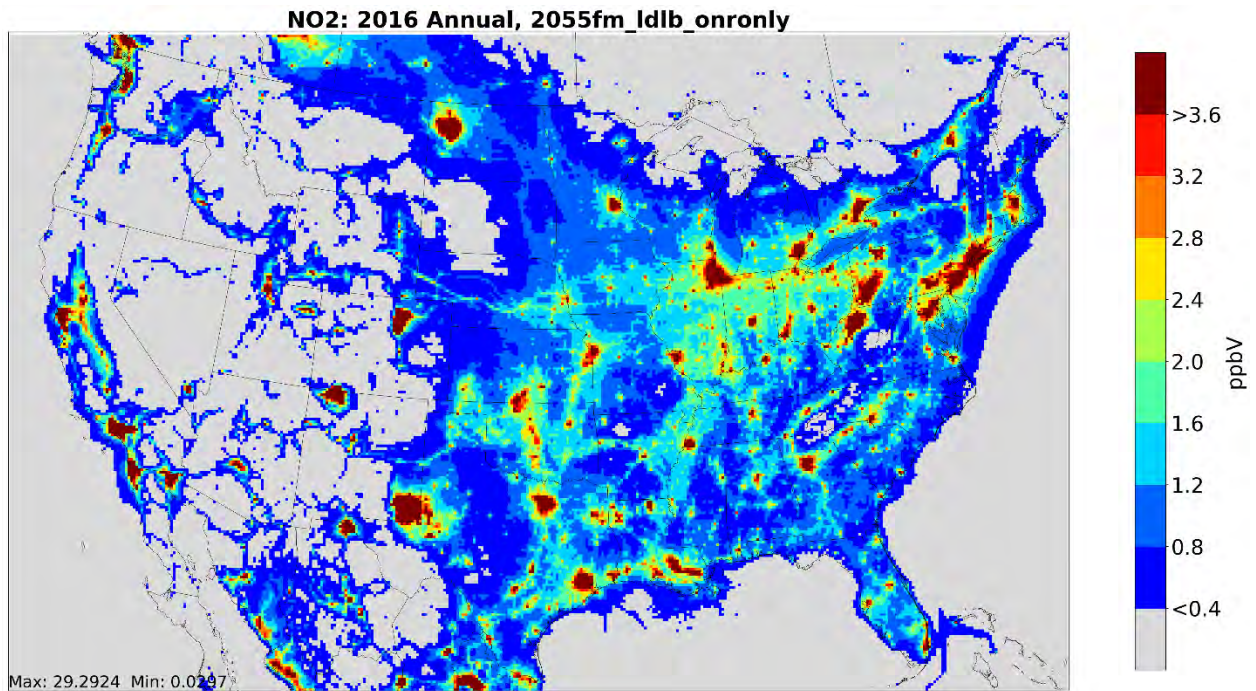


Figure 8-12 Projected Illustrative Annual Average NO₂ Concentrations in 2055 Onroad-Only Scenario (ppb)

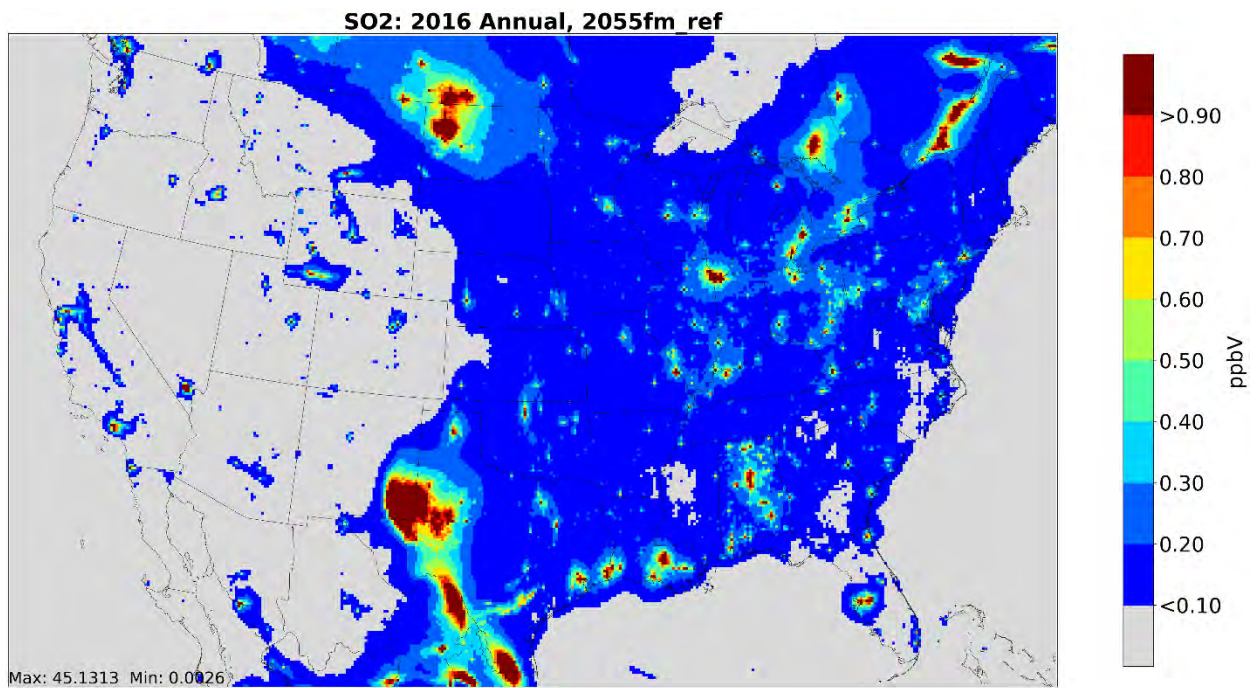


Figure 8-13 Projected Illustrative Annual Average SO₂ Concentrations in 2055 Reference Case (ppb)

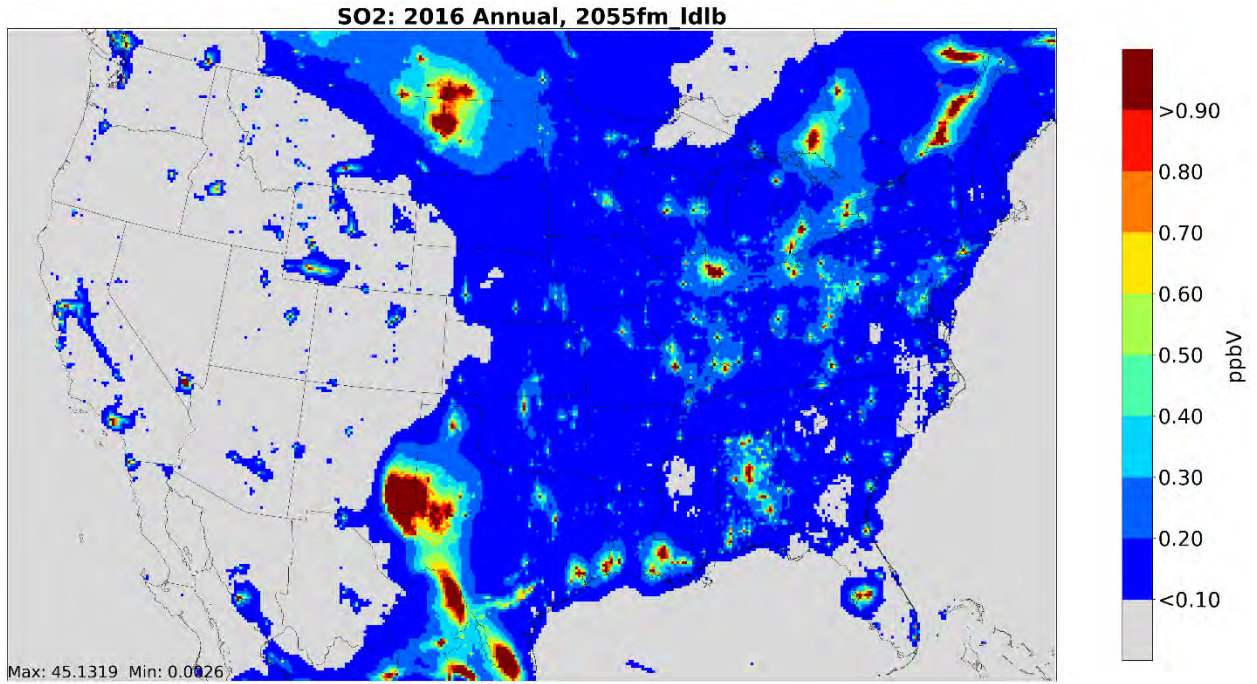


Figure 8-14 Projected Illustrative Annual Average SO₂ Concentrations in 2055 LMDV Regulatory Scenario (ppb)

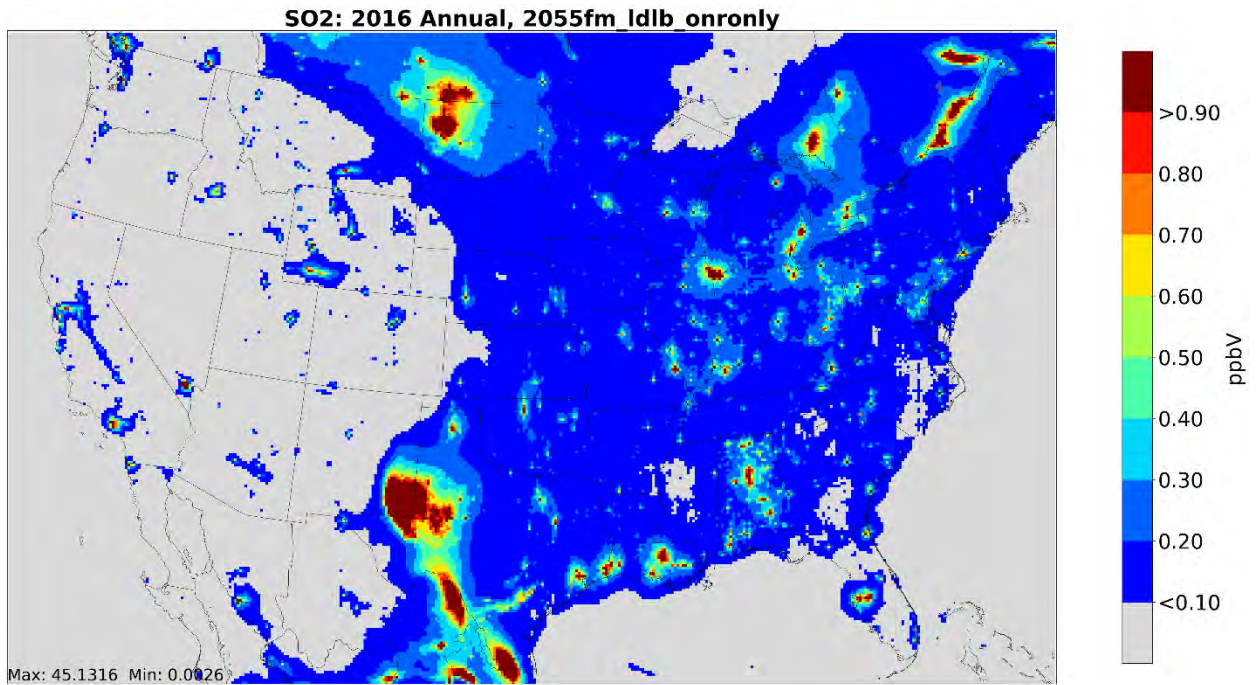


Figure 8-15 Projected Illustrative Annual Average SO₂ Concentrations in 2055 Onroad-Only Scenario (ppb)

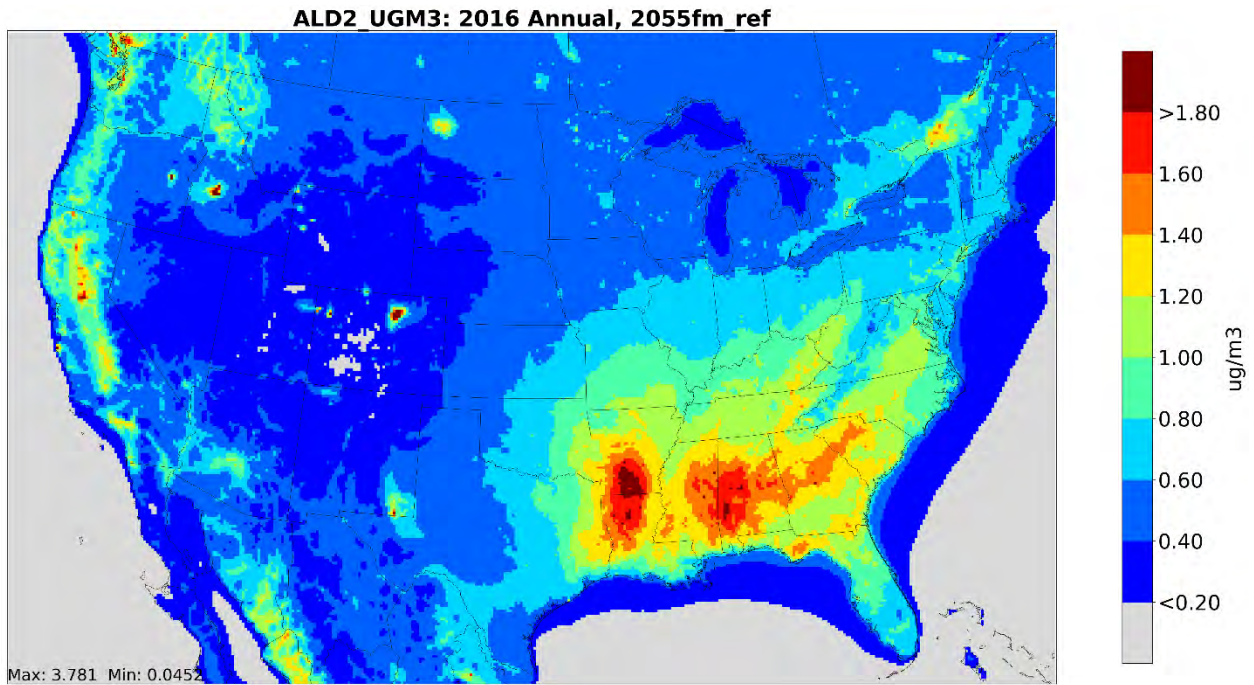


Figure 8-16 Projected Illustrative Annual Average Acetaldehyde Concentrations in 2055 Reference Case (ug/m³)

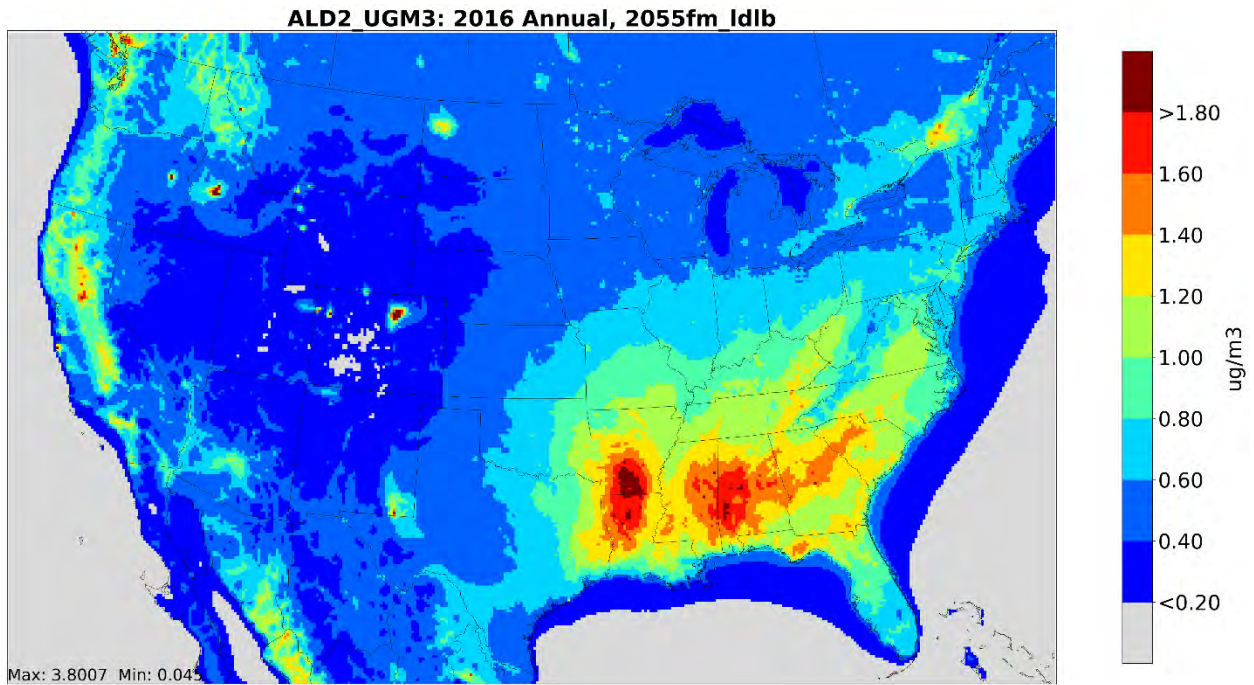


Figure 8-17 Projected Illustrative Annual Average Acetaldehyde Concentrations in 2055 LMDV Regulatory Scenario (ug/m³)

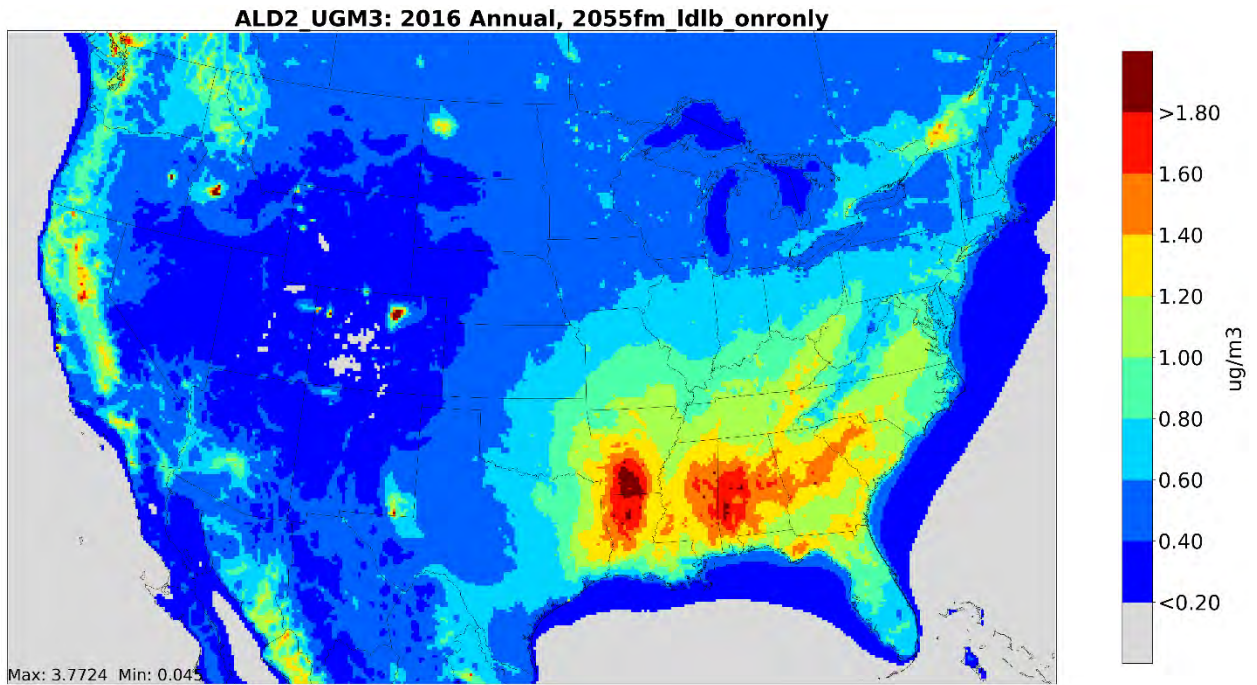


Figure 8-18 Projected Illustrative Annual Average Acetaldehyde Concentrations in 2055 Onroad-Only Scenario (ug/m³)

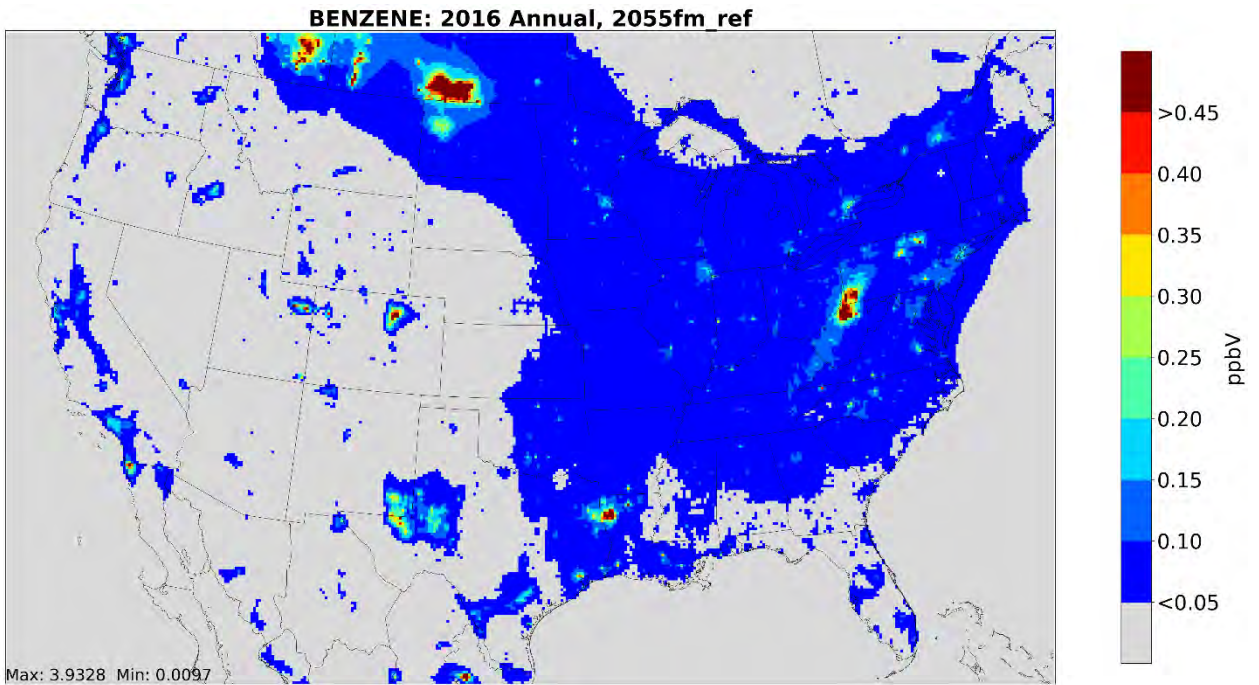


Figure 8-19 Projected Illustrative Annual Average Benzene Concentrations in 2055 Reference Case (ug/m³)

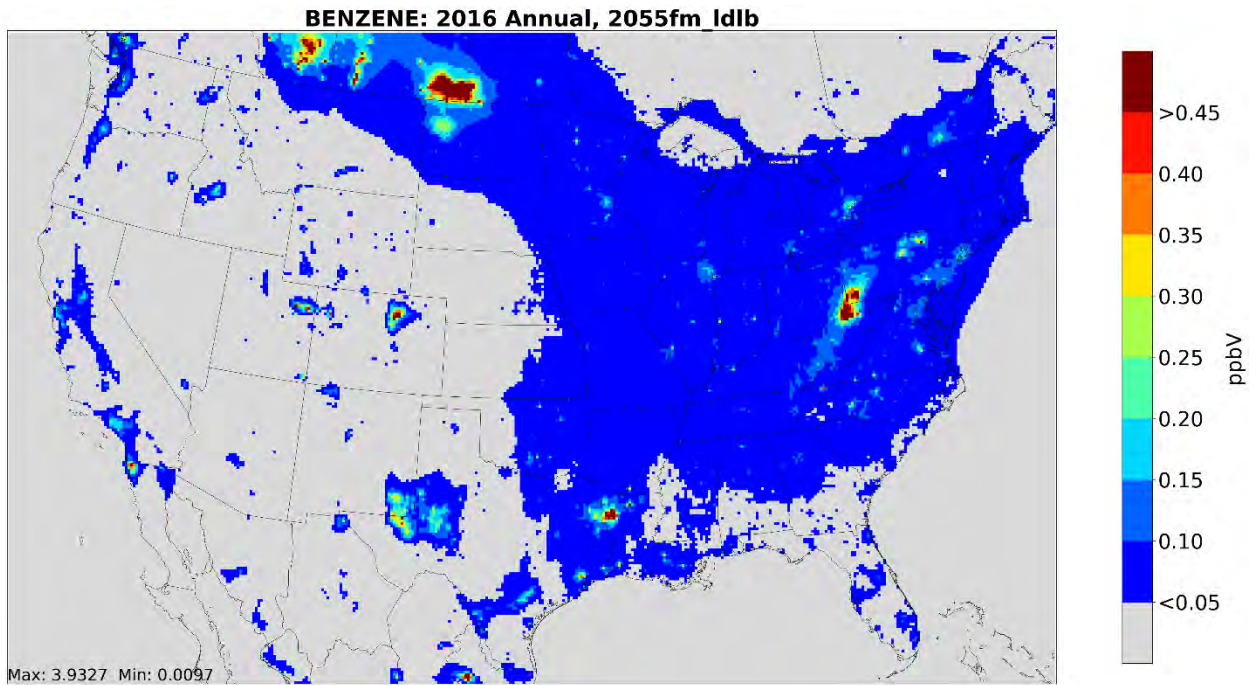


Figure 8-20 Projected Illustrative Annual Average Benzene Concentrations in 2055 LMDV Regulatory Scenario ($\mu\text{g}/\text{m}^3$)

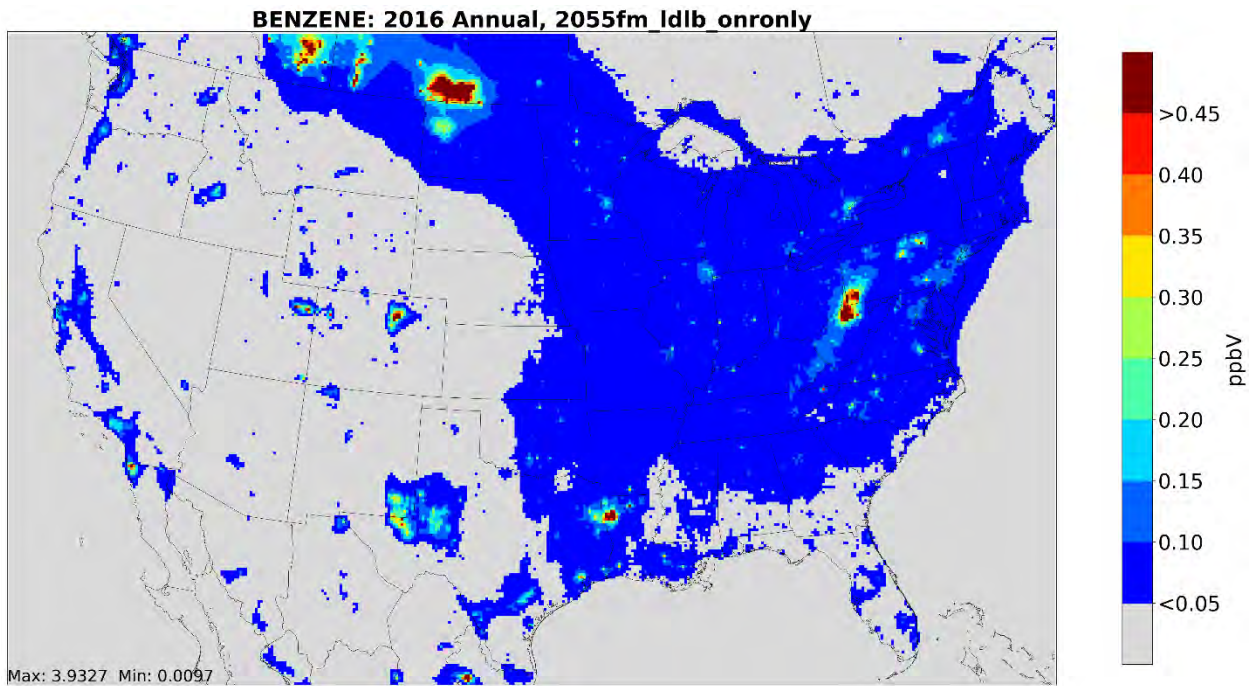


Figure 8-21 Projected Illustrative Annual Average Benzene Concentrations in 2055 Onroad-Only Scenario ($\mu\text{g}/\text{m}^3$)

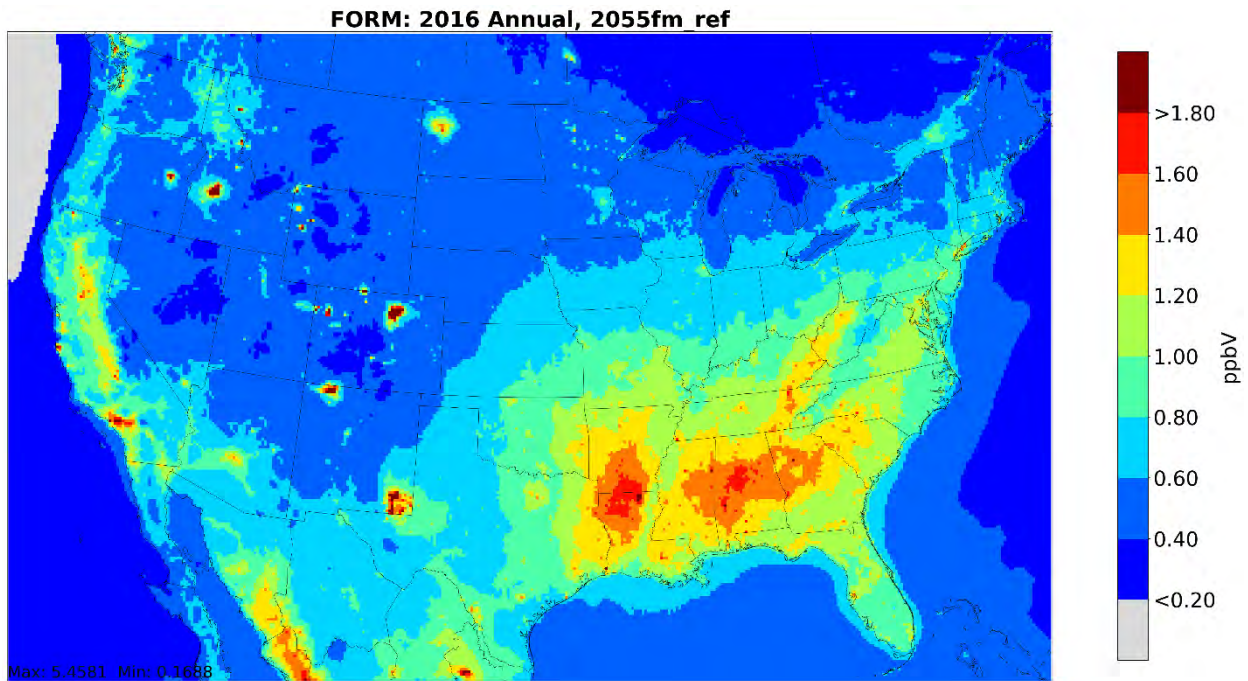


Figure 8-22 Projected Illustrative Annual Average Formaldehyde Concentrations in 2055 Reference Case ($\mu\text{g}/\text{m}^3$)

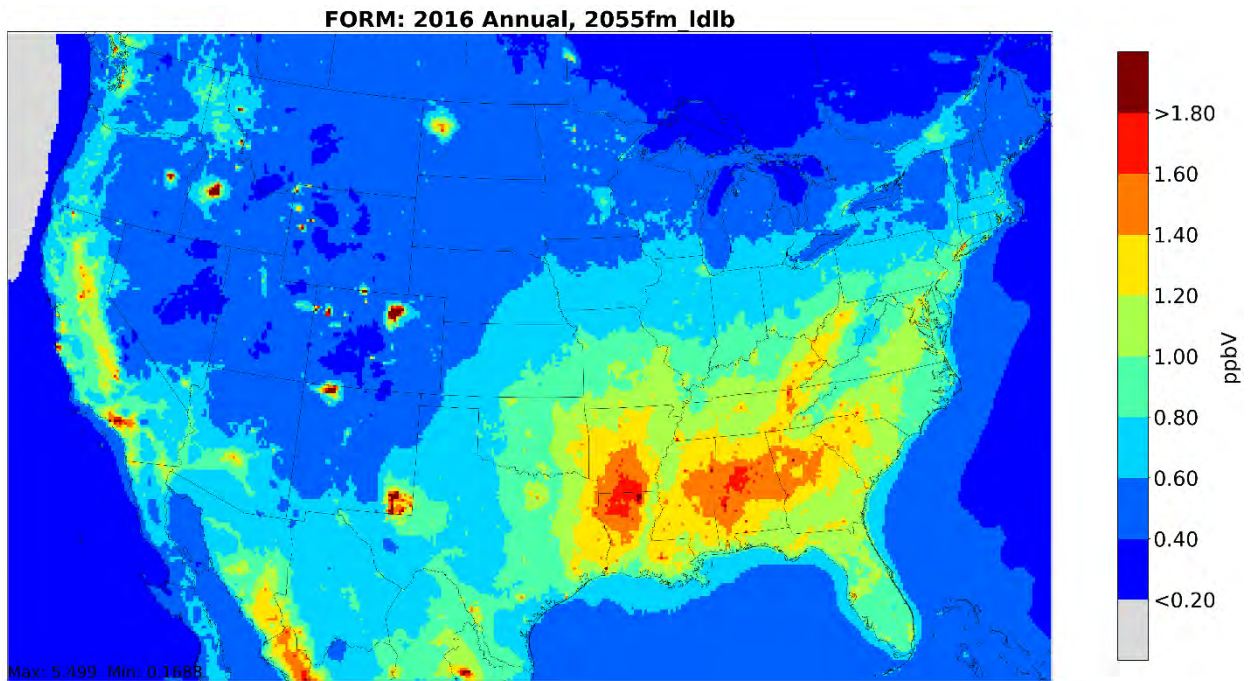


Figure 8-23 Projected Illustrative Annual Average Formaldehyde Concentrations in 2055 LMDV Regulatory Scenario ($\mu\text{g}/\text{m}^3$)

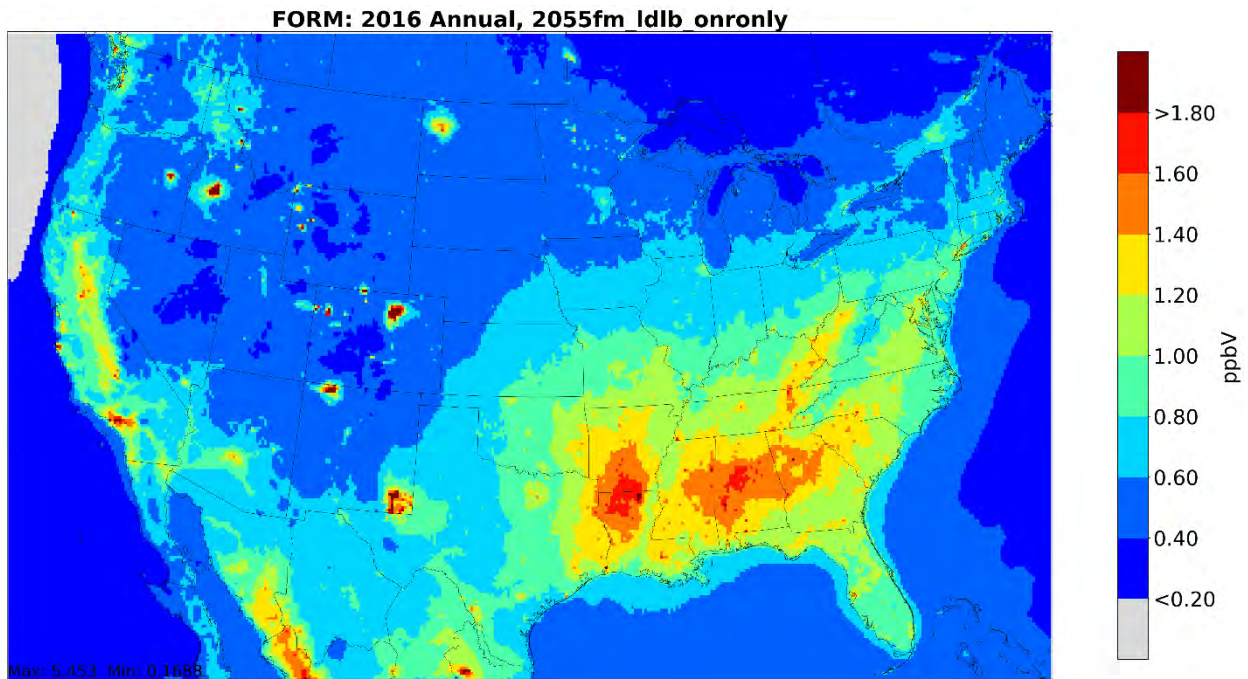


Figure 8-24 Projected Illustrative Annual Average Formaldehyde Concentrations in 2055 Onroad-Only Scenario (ug/m^3)

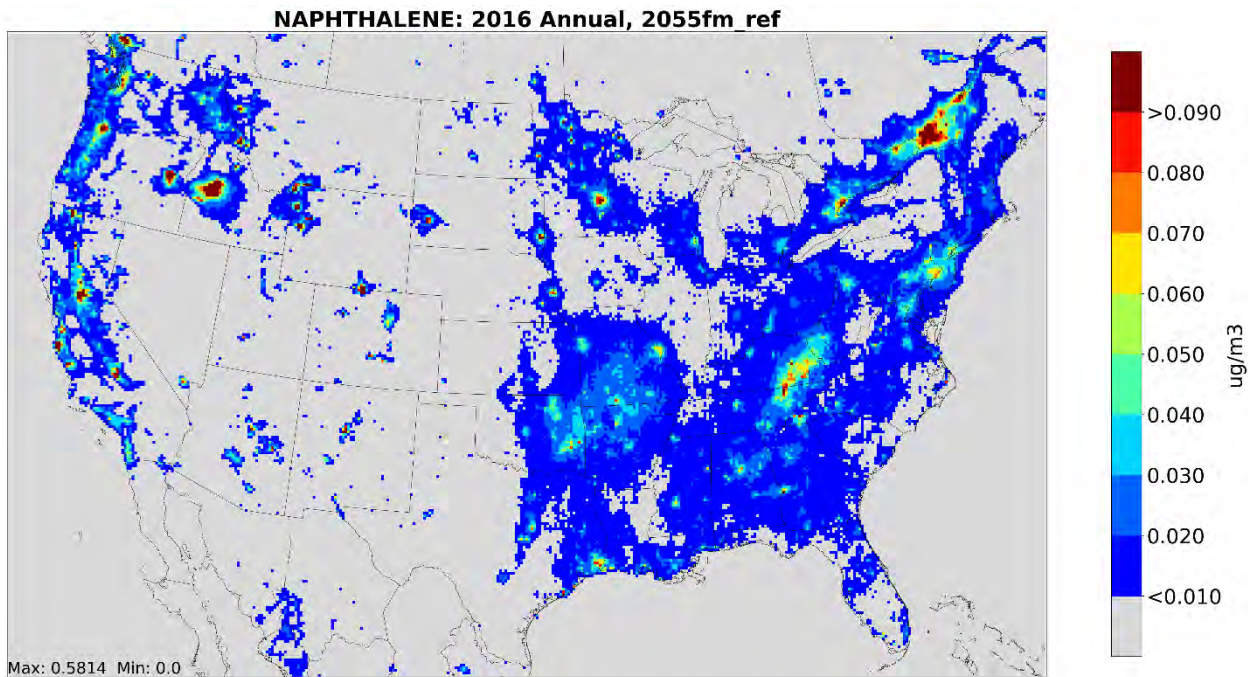


Figure 8-25 Projected Illustrative Annual Average Naphthalene Concentrations in 2055 Reference Case (ug/m^3)

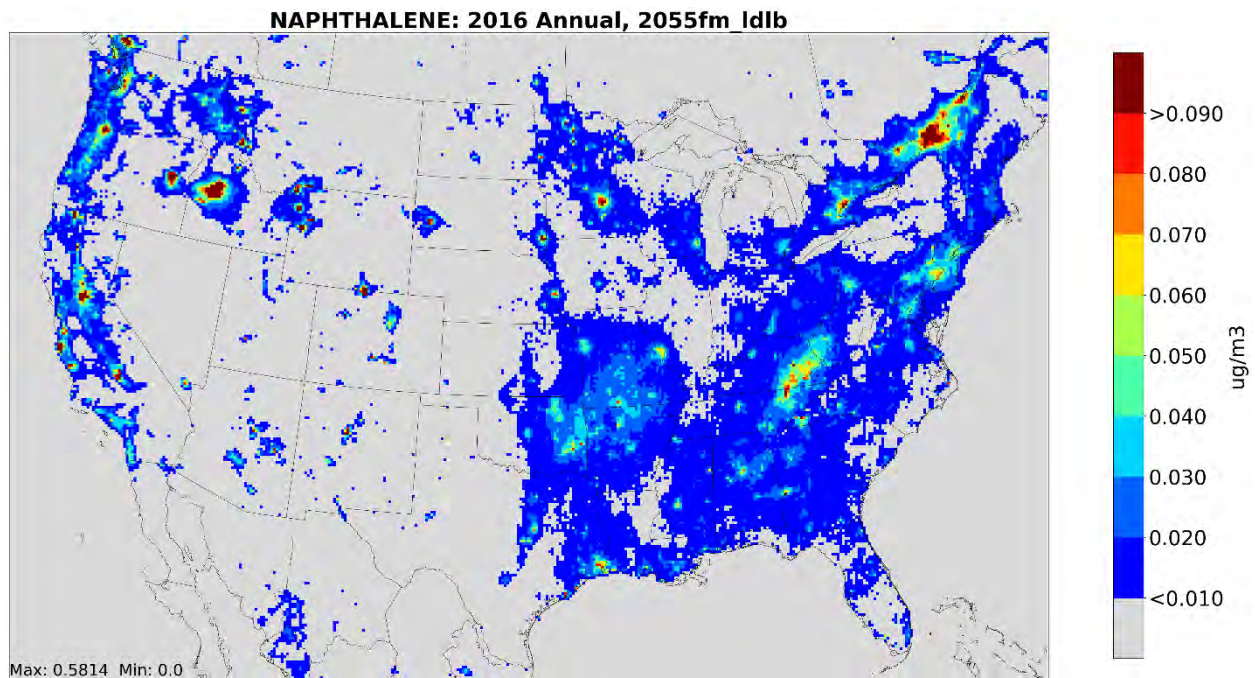


Figure 8-26 Projected Illustrative Annual Average Naphthalene Concentrations in 2055 LMDV Regulatory Scenario (ug/m³)

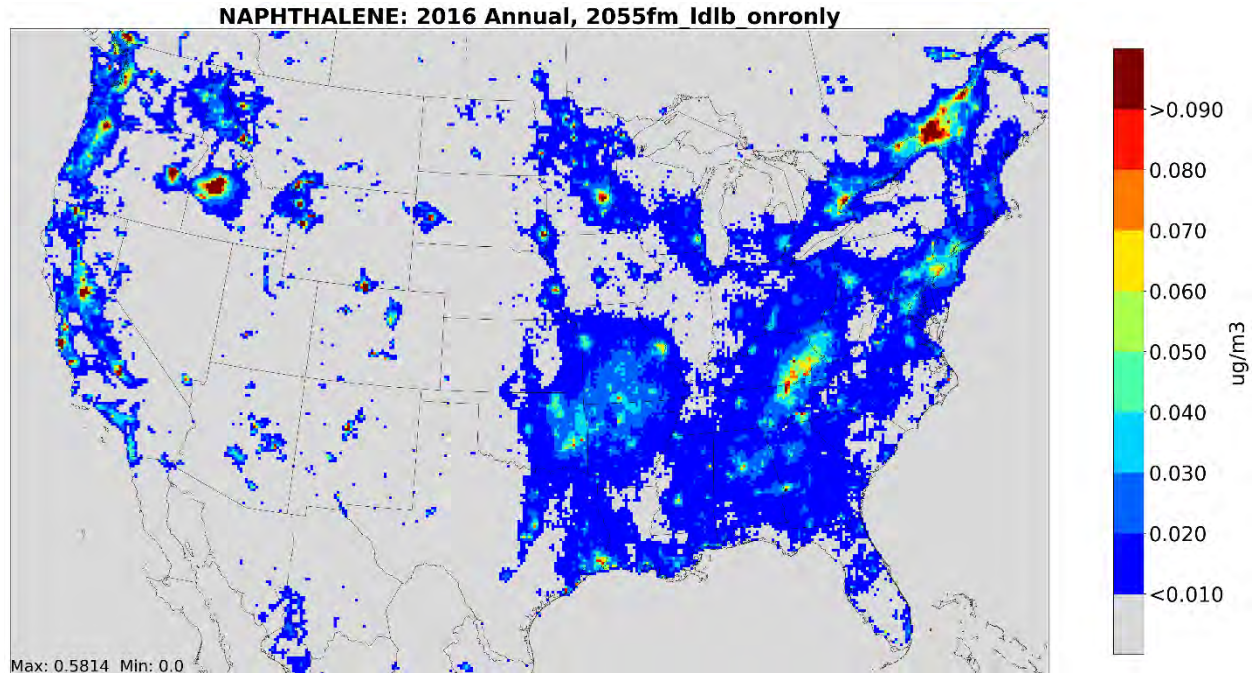


Figure 8-27 Projected Illustrative Annual Average Naphthalene Concentrations in 2055 Onroad-Only Scenario (ug/m³)

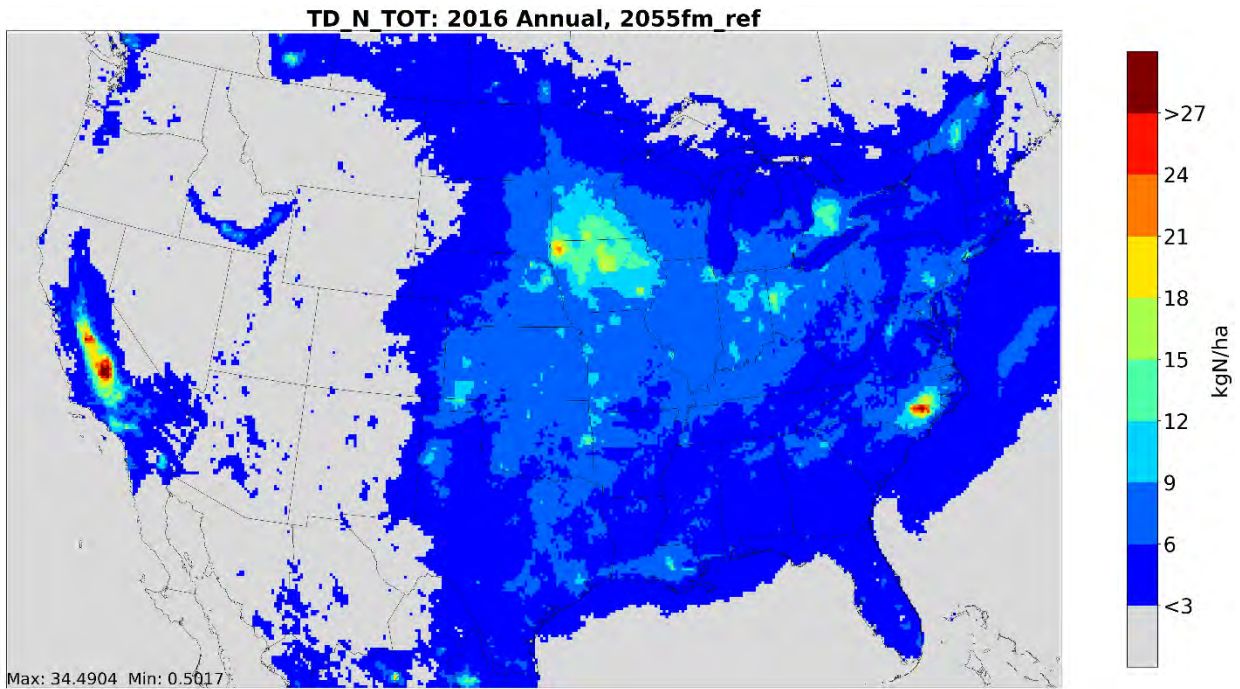


Figure 8-28 Projected Illustrative Annual Nitrogen Deposition in 2055 Reference Case (kg N/ha)

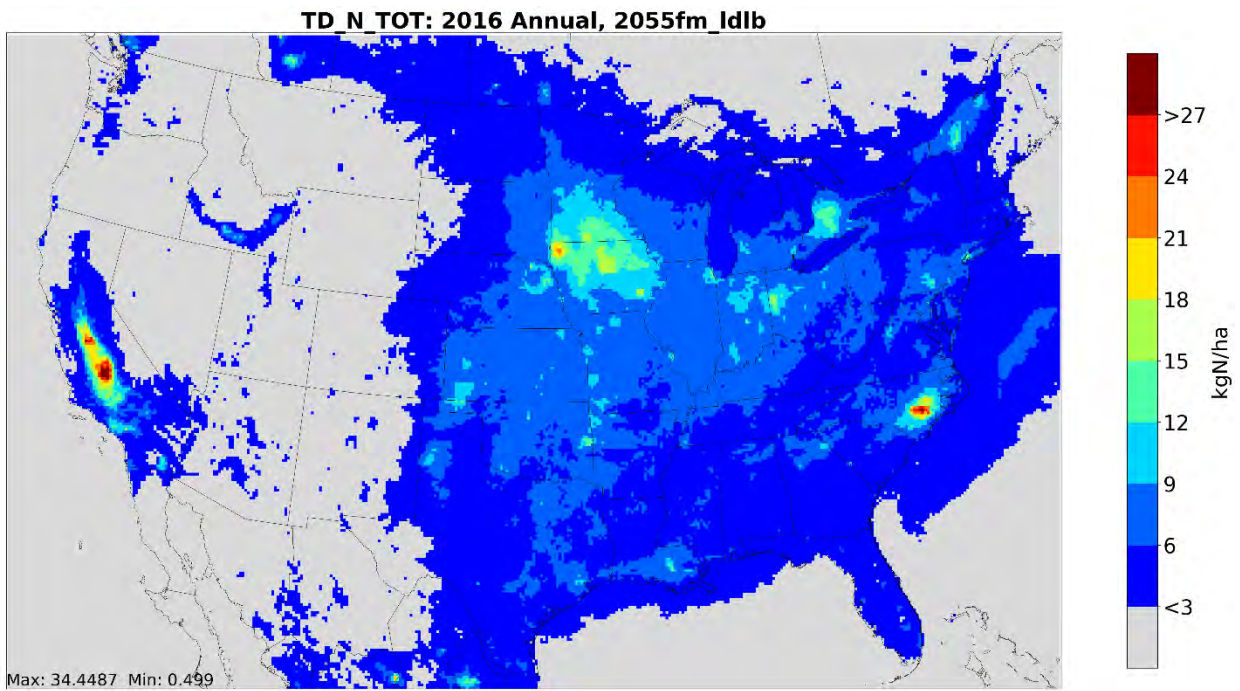


Figure 8-29 Projected Illustrative Annual Nitrogen Deposition in 2055 LMDV Regulatory Scenario (kg N/ha)

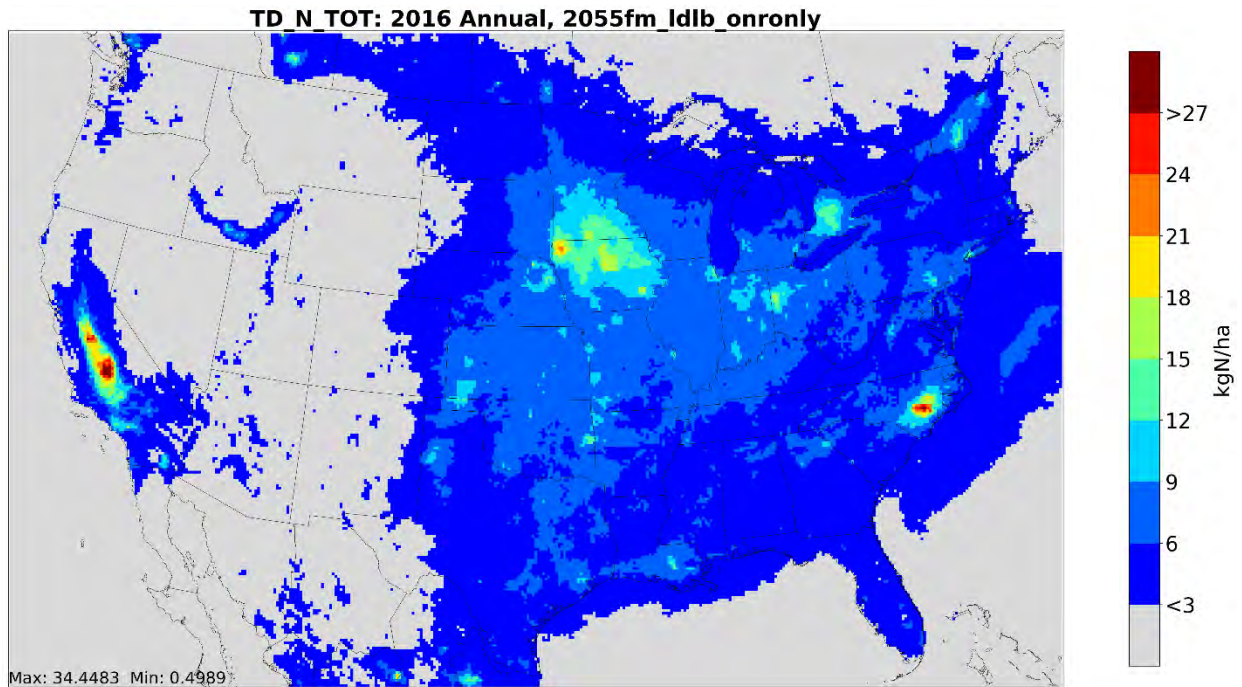


Figure 8-30 Projected Illustrative Annual Nitrogen Deposition in 2055 Onroad-Only Scenario (kg N/ha)

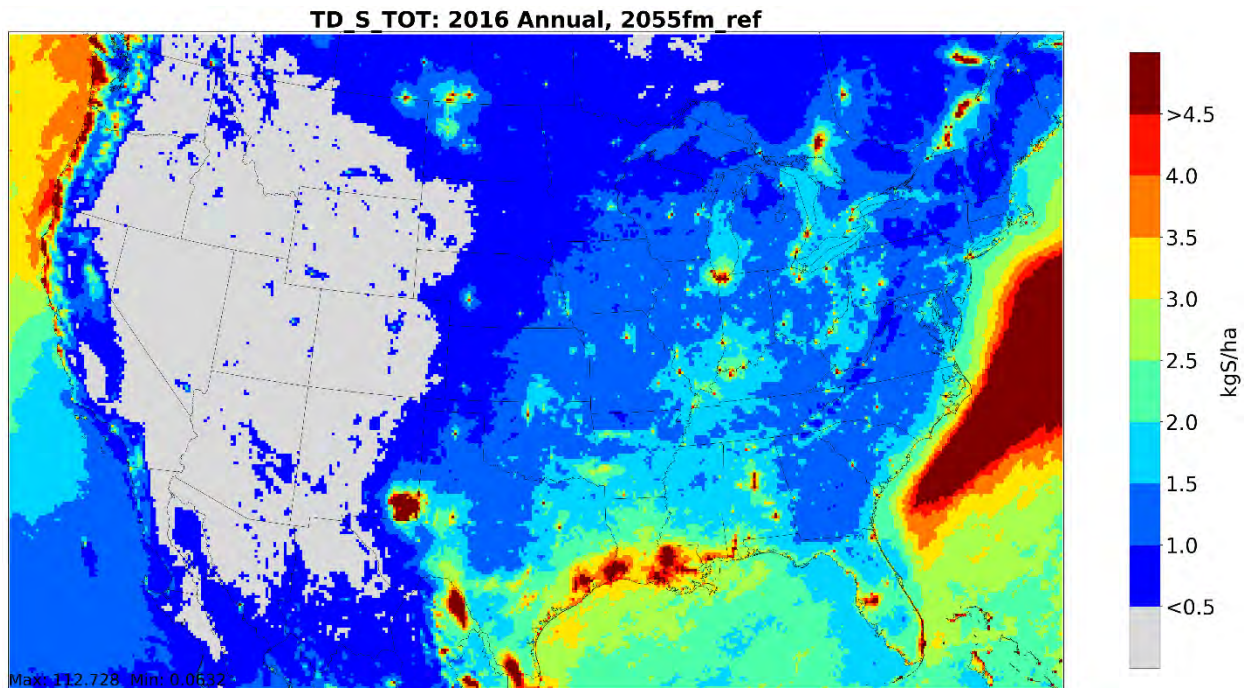


Figure 8-31 Projected Illustrative Annual Sulfur Deposition in 2055 Reference Case (kg S/ha)

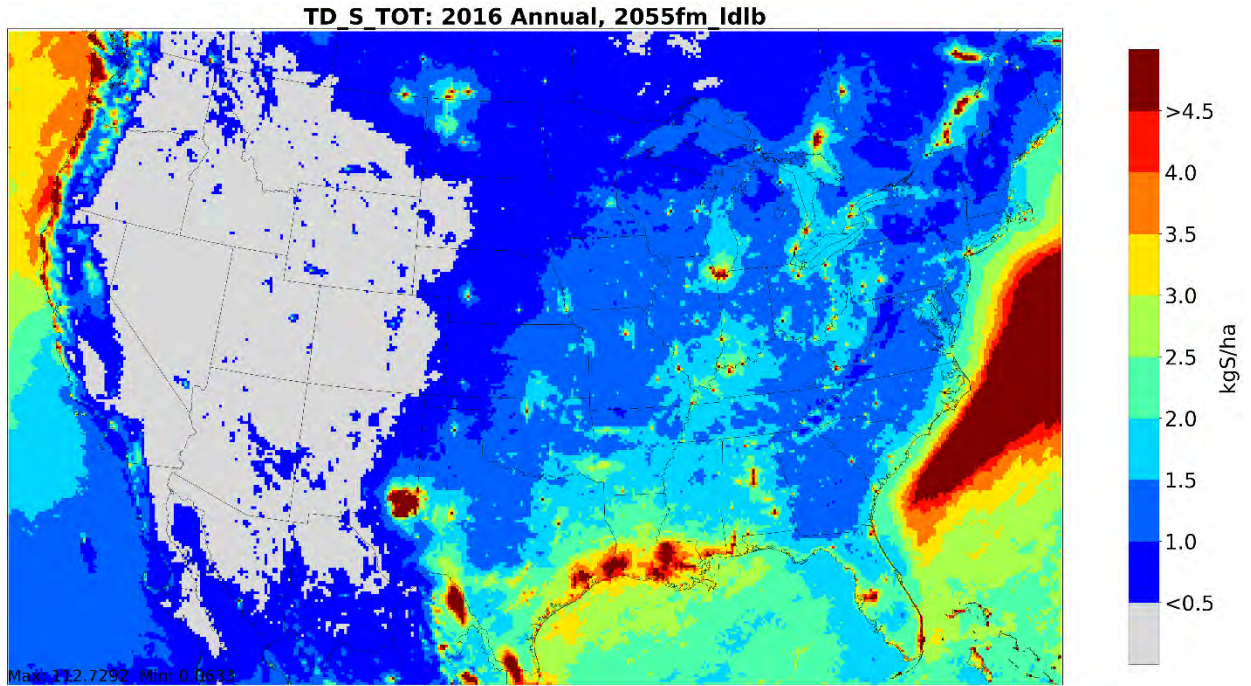


Figure 8-32 Projected Illustrative Annual Sulfur Deposition in 2055 LMDV Regulatory Scenario (kg S/ha)

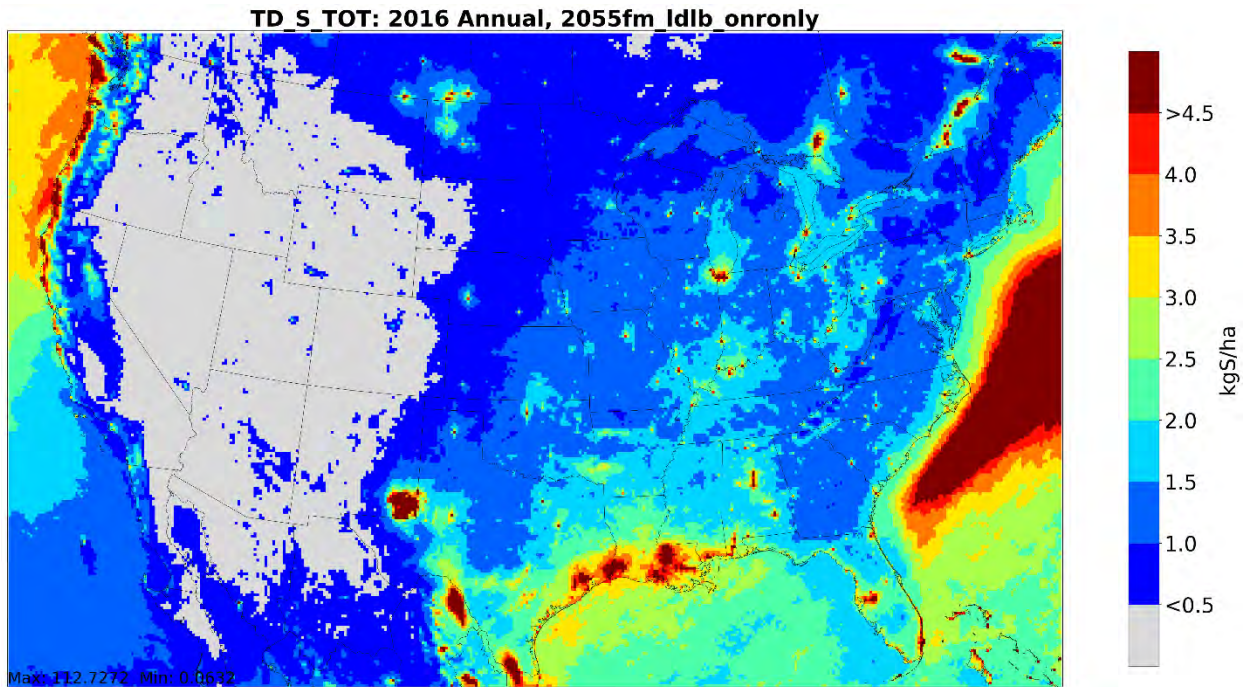


Figure 8-33 Projected Illustrative Annual Sulfur Deposition in 2055 Onroad-Only Scenario (kg S/ha)

8.2 Seasonal Air Toxics Maps

The following section presents maps of January and July monthly average ambient concentrations of acetaldehyde, benzene, formaldehyde and naphthalene in the 2055 reference case and the 2055 LMDV regulatory scenario. Also presented are maps of January and July monthly average changes in ambient concentrations of acetaldehyde, benzene, formaldehyde and naphthalene in 2055.

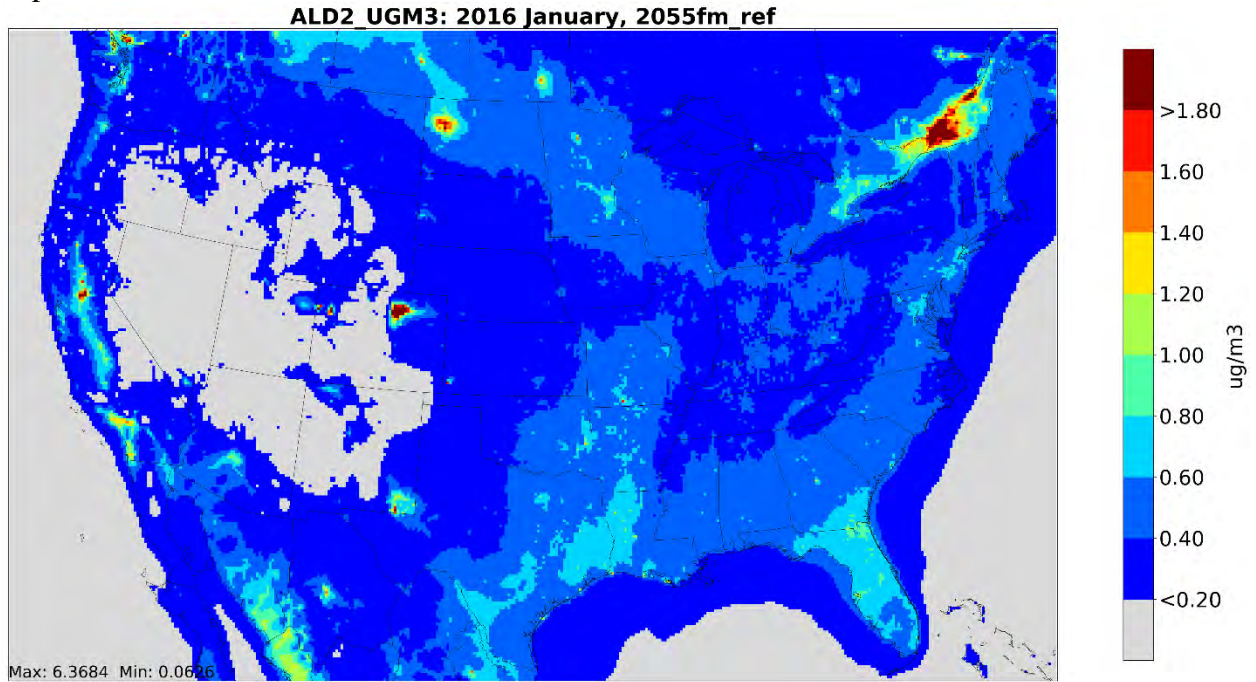


Figure 8-34 Projected Illustrative January Average Acetaldehyde Concentrations in 2055 Reference Case (ug/m³)

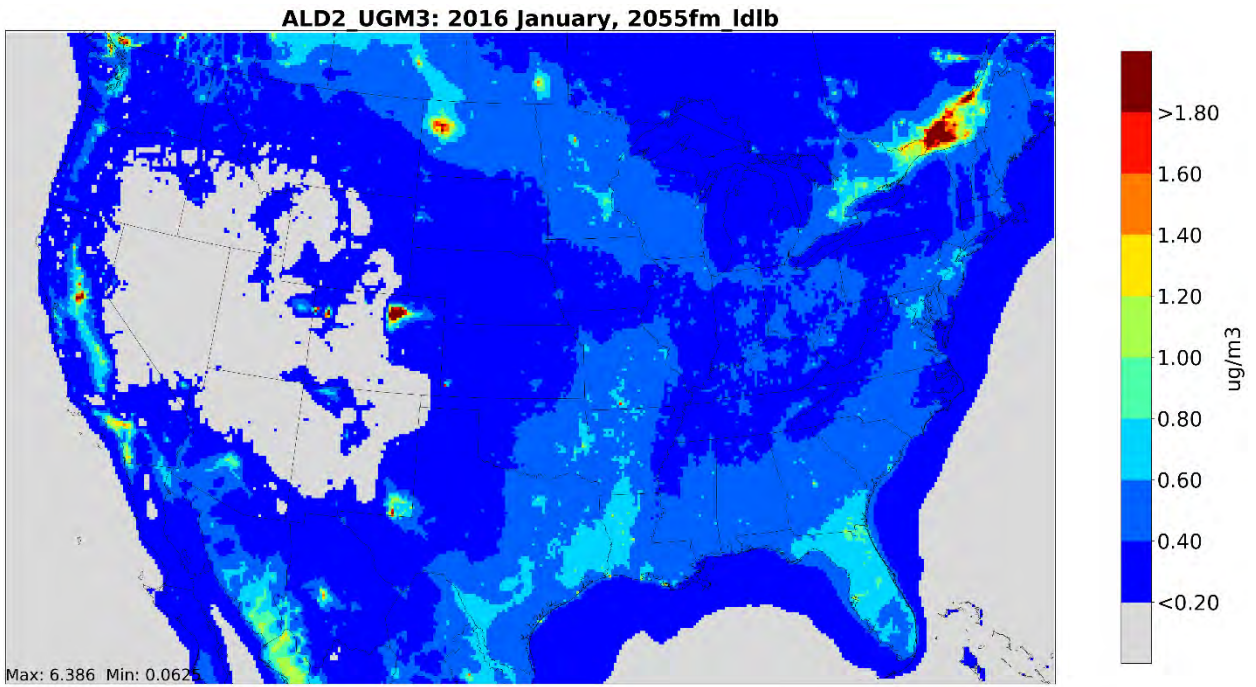


Figure 8-35 Projected Illustrative January Average Acetaldehyde Concentrations in 2055 LMDV Regulatory Scenario

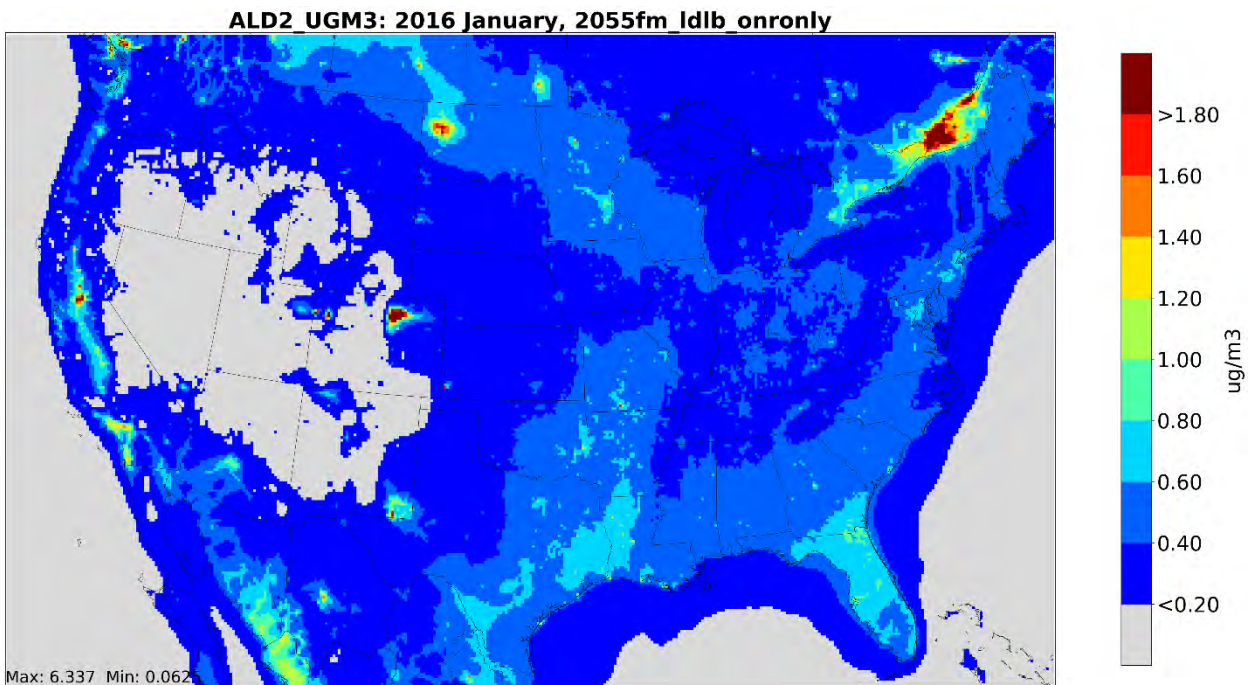


Figure 8-36 Projected Illustrative January Average Acetaldehyde Concentrations in 2055 Onroad-Only Scenario

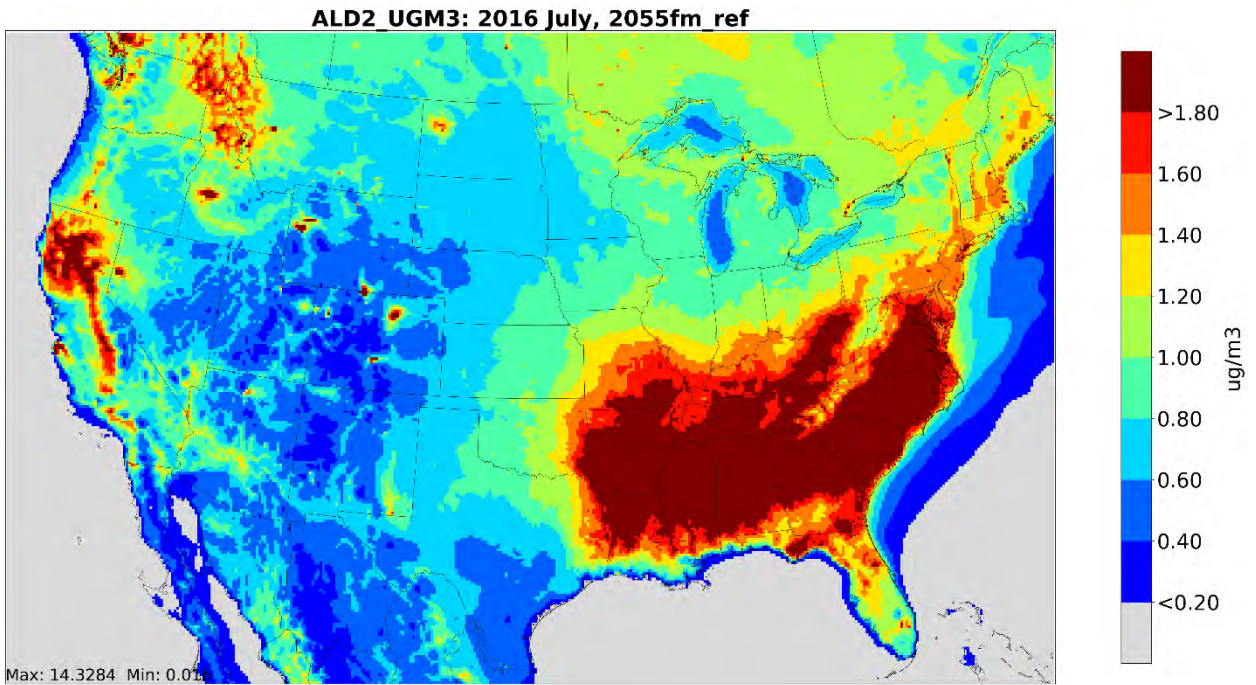


Figure 8-37 Projected Illustrative July Average Acetaldehyde Concentrations in 2055 Reference Case

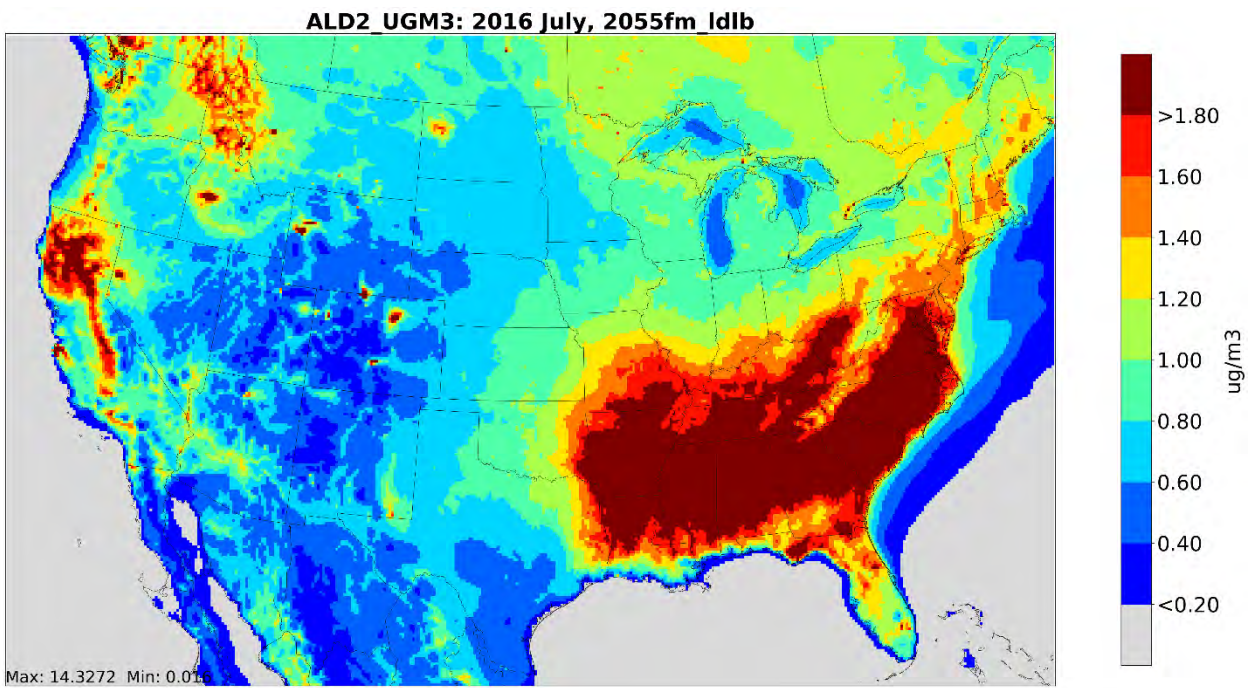


Figure 8-38 Projected Illustrative July Average Acetaldehyde Concentrations in 2055 LMDV Regulatory Scenario

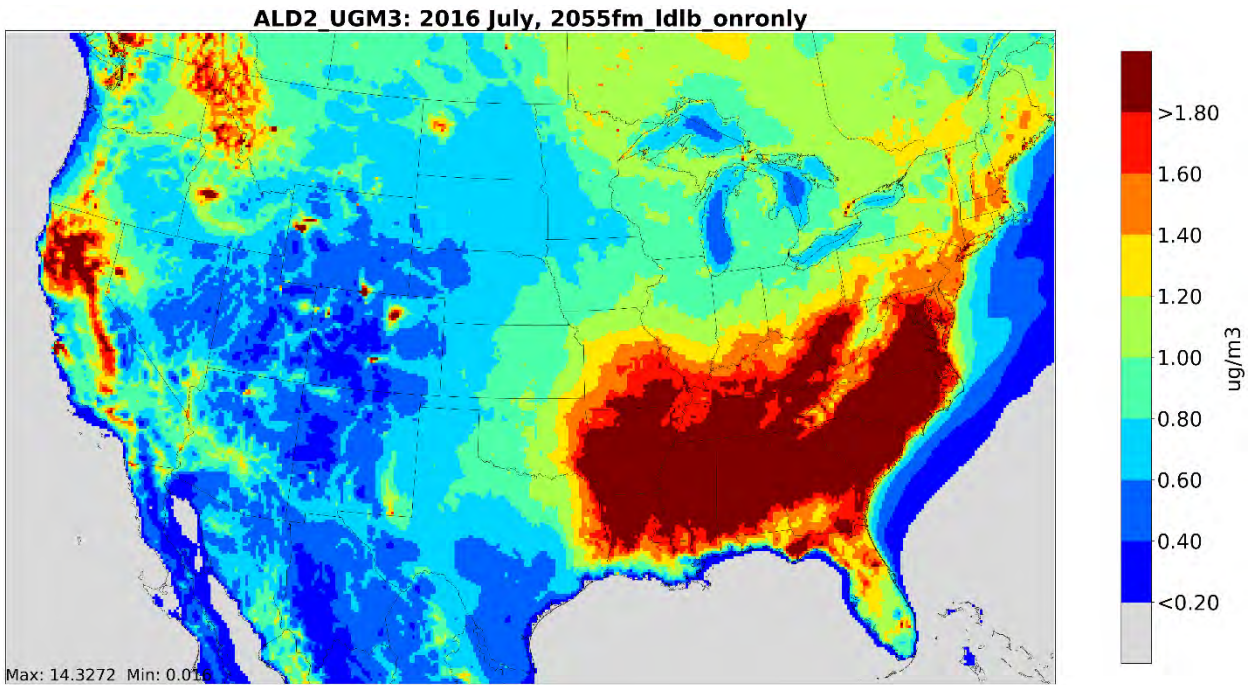


Figure 8-39 Projected Illustrative July Average Acetaldehyde Concentrations in 2055 Onroad-Only Scenario

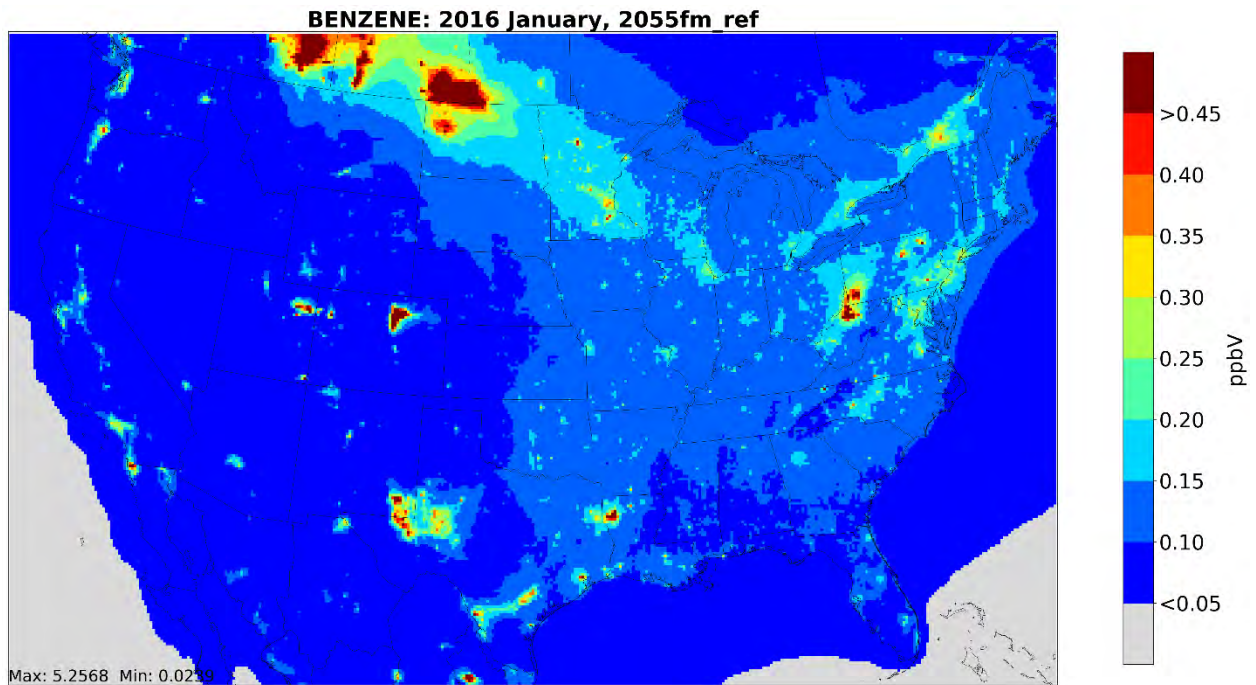


Figure 8-40 Projected Illustrative January Average Benzene Concentrations in 2055 Reference Case

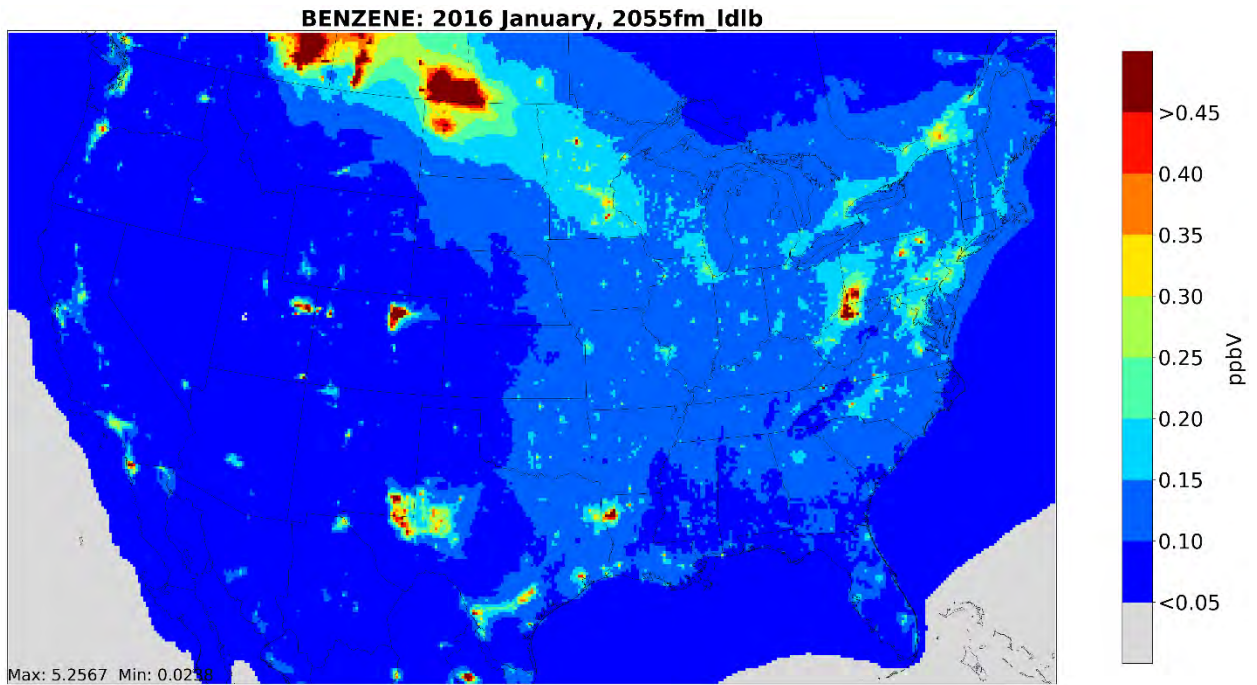


Figure 8-41 Projected Illustrative January Average Benzene Concentrations in 2055 LMDV Regulatory Scenario

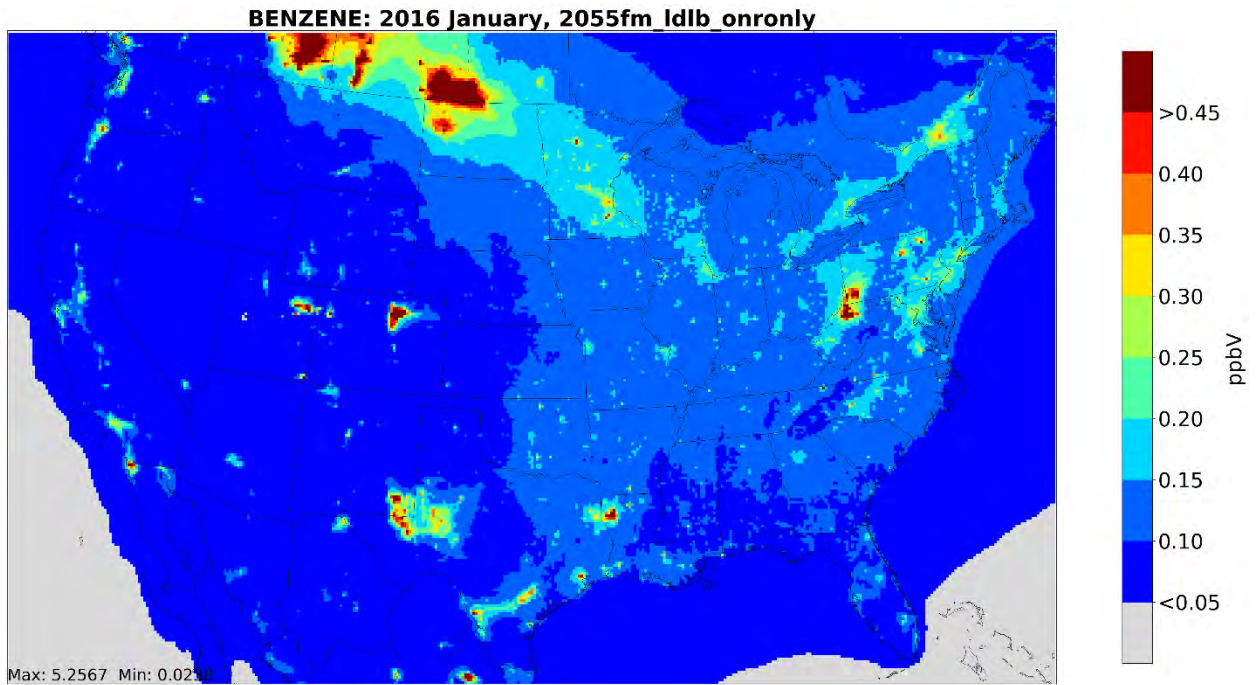


Figure 8-42 Projected Illustrative January Average Benzene Concentrations in 2055 Onroad-Only Scenario

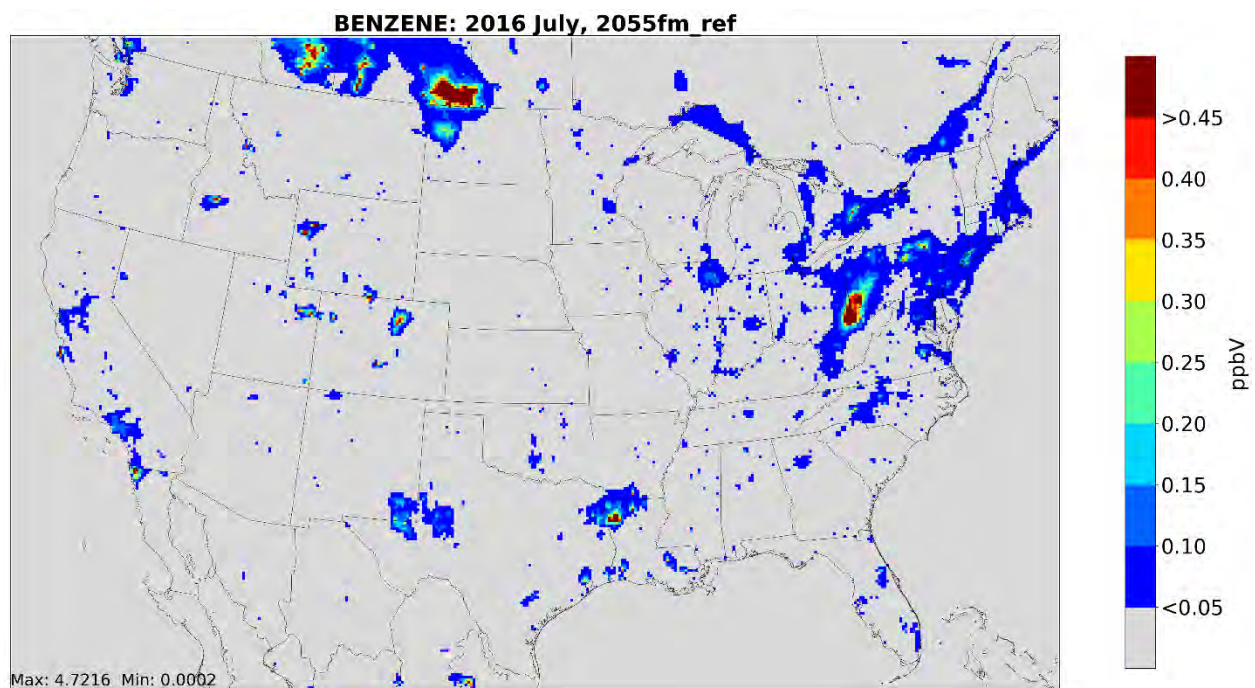


Figure 8-43 Projected Illustrative July Average Benzene Concentrations in 2055 Reference Case

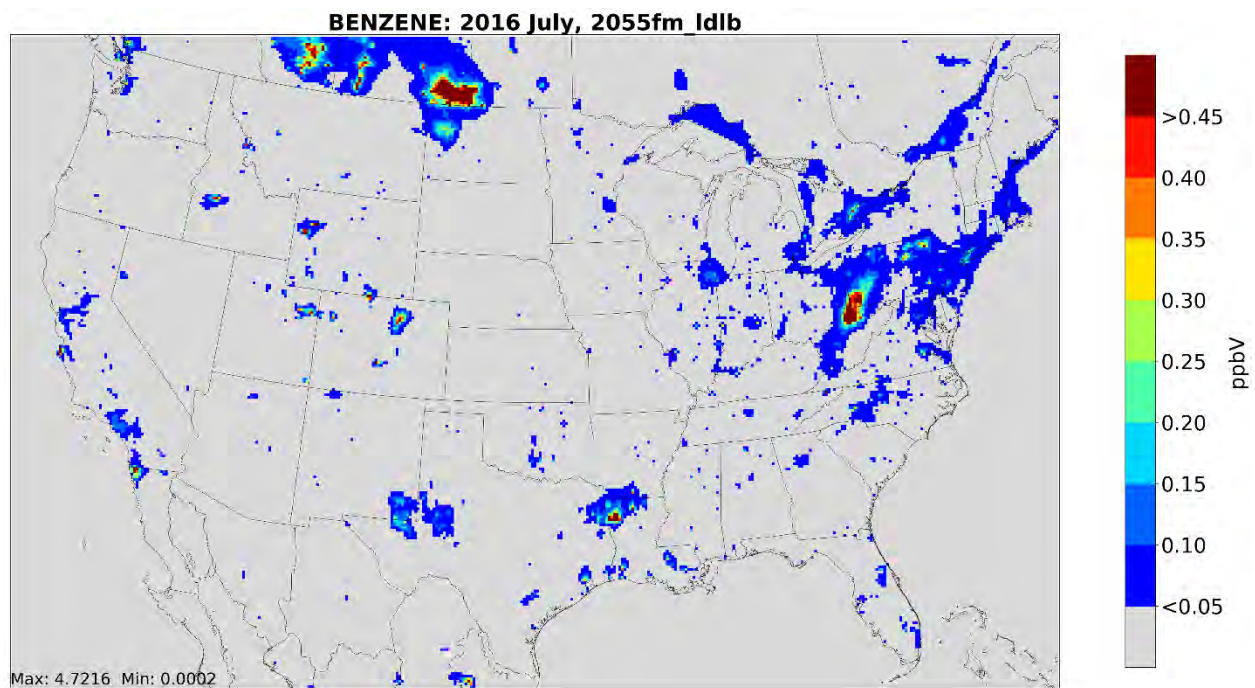


Figure 8-44 Projected Illustrative July Average Benzene Concentrations in 2055 LMDV Regulatory Scenario

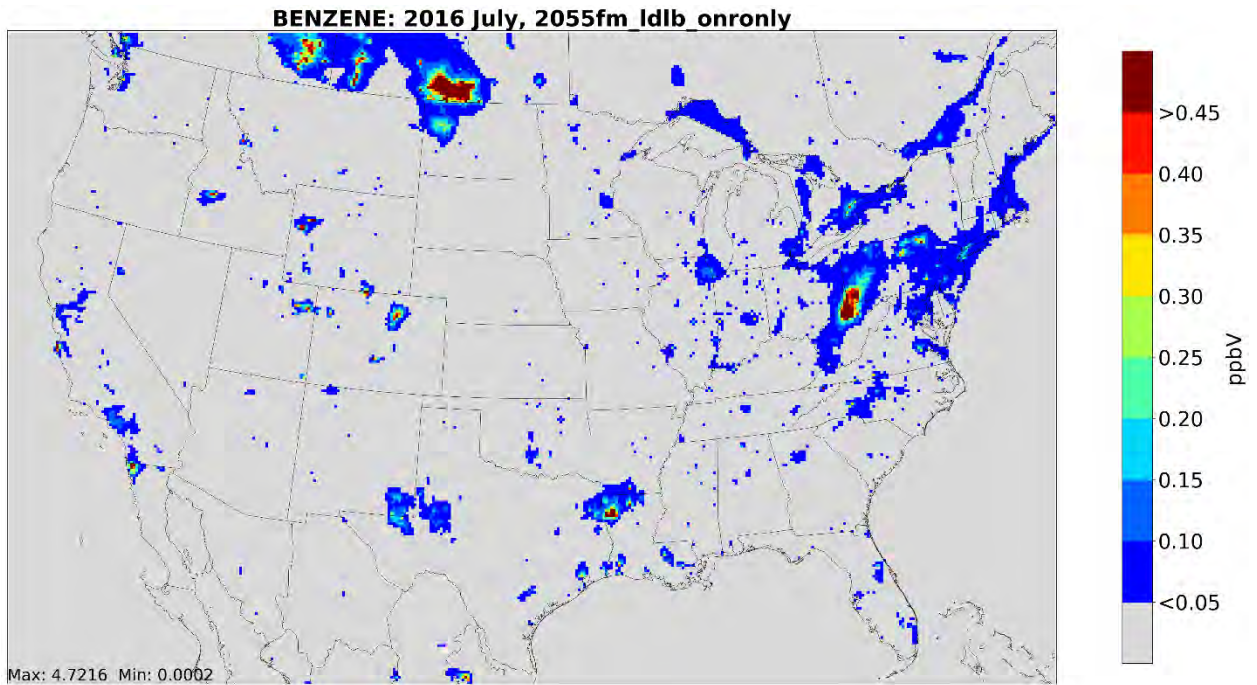


Figure 8-45 Projected Illustrative July Average Benzene Concentrations in 2055 Onroad-Only Scenario

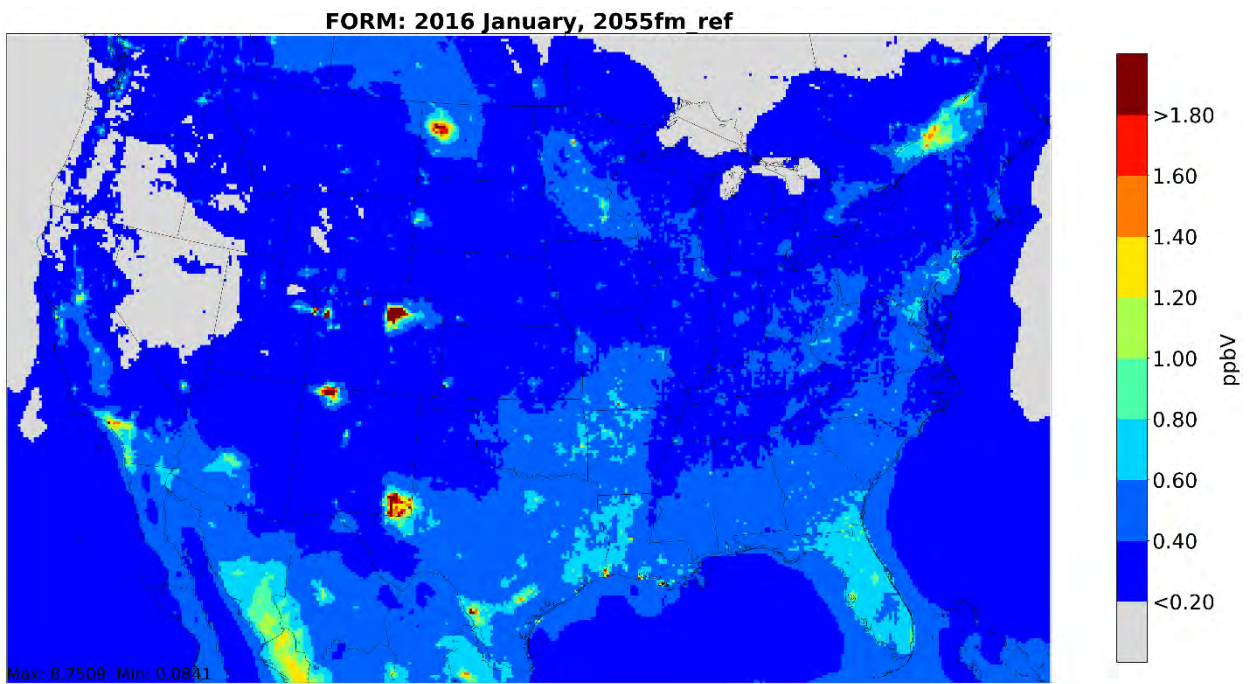


Figure 8-46 Projected Illustrative January Average Formaldehyde Concentrations in 2055 Reference Case

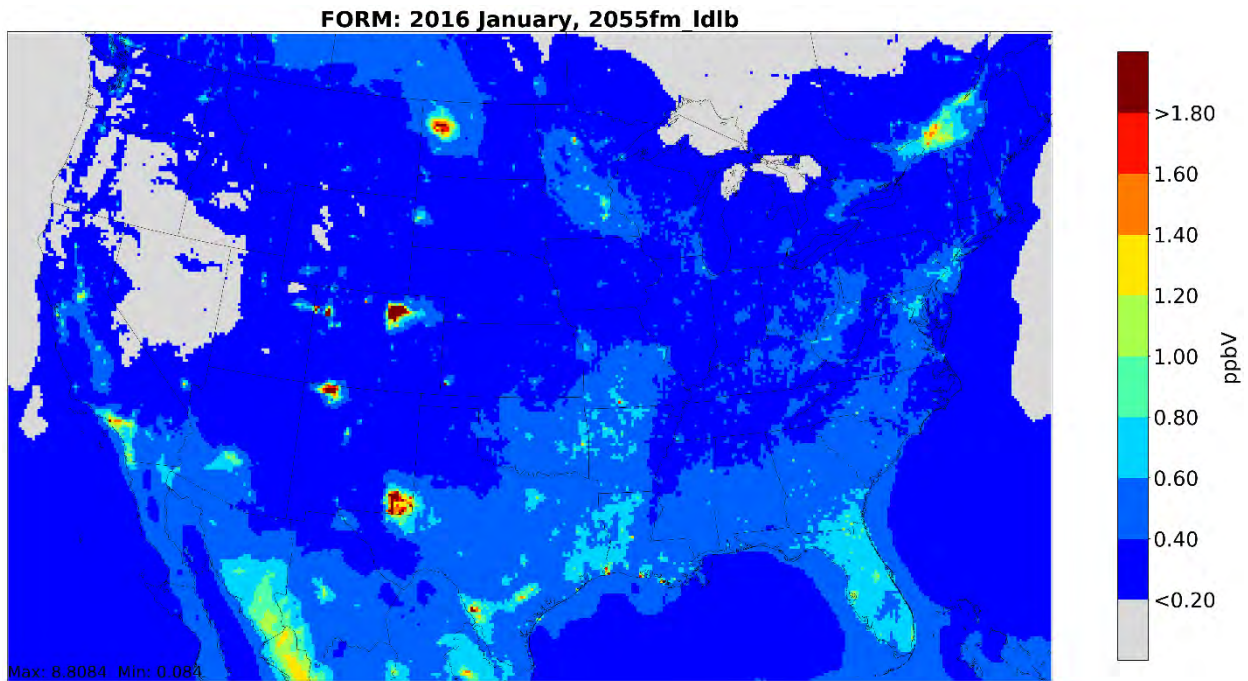


Figure 8-47 Projected Illustrative January Average Formaldehyde Concentrations in 2055 LMDV Regulatory Scenario

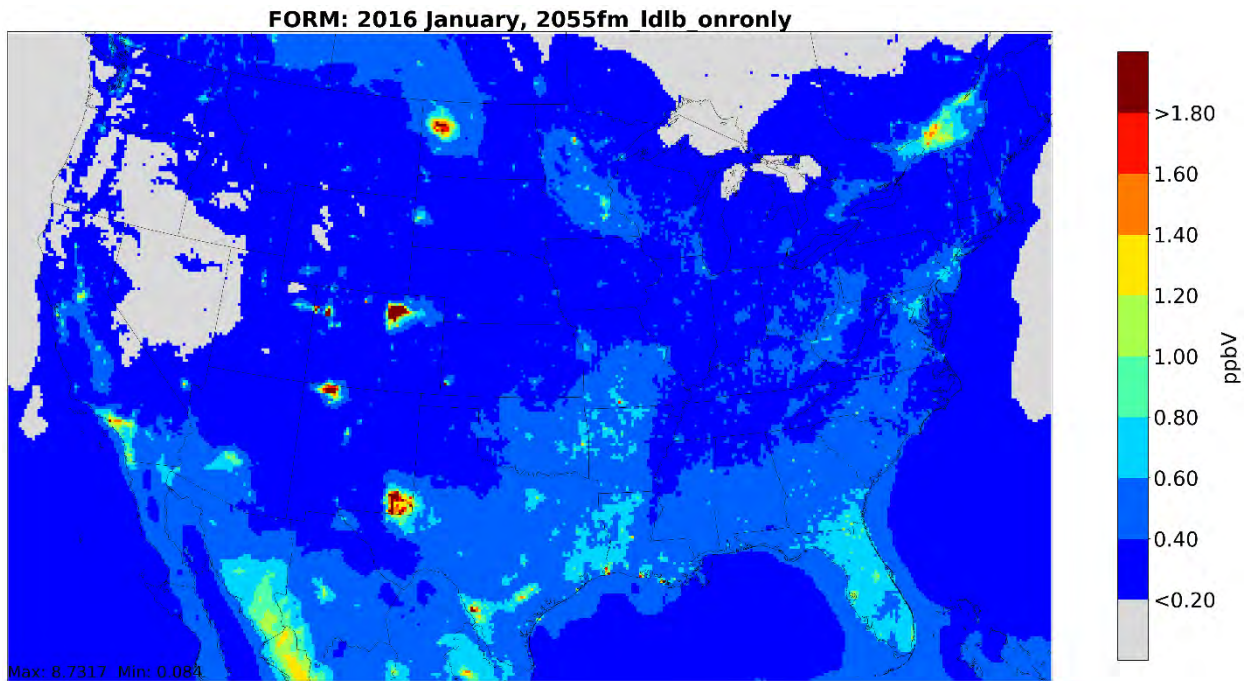


Figure 8-48 Projected Illustrative January Average Formaldehyde Concentrations in 2055 Onroad-Only Scenario

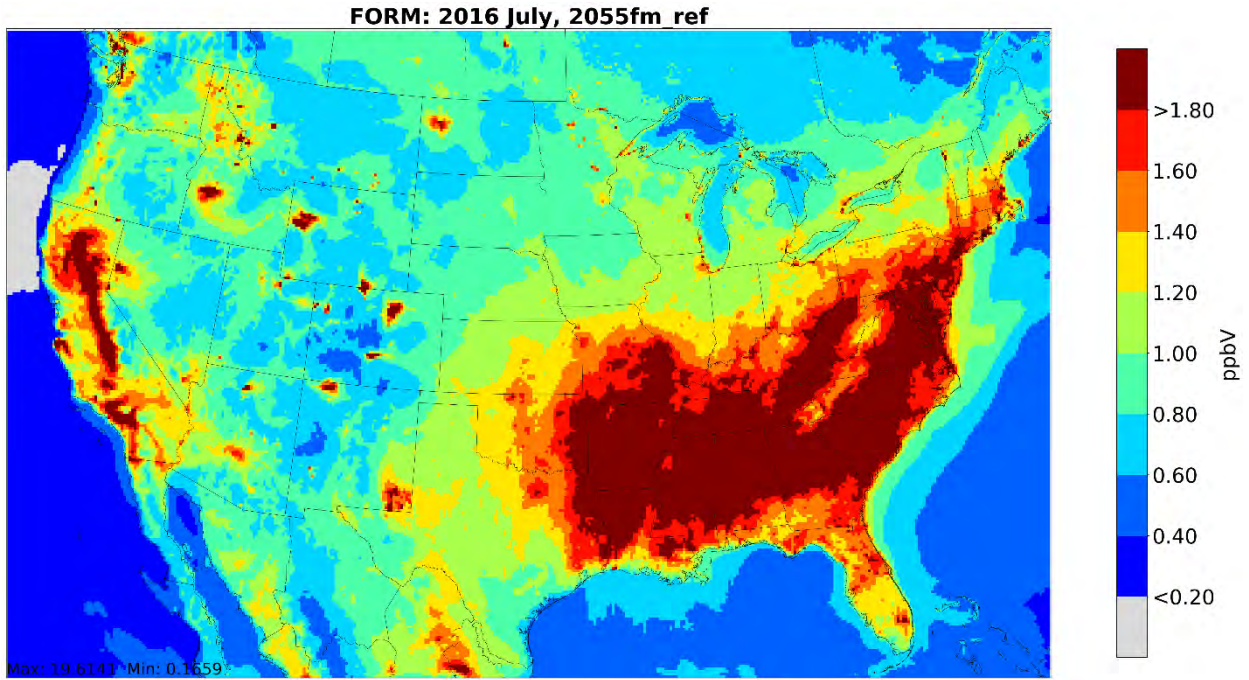


Figure 8-49 Projected Illustrative July Average Formaldehyde Concentrations in 2055 Reference Case

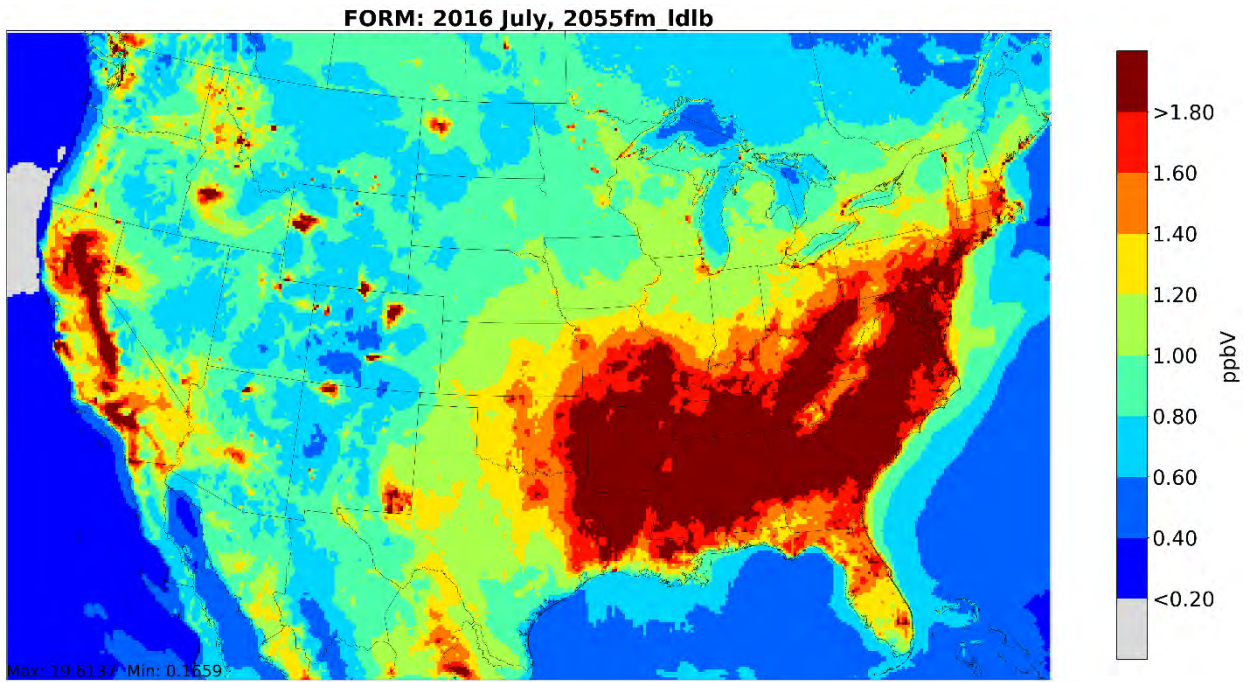


Figure 8-50 Projected Illustrative July Average Formaldehyde Concentrations in 2055 LMDV Regulatory Scenario

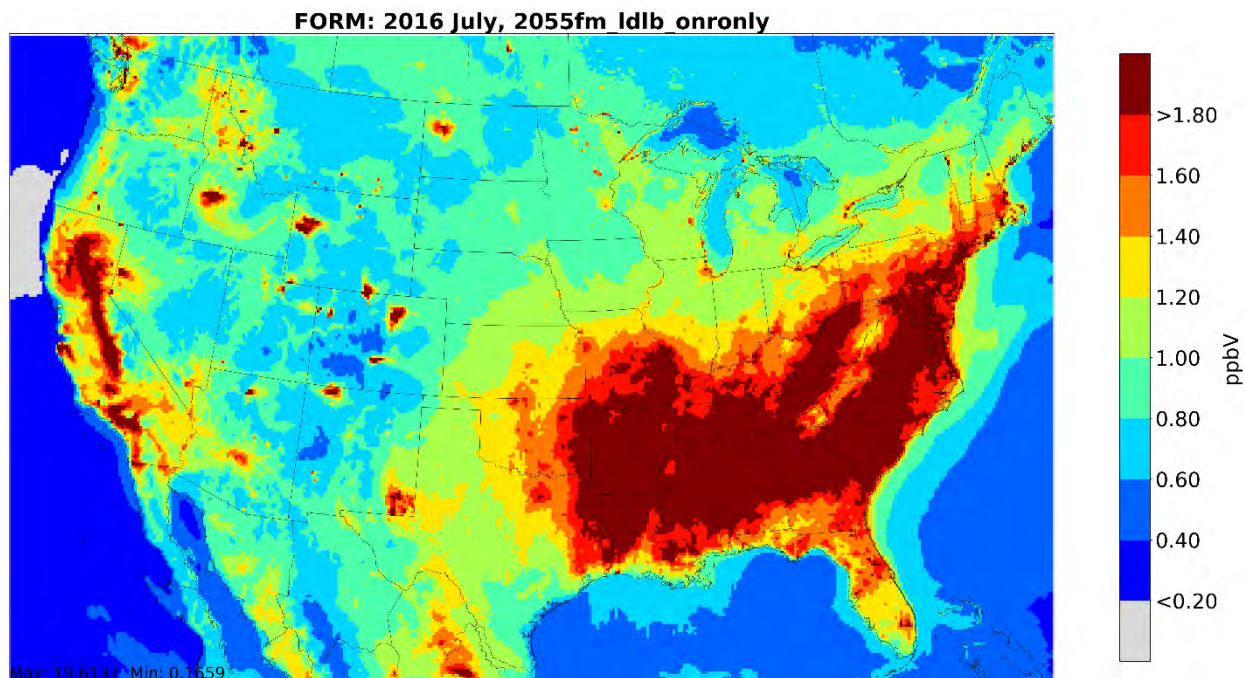


Figure 8-51 Projected Illustrative July Average Formaldehyde Concentrations in 2055 Onroad-Only Scenario

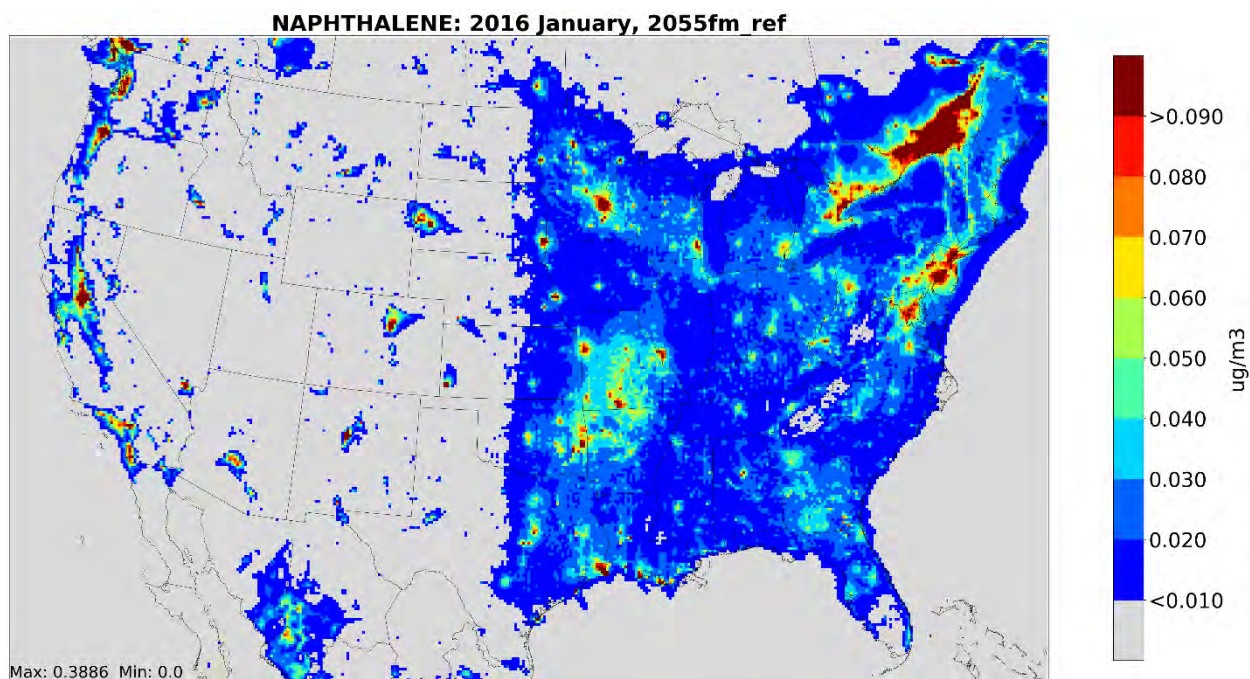


Figure 8-52 Projected Illustrative January Average Naphthalene Concentrations in 2055 Reference Case

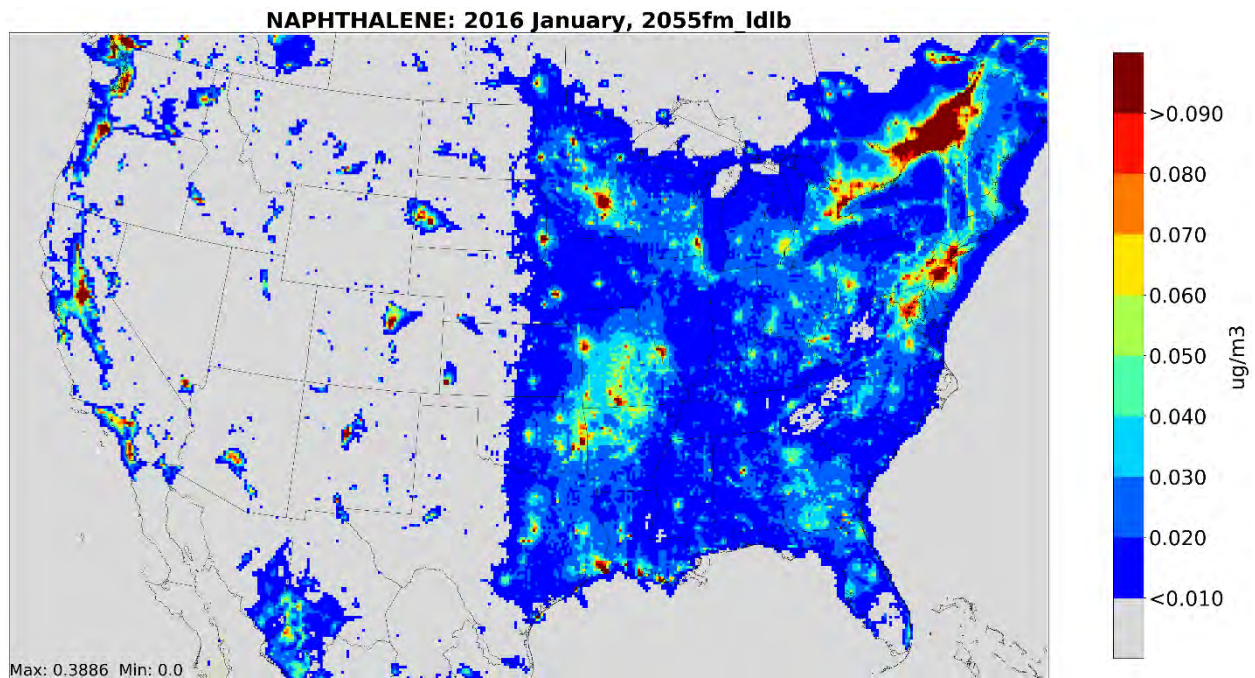


Figure 8-53 Projected Illustrative January Average Naphthalene Concentrations in 2055 LMDV Regulatory Scenario

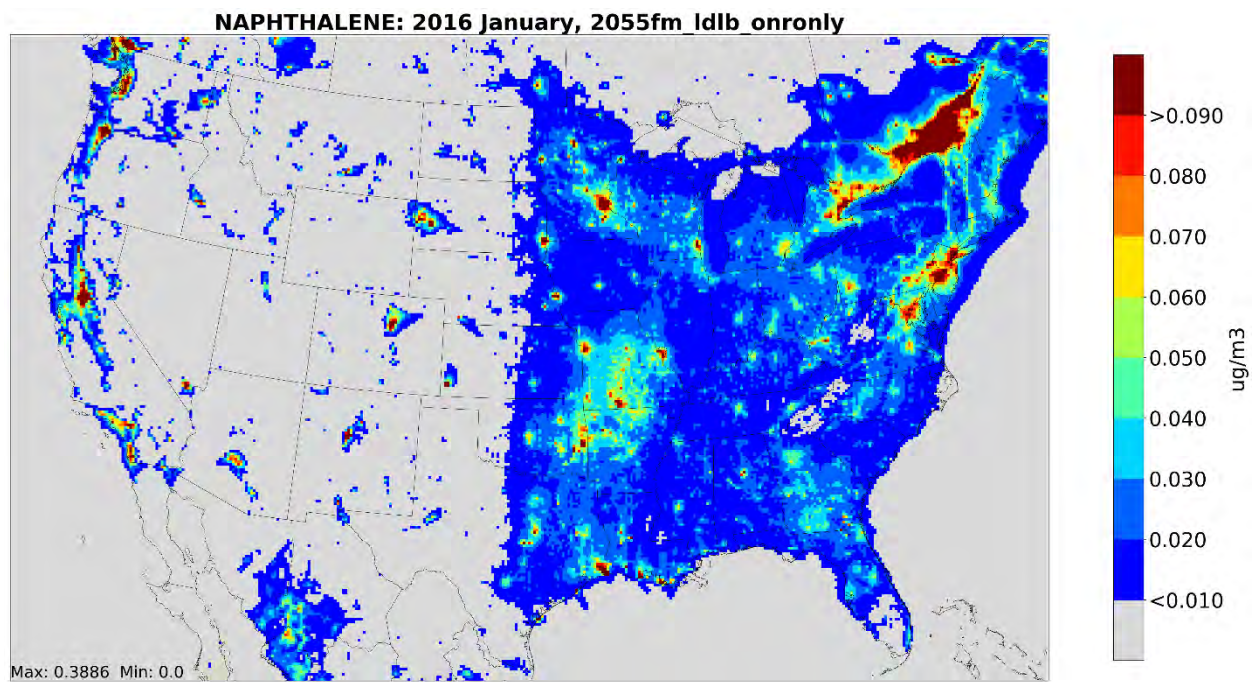


Figure 8-54 Projected Illustrative January Average Naphthalene Concentrations in 2055 Onroad-Only Scenario

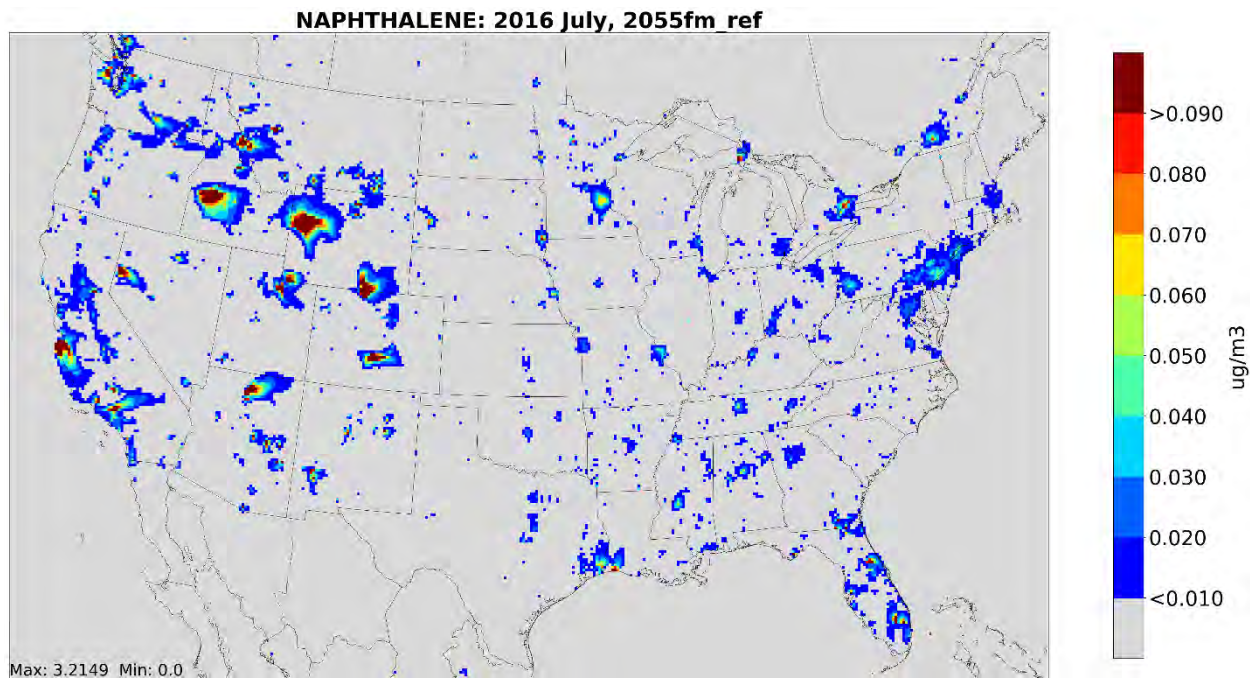


Figure 8-55 Projected Illustrative July Average Naphthalene Concentrations in 2055 Reference Case

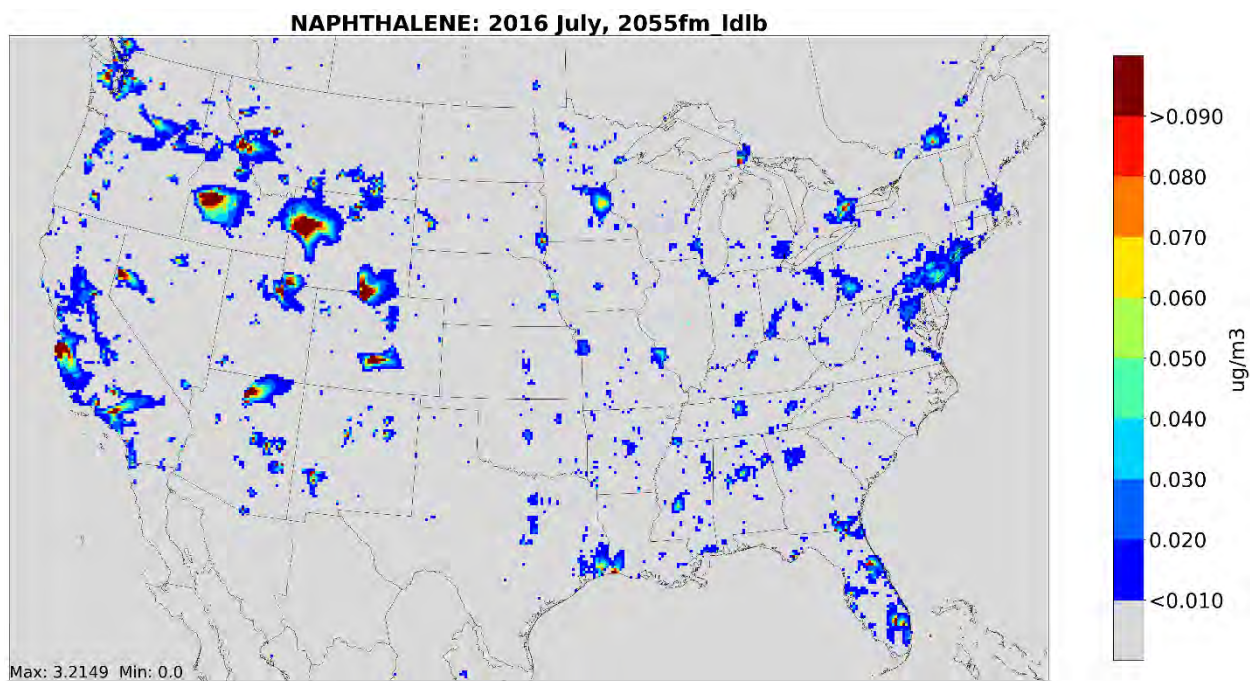


Figure 8-56 Projected Illustrative July Average Naphthalene Concentrations in 2055 LMDV Regulatory Scenario

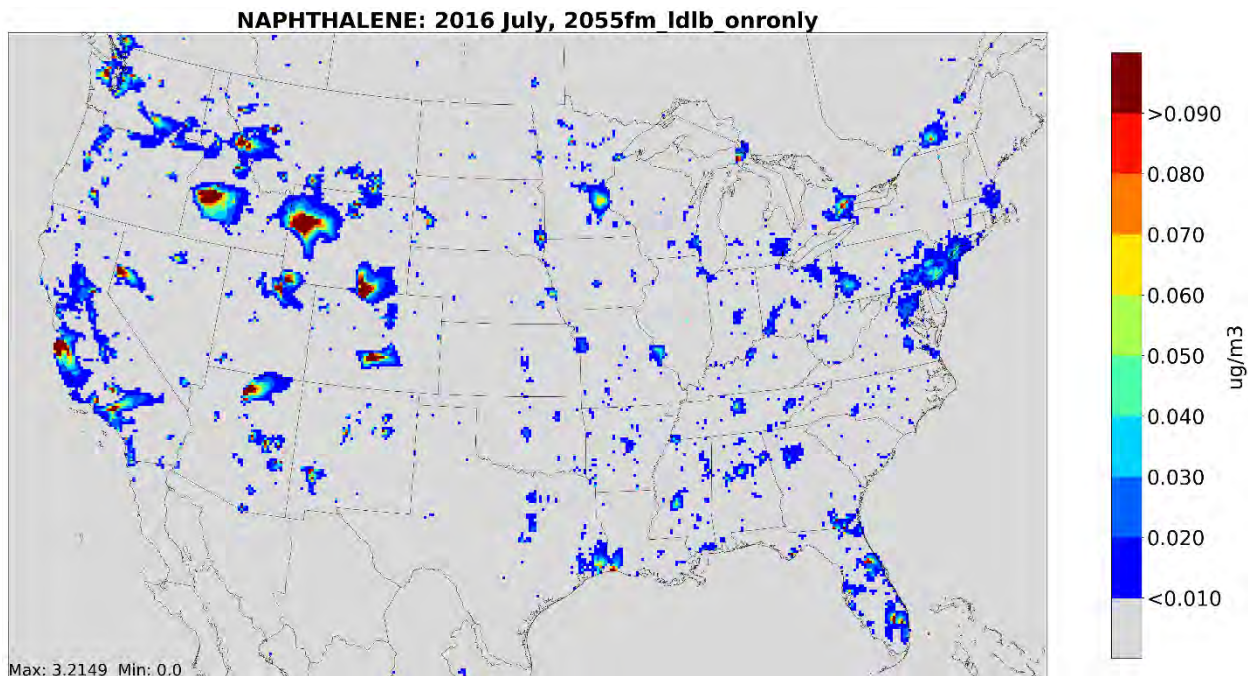


Figure 8-57 Projected Illustrative July Average Naphthalene Concentrations in 2055 Onroad-Only Scenario

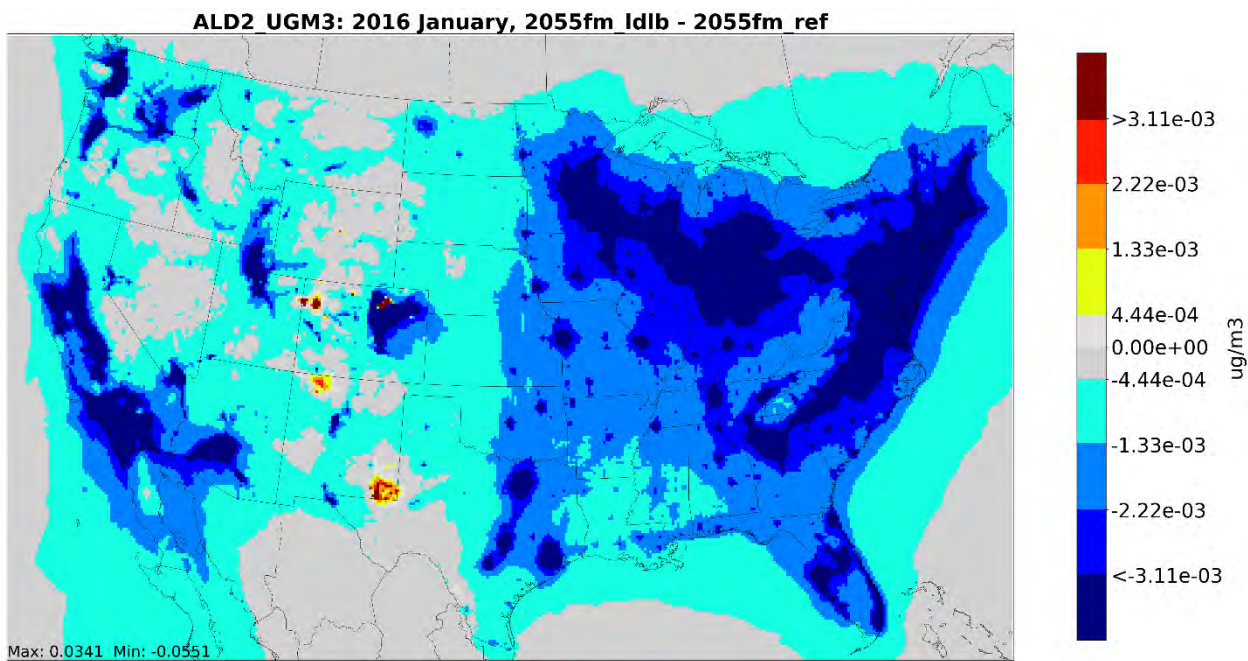


Figure 8-58 Projected Illustrative Changes in Average Acetaldehyde Concentrations in January 2055 due to LMDV Regulatory Scenario

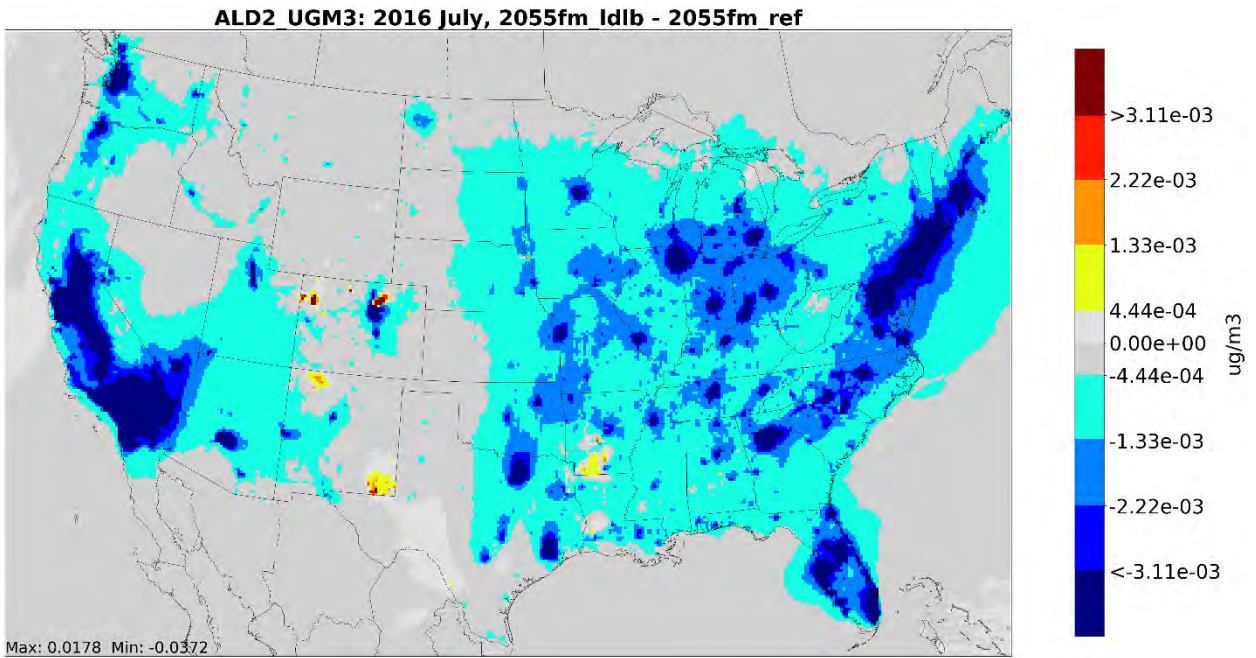


Figure 8-59 Projected Illustrative Changes in Average Acetaldehyde Concentrations in July 2055 due to LMDV Regulatory Scenario

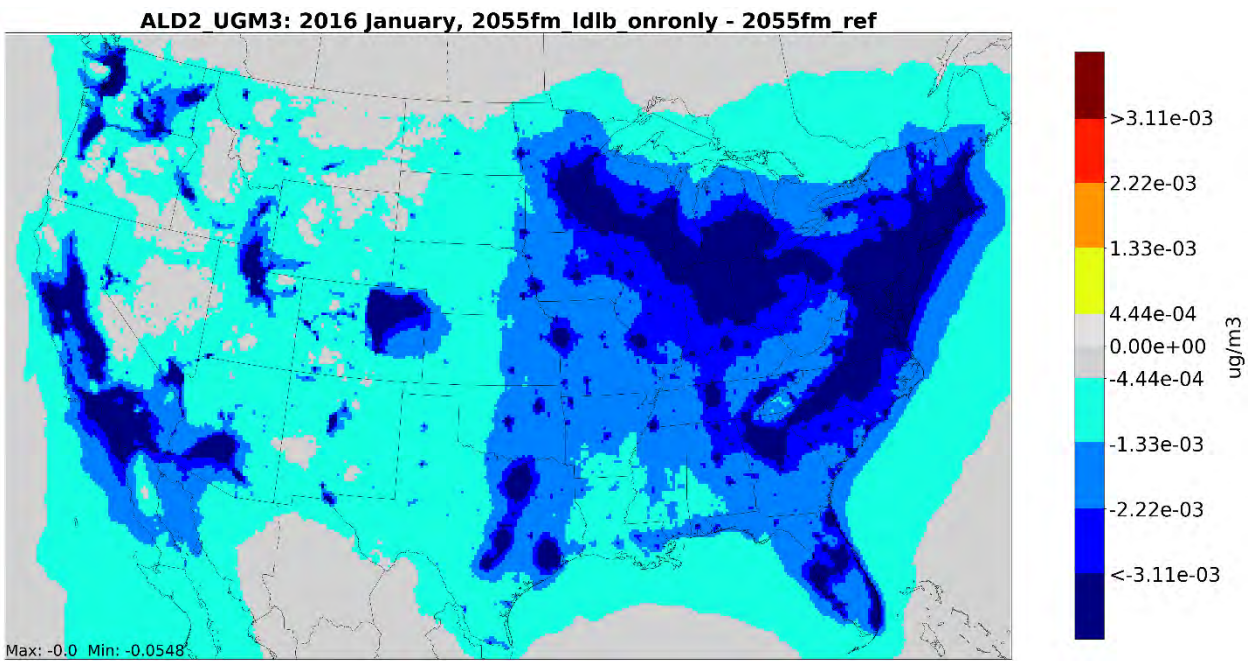


Figure 8-60 Projected Illustrative Changes in Average Acetaldehyde Concentrations in January 2055 from "Onroad Only" Emissions Changes

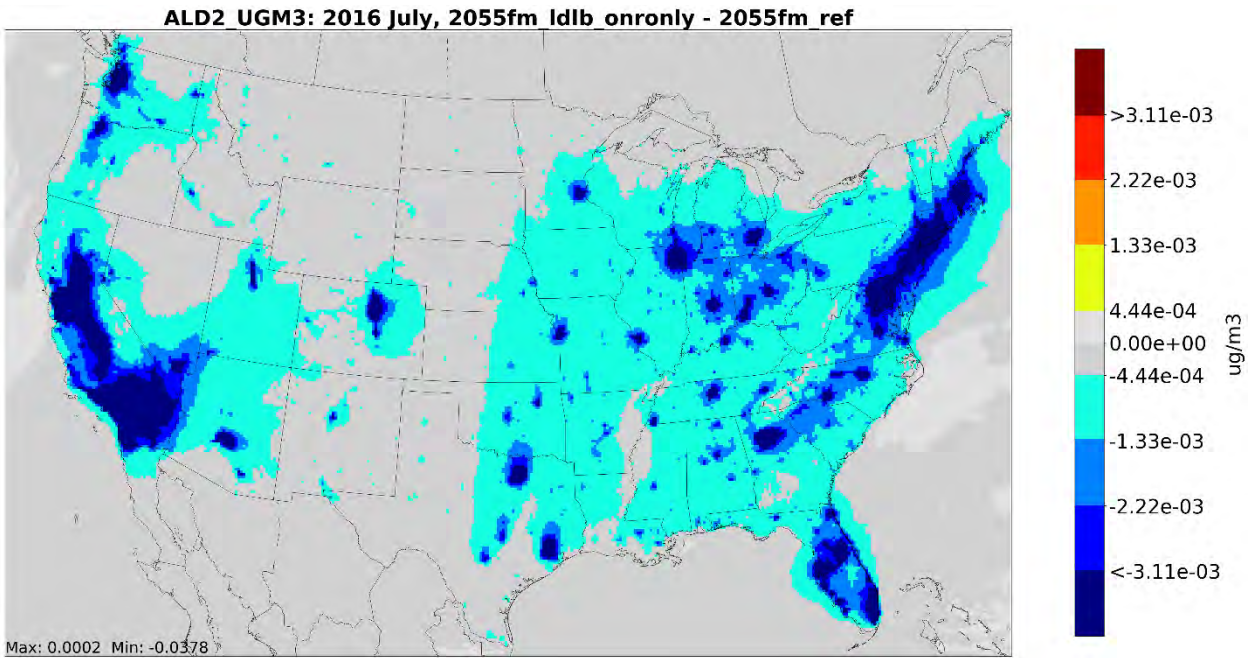


Figure 8-61 Projected Illustrative Changes in Average Acetaldehyde Concentrations in July 2055 from “Onroad Only” Emissions Changes

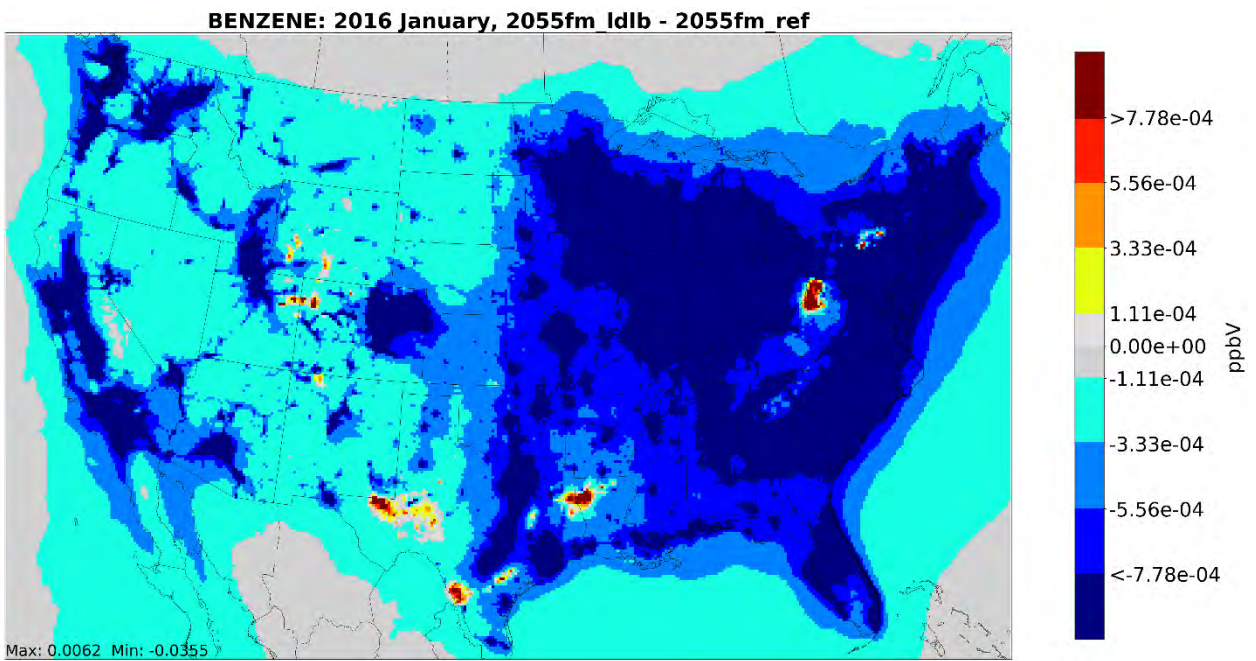


Figure 8-62 Projected Illustrative Changes in Average Benzene Concentrations in January 2055 due to LMDV Regulatory Scenario

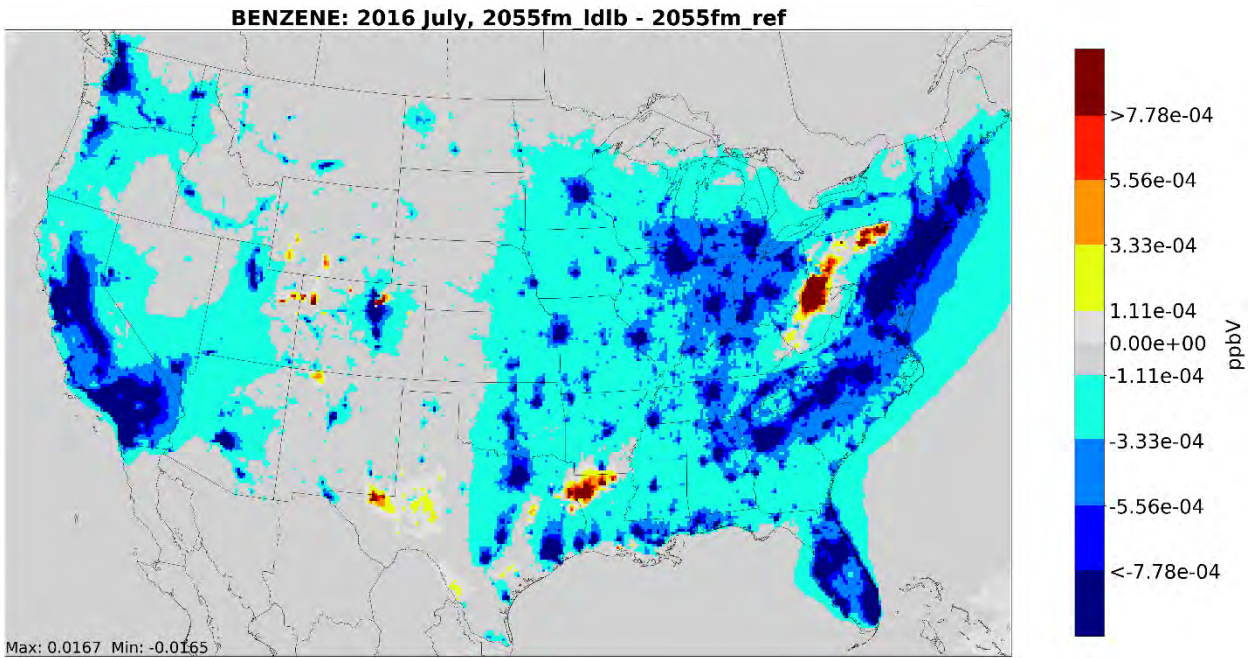


Figure 8-63 Projected Illustrative Changes in Average Benzene Concentrations in July 2055 due to LMDV Regulatory Scenario

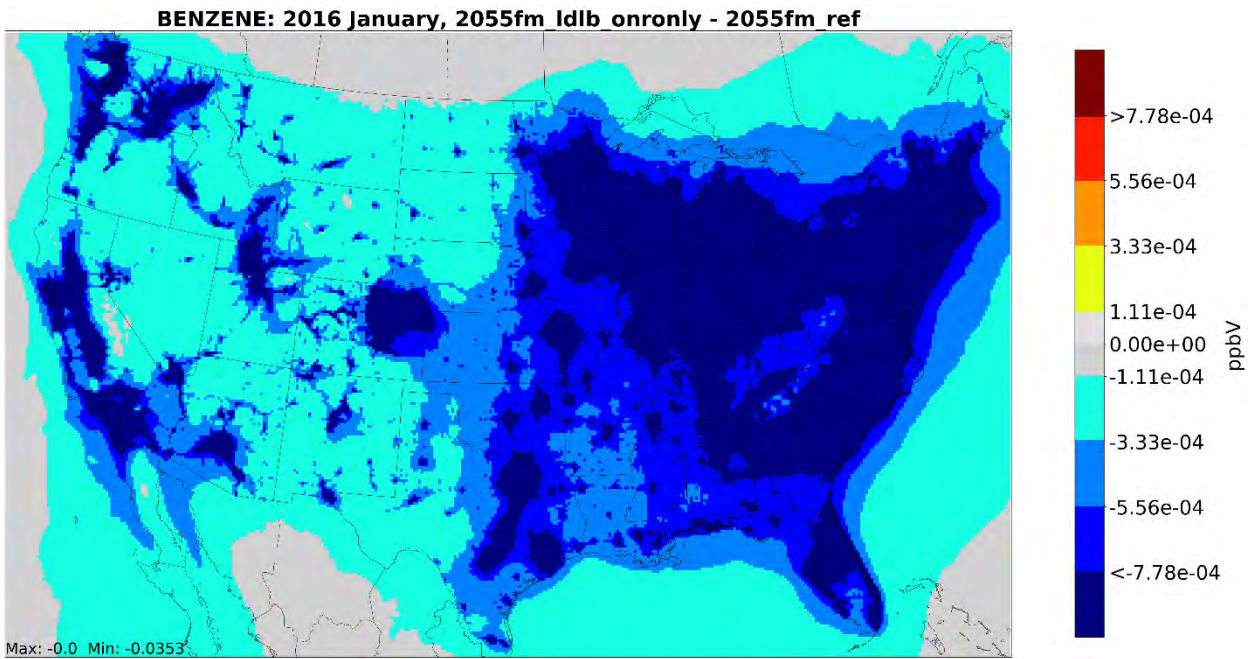


Figure 8-64 Projected Illustrative Changes in Average Benzene Concentrations in January 2055 from "Onroad Only" Emissions Changes

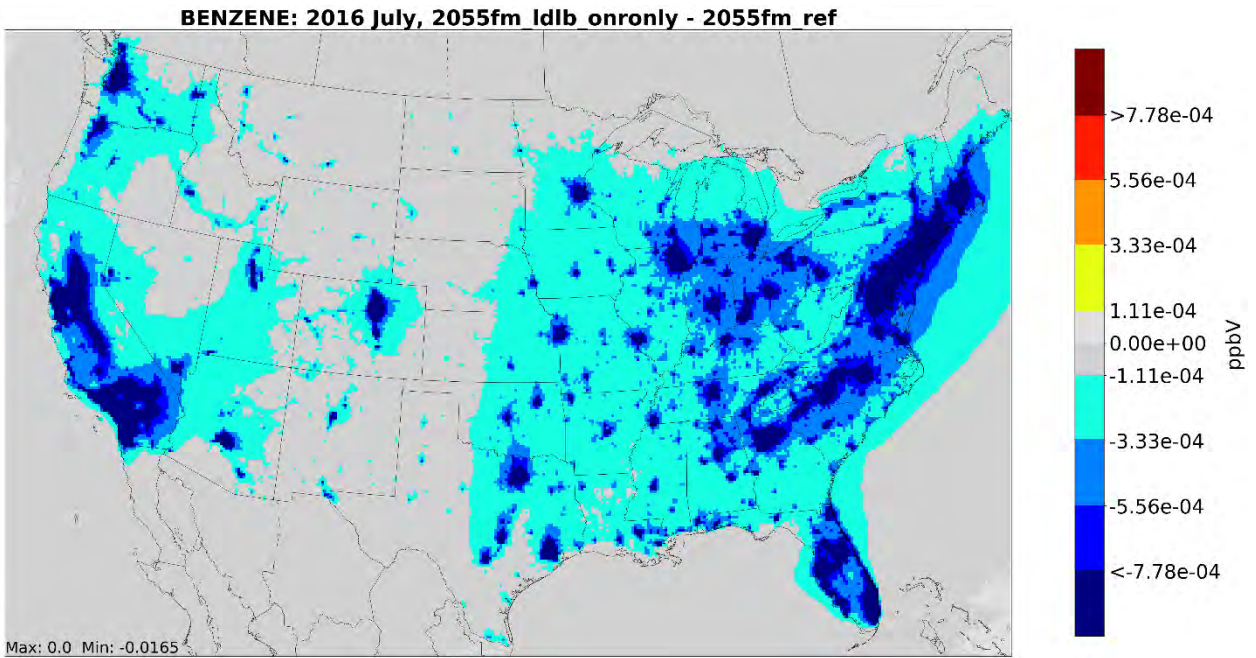


Figure 8-65 Projected Illustrative Changes in Average Benzene Concentrations in July 2055 from “Onroad Only” Emissions Changes

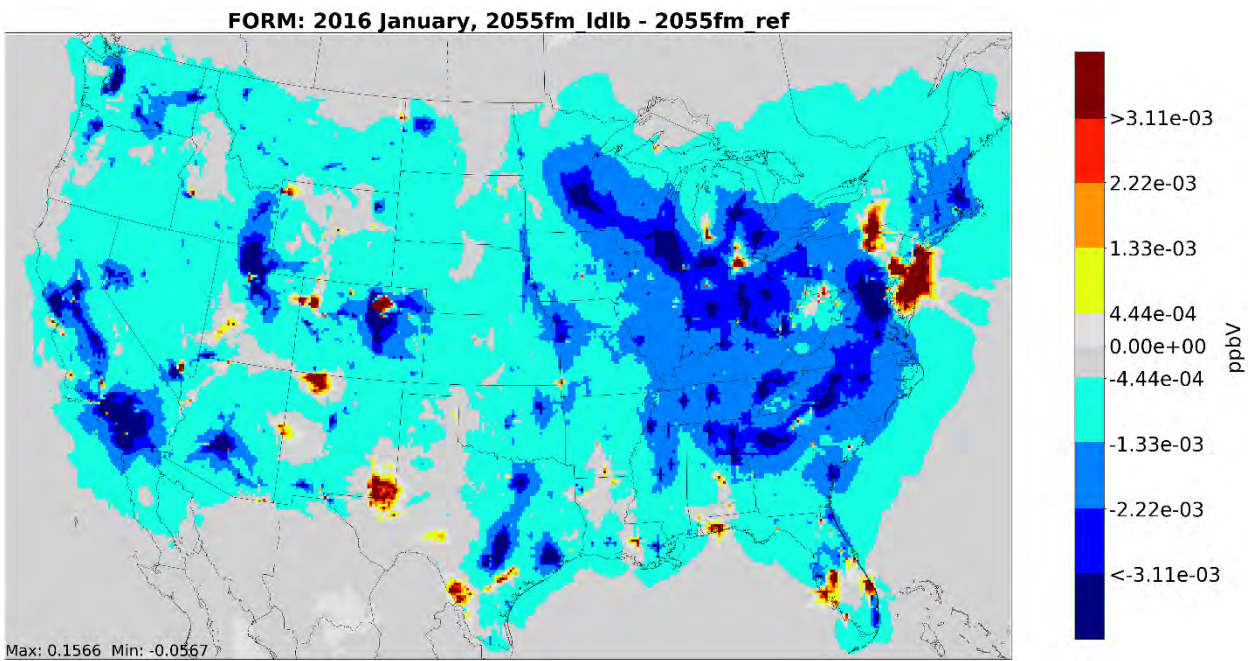


Figure 8-66 Projected Illustrative Changes in Average Formaldehyde Concentrations in January 2055 due to LMDV Regulatory Scenario

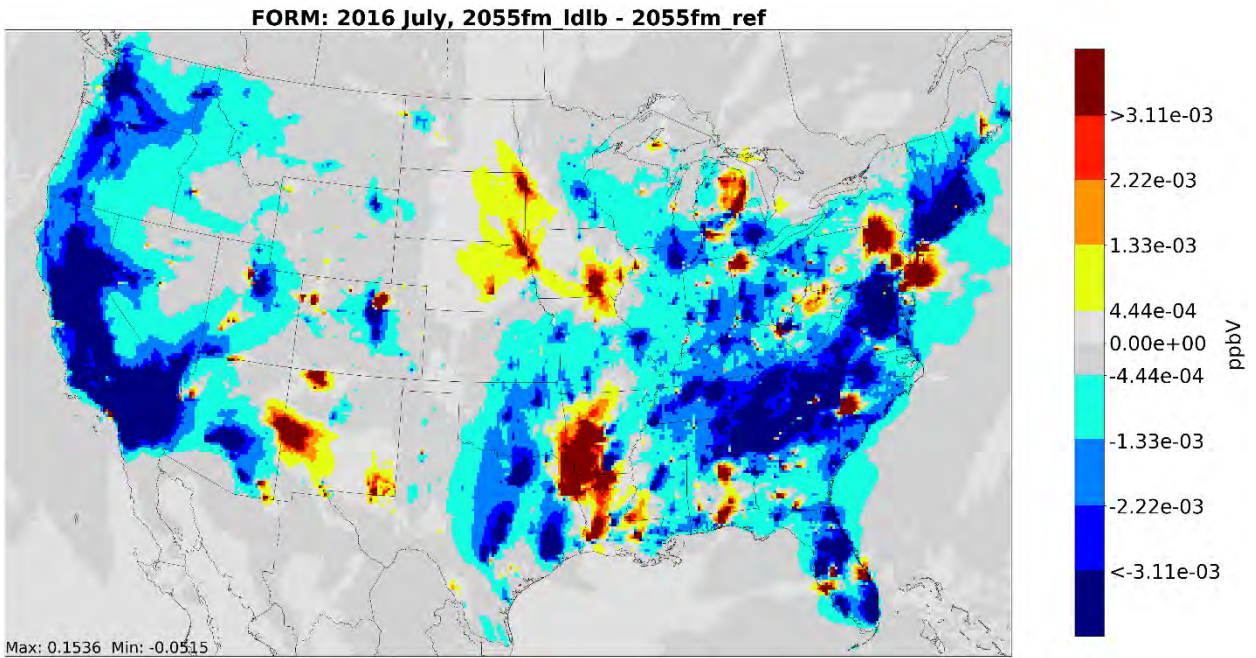


Figure 8-67 Projected Illustrative Changes in Average Formaldehyde Concentrations in July 2055 due to LMDV Regulatory Scenario

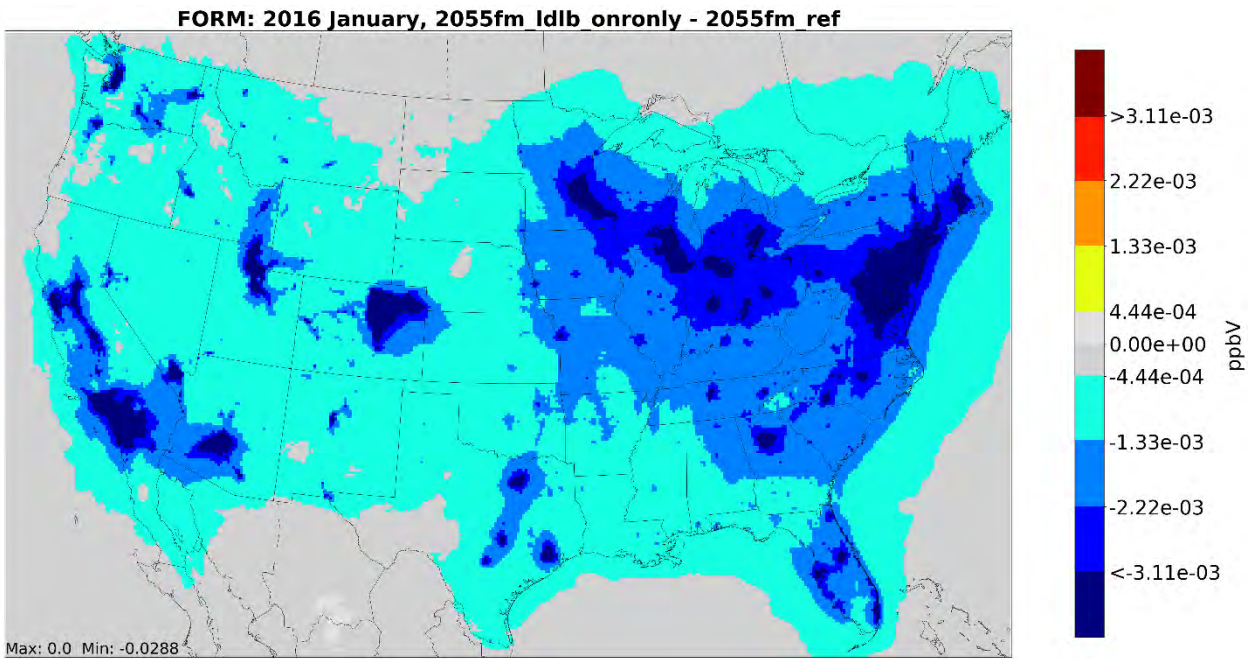


Figure 8-68 Projected Illustrative Changes in Average Formaldehyde Concentrations in January 2055 from "Onroad Only" Emissions Changes

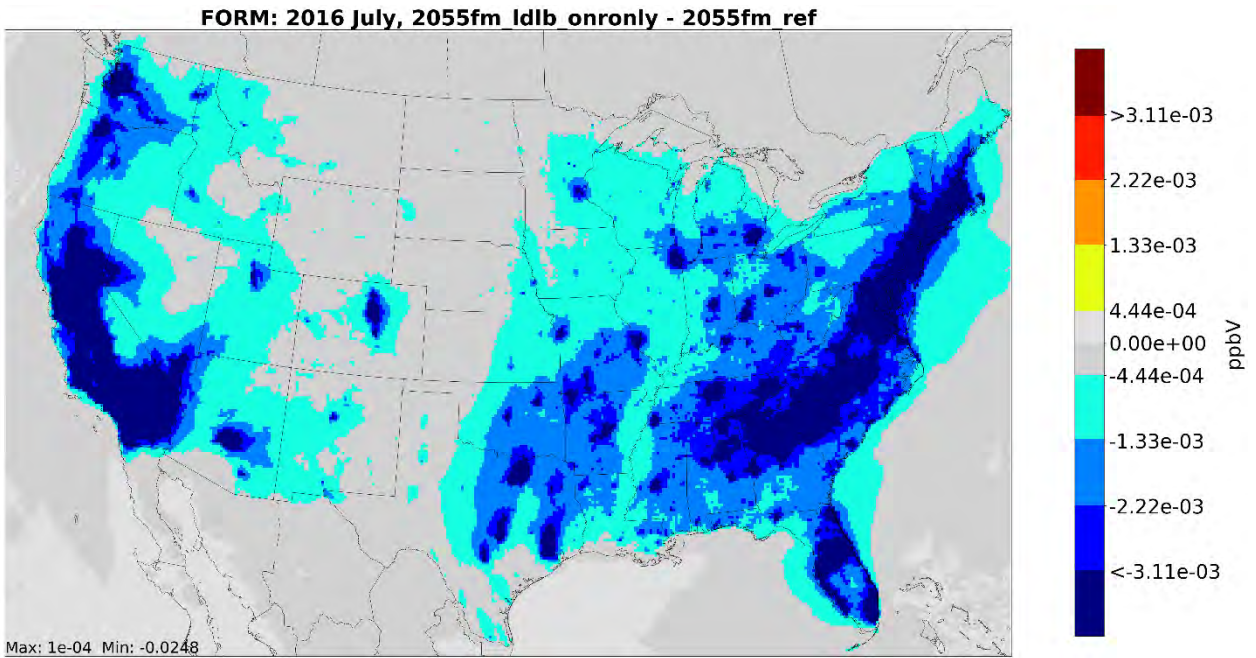


Figure 8-69 Projected Illustrative Changes in Average Formaldehyde Concentrations in July 2055 from “Onroad Only” Emissions Changes

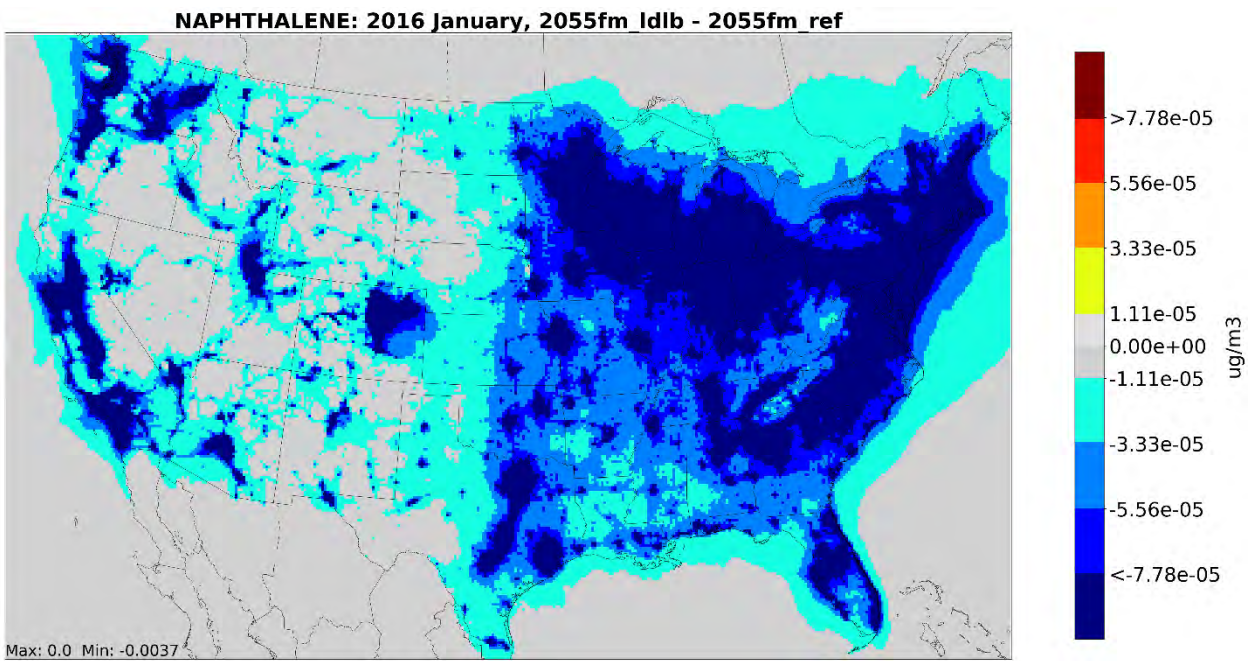


Figure 8-70 Projected Illustrative Changes in Average Naphthalene Concentrations in January 2055 due to LMDV Regulatory Scenario

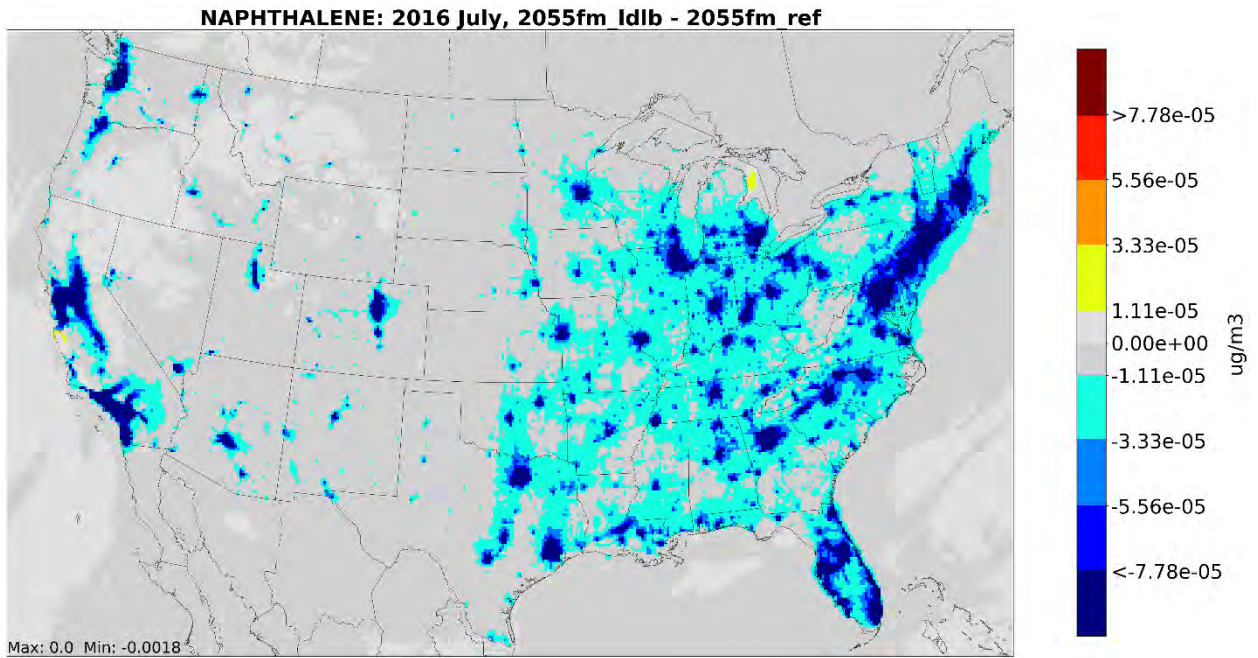


Figure 8-71 Projected Illustrative Changes in Average Naphthalene Concentrations in July 2055 due to LMDV Regulatory Scenario

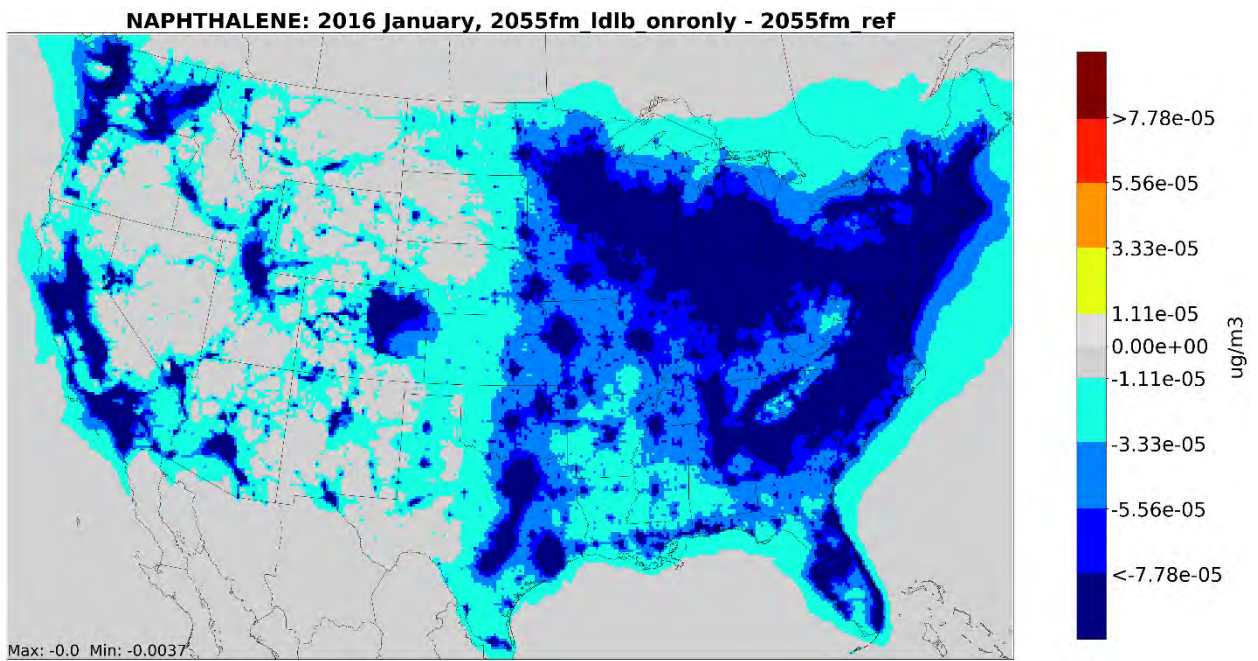


Figure 8-72 Projected Illustrative Changes in Average Naphthalene Concentrations in January 2055 from "Onroad Only" Emissions Changes

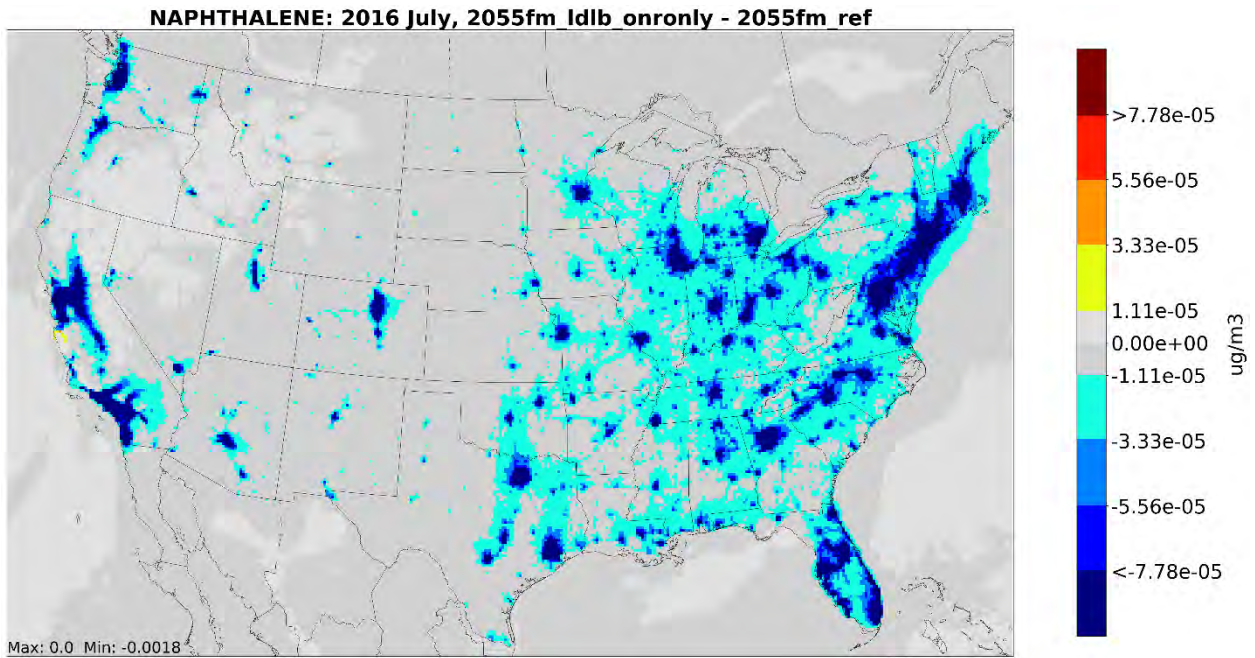


Figure 8-73 Projected Illustrative Changes in Average Naphthalene Concentrations in July 2055 from “Onroad Only” Emissions Changes

8.3 Projected Visibility in Mandatory Class I Federal Areas

Class I Area Name	State	2016 Baseline Visibility (dv) on 20% Most Impaired Days	2055 Reference Visibility (dv) on 20% Most Impaired Days	2055 LMDV Regulatory Scenario Visibility (dv) on 20% Most Impaired Days	2055 Onroad-Only Scenario Visibility (dv) on 20% Most Impaired Days	Natural Background (dv) on 20% Most Impaired Days
Sipsey Wilderness	Alabama	19.03	15.54	15.49	15.47	9.62
Chiricahua NM	Arizona	9.41	8.86	8.86	8.84	4.93
Chiricahua Wilderness	Arizona	9.41	8.86	8.86	8.84	4.93
Galiuro Wilderness	Arizona	9.41	8.86	8.86	8.84	4.93
Grand Canyon NP	Arizona	6.87	6.45	6.44	6.44	4.16
Mazatzal Wilderness	Arizona	9.47	9.03	9.01	9.01	5.22
Mount Baldy Wilderness	Arizona	7.29	6.95	6.96	6.94	4.18
Petrified Forest NP	Arizona	8.16	7.57	7.59	7.55	4.21
Pine Mountain Wilderness	Arizona	9.47	9.03	9.01	9.01	5.22
Saguaro NM	Arizona	10.75	10.26	10.23	10.23	5.14
Superstition Wilderness	Arizona	10.45	9.97	9.96	9.95	5.14

Class I Area Name	State	2016 Baseline Visibility (dv) on 20% Most Impaired Days	2055 Reference Visibility (dv) on 20% Most Impaired Days	2055 LMDV Regulatory Scenario Visibility (dv) on 20% Most Impaired Days	2055 Onroad- Only Scenario Visibility (dv) on 20% Most Impaired Days	Natural Background (dv) on 20% Most Impaired Days
Sycamore Canyon Wilderness	Arizona	11.96	11.62	11.6	11.6	4.68
Caney Creek Wilderness	Arkansas	18.29	14.49	14.53	14.45	9.54
Upper Buffalo Wilderness	Arkansas	17.95	14.76	14.76	14.71	9.41
Agua Tibia Wilderness	California	16.34	15.41	15.32	15.32	7.66
Ansel Adams Wilderness (Minarets)	California	10.98	10.39	10.36	10.36	6.06
Caribou Wilderness	California	10.23	9.74	9.73	9.73	6.1
Cucamonga Wilderness	California	13.19	11.99	11.8	11.8	6.12
Desolation Wilderness	California	9.31	8.9	8.88	8.88	4.91
Dome Land Wilderness	California	15.14	14.37	14.35	14.35	6.19
Emigrant Wilderness	California	11.57	11.15	11.13	11.13	6.29
Hoover Wilderness	California	7.65	7.35	7.34	7.34	4.9
John Muir Wilderness	California	10.98	10.39	10.36	10.36	6.06
Joshua Tree NM	California	12.87	12.18	12.14	12.14	6.09
Kaiser Wilderness	California	10.98	10.39	10.36	10.36	6.06
Kings Canyon NP	California	18.43	17.52	17.48	17.48	6.29
Lassen Volcanic NP	California	10.23	9.74	9.73	9.73	6.1
Lava Beds NM	California	9.67	9.33	9.32	9.32	6.18
Mokelumne Wilderness	California	9.31	8.9	8.88	8.88	4.91
Pinnacles NM	California	14.1	13.49	13.46	13.45	6.94
Redwood NP	California	12.65	12.4	12.4	12.4	8.59
San Gabriel Wilderness	California	13.19	11.99	11.8	11.8	6.12
San Geronio Wilderness	California	14.45	12.96	12.83	12.82	6.2
San Jacinto Wilderness	California	14.45	12.96	12.83	12.82	6.2
San Rafael Wilderness	California	14.11	13.29	13.26	13.26	6.8
Sequoia NP	California	18.43	17.52	17.48	17.48	6.29
South Warner Wilderness	California	9.67	9.33	9.32	9.32	6.18
Thousand Lakes Wilderness	California	10.23	9.74	9.73	9.73	6.1
Ventana Wilderness	California	14.1	13.49	13.46	13.45	6.94
Yosemite NP	California	11.57	11.15	11.13	11.13	6.29
Black Canyon of the Gunnison NM	Colorado	6.55	6.17	6.18	6.16	3.97
Eagles Nest Wilderness	Colorado	4.98	4.57	4.56	4.56	3.02
Flat Tops Wilderness	Colorado	4.98	4.57	4.56	4.56	3.02
Great Sand Dunes NM	Colorado	8.02	7.54	7.53	7.53	4.45
La Garita Wilderness	Colorado	6.55	6.17	6.18	6.16	3.97

Class I Area Name	State	2016 Baseline Visibility (dv) on 20% Most Impaired Days	2055 Reference Visibility (dv) on 20% Most Impaired Days	2055 LMDV Regulatory Scenario Visibility (dv) on 20% Most Impaired Days	2055 Onroad- Only Scenario Visibility (dv) on 20% Most Impaired Days	Natural Background (dv) on 20% Most Impaired Days
Maroon Bells-Snowmass Wilderness	Colorado	4.98	4.57	4.56	4.56	3.02
Mesa Verde NP	Colorado	6.51	5.88	5.87	5.86	4.2
Mount Zirkel Wilderness	Colorado	5.47	4.97	4.95	4.95	3.16
Rawah Wilderness	Colorado	5.47	4.97	4.95	4.95	3.16
Rocky Mountain NP	Colorado	8.41	7.58	7.54	7.53	4.94
Weminuche Wilderness	Colorado	6.55	6.17	6.18	6.16	3.97
West Elk Wilderness	Colorado	4.98	4.57	4.56	4.56	3.02
Chassahowitzka	Florida	17.41	15.69	15.67	15.66	9.03
Everglades NP	Florida	14.9	14.16	14.15	14.15	8.33
St. Marks	Florida	17.39	15.44	15.44	15.42	9.13
Cohutta Wilderness	Georgia	17.37	14.07	14.04	14.02	9.88
Okefenokee	Georgia	17.39	15.93	15.91	15.91	9.45
Wolf Island	Georgia	17.39	15.93	15.91	15.91	9.45
Craters of the Moon NM	Idaho	8.5	7.83	7.79	7.78	4.97
Sawtooth Wilderness	Idaho	8.61	8.34	8.33	8.33	4.7
Selway-Bitterroot Wilderness	Idaho	8.37	8.13	8.12	8.12	5.45
Mammoth Cave NP	Kentucky	21.02	16.78	16.67	16.68	9.8
Breton	Louisiana	18.97	17.4	17.4	17.38	9.23
Acadia NP	Maine	14.54	13.36	13.32	13.31	10.39
Moosehorn	Maine	13.32	12.49	12.46	12.46	9.98
Roosevelt Campobello International Park	Maine	13.32	12.49	12.46	12.46	9.98
Isle Royale NP	Michigan	15.54	14.37	14.34	14.32	10.17
Seney	Michigan	17.57	15.75	15.68	15.67	11.11
Boundary Waters Canoe Area	Minnesota	13.96	12.83	12.81	12.79	9.09
Voyageurs NP	Minnesota	14.18	13.18	13.18	13.15	9.37
Hercules-Glades Wilderness	Missouri	18.72	15.5	15.55	15.45	9.3
Mingo	Missouri	20.13	16.74	16.64	16.64	9.18
Anaconda-Pintler Wilderness	Montana	8.37	8.13	8.12	8.12	5.45
Bob Marshall Wilderness	Montana	10.06	9.84	9.83	9.83	5.53
Cabinet Mountains Wilderness	Montana	9.87	9.6	9.59	9.59	5.64
Gates of the Mountains Wilderness	Montana	7.47	7.33	7.33	7.32	4.53
Glacier NP	Montana	13.77	13.36	13.33	13.33	6.9
Medicine Lake	Montana	15.3	15.42	15.43	15.4	5.95
Mission Mountains Wilderness	Montana	10.06	9.84	9.83	9.83	5.53

Class I Area Name	State	2016 Baseline Visibility (dv) on 20% Most Impaired Days	2055 Reference Visibility (dv) on 20% Most Impaired Days	2055 LMDV Regulatory Scenario Visibility (dv) on 20% Most Impaired Days	2055 Onroad- Only Scenario Visibility (dv) on 20% Most Impaired Days	Natural Background (dv) on 20% Most Impaired Days
Red Rock Lakes	Montana	7.52	7.2	7.2	7.19	3.97
Scapegoat Wilderness	Montana	10.06	9.84	9.83	9.83	5.53
UL Bend	Montana	10.93	11.02	11.01	11.01	5.87
Jarbidge Wilderness	Nevada	7.97	7.78	7.77	7.77	5.23
Great Gulf Wilderness	New Hampshire	13.07	11.57	11.54	11.53	9.78
Presidential Range-Dry River Wilderness	New Hampshire	13.07	11.57	11.54	11.53	9.78
Brigantine	New Jersey	19.31	16.84	16.74	16.71	10.68
Bandelier NM	New Mexico	8.44	7.8	7.79	7.77	4.59
Bosque del Apache	New Mexico	10.47	9.71	9.71	9.69	5.39
Carlsbad Caverns NP	New Mexico	12.64	12.66	12.66	12.65	4.83
Gila Wilderness	New Mexico	7.58	7.16	7.19	7.15	4.2
Pecos Wilderness	New Mexico	5.95	5.4	5.42	5.38	3.5
Salt Creek	New Mexico	14.97	14.69	14.67	14.66	5.49
San Pedro Parks Wilderness	New Mexico	6.43	5.9	5.94	5.89	3.33
Wheeler Peak Wilderness	New Mexico	5.95	5.4	5.42	5.38	3.5
White Mountain Wilderness	New Mexico	9.95	9.65	9.65	9.64	4.89
Linville Gorge Wilderness	North Carolina	16.42	12.83	12.82	12.79	9.7
Shining Rock Wilderness	North Carolina	15.49	12.09	12.08	12.06	10.25
Swanquarter	North Carolina	16.3	14.01	13.93	13.92	10.01
Lostwood	North Dakota	16.18	16.33	16.3	16.3	5.87
Theodore Roosevelt NP	North Dakota	14.06	13.7	13.66	13.67	5.94
Wichita Mountains	Oklahoma	18.12	15.68	15.66	15.62	6.92
Crater Lake NP	Oregon	7.98	7.71	7.71	7.71	5.16
Diamond Peak Wilderness	Oregon	7.98	7.71	7.71	7.71	5.16
Eagle Cap Wilderness	Oregon	11.19	10.33	10.31	10.31	6.58
Gearhart Mountain Wilderness	Oregon	7.98	7.71	7.71	7.71	5.16
Hells Canyon Wilderness	Oregon	12.33	11.57	11.53	11.53	6.57
Kalmiopsis Wilderness	Oregon	11.97	11.56	11.55	11.55	7.78
Mount Hood Wilderness	Oregon	9.27	8.84	8.83	8.83	6.59
Mount Jefferson Wilderness	Oregon	11.28	10.9	10.89	10.89	7.3
Mount Washington Wilderness	Oregon	11.28	10.9	10.89	10.89	7.3
Mountain Lakes Wilderness	Oregon	7.98	7.71	7.71	7.71	5.16
Strawberry Mountain Wilderness	Oregon	11.19	10.33	10.31	10.31	6.58
Three Sisters Wilderness	Oregon	11.28	10.9	10.89	10.89	7.3

Class I Area Name	State	2016 Baseline Visibility (dv) on 20% Most Impaired Days	2055 Reference Visibility (dv) on 20% Most Impaired Days	2055 LMDV Regulatory Scenario Visibility (dv) on 20% Most Impaired Days	2055 Onroad-Only Scenario Visibility (dv) on 20% Most Impaired Days	Natural Background (dv) on 20% Most Impaired Days
Cape Romain	South Carolina	17.67	15.8	15.8	15.77	9.78
Badlands NP	South Dakota	12.33	11.87	11.85	11.85	6.09
Wind Cave NP	South Dakota	10.53	9.94	9.93	9.93	5.64
Great Smoky Mountains NP	Tennessee	17.21	13.85	13.82	13.8	10.05
Joyce-Kilmer-Slickrock Wilderness	Tennessee	17.21	13.85	13.82	13.8	10.05
Big Bend NP	Texas	14.06	13.48	13.5	13.48	5.33
Guadalupe Mountains NP	Texas	12.64	12.66	12.66	12.65	4.83
Arches NP	Utah	6.76	5.97	5.94	5.94	4.13
Bryce Canyon NP	Utah	6.6	6.11	6.1	6.1	4.08
Canyonlands NP	Utah	6.76	5.97	5.94	5.94	4.13
Capitol Reef NP	Utah	7.18	6.65	6.64	6.63	4
Zion NP	Utah	8.76	8.38	8.36	8.36	5.18
Lye Brook Wilderness	Vermont	14.75	12.86	12.78	12.77	10.24
James River Face Wilderness	Virginia	17.89	14.25	14.16	14.16	9.47
Shenandoah NP	Virginia	17.07	12.85	12.76	12.77	9.52
Alpine Lake Wilderness	Washington	12.74	11.83	11.77	11.75	7.27
Glacier Peak Wilderness	Washington	9.98	9.59	9.57	9.57	6.89
Goat Rocks Wilderness	Washington	7.98	7.66	7.65	7.65	6.14
Mount Adams Wilderness	Washington	7.98	7.66	7.65	7.65	6.14
Mount Rainier NP	Washington	12.66	12.15	12.14	12.12	7.66
North Cascades NP	Washington	9.98	9.59	9.57	9.57	6.89
Olympic NP	Washington	11.9	11.73	11.72	11.72	6.9
Pasayten Wilderness	Washington	9.46	9.06	9.05	9.05	5.96
Dolly Sods Wilderness	West Virginia	17.65	13.39	13.31	13.34	8.92
Otter Creek Wilderness	West Virginia	17.65	13.39	13.31	13.34	8.92
Bridger Wilderness	Wyoming	6.77	6.41	6.4	6.4	3.92
Fitzpatrick Wilderness	Wyoming	6.77	6.41	6.4	6.4	3.92
Grand Teton NP	Wyoming	7.52	7.2	7.2	7.19	3.97
North Absaroka Wilderness	Wyoming	7.17	6.85	6.85	6.84	4.55
Teton Wilderness	Wyoming	7.52	7.2	7.2	7.19	3.97
Washakie Wilderness	Wyoming	7.17	6.85	6.85	6.84	4.55
Yellowstone NP	Wyoming	7.52	7.2	7.2	7.19	3.97

^a The level of visibility impairment in an area is based on the light-extinction coefficient and a unitless visibility index, called a “deciview”, which is used in the valuation of visibility. The deciview metric provides a scale for

perceived visual changes over the entire range of conditions, from clear to hazy. Under many scenic conditions, the average person can generally perceive a change of one deciview. The higher the deciview value, the worse the visibility. Thus, an improvement in visibility is a decrease in deciview value.