Effects of Light-duty Vehicle Emissions Standards and Gasoline Sulfur Level on Ambient Fine Particulate Matter

Final Report

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Acronyms and Abbreviations

API	American Petroleum Institute
ARB	Air Resources Board, California
CAMx	Comprehensive Air Quality Model with Extensions
CB05	Carbon Bond Mechanism 5
CO	Carbon monoxide
CONUS	Continental United States
CRC	Coordinating Research Council
EPA	Environmental Protection Agency
g-LDV	Gasoline fueled light duty vehicles (passenger cars and light trucks)
LDGV	Light duty gasoline vehicles (passenger cars)
LDGT1	Light duty gasoline trucks weighing less than 6,000 lbs
LDGT2	Light duty gasoline trucks weighing between 6,001 and 8,500 lbs
LEV	Low Emission Vehicle
MOBILE6	Mobile emission modeling software
MOVES	Motor Vehicle Emission Simulator
NOx	Oxides of nitrogen
O3	Ozone
ppb	parts per billion
ppm	parts per million
PM	Particulate matter
$PM_{2.5}$	Particulate matter with diameter smaller than 2.5 micrometers
PM SO_4	Particulate sulfate
SCC	Standard classification code
SO_2	Sulfur dioxide
SPECIATE	Speciation database
THC	Total hydrocarbons
VMT	Vehicle miles traveled
VOC	Volatile organic compound
WRF	Weather Research and Forecast Model

EXECUTIVE SUMMARY

More stringent vehicle emission regulations and fuel property standards are being considered in the United States to improve air quality and attain compliance with national ambient air quality standards. We present a computer modeling study of the impact of past, present and potential future US Federal emissions standards for on-road gasoline-fueled light duty vehicles (g-LDVs) on summertime ground-level ambient concentrations fine particulate matter ($PM_{2.5}$, particulate matter with diameter smaller than 2.5 micrometers) in the eastern US.

The US Environmental Protection Agency (EPA) Motor Vehicle Emission Simulator (MOVES) model was used to derive on-road vehicle emissions. This was complemented by a suite of other advanced emissions models for developing other source inventories. Air quality modeling was performed with the Comprehensive Air Quality Model with Extensions (CAMx). Modeling was conducted over a 12 km horizontal resolution domain in the eastern US nested within a 36 km continental US (CONUS) domain. Modeling was conducted earlier for summertime ozone (ENVIRON, 2012) and is now extended here for $PM_{2.5}$. Information on methods adopted in the ozone study is reproduced here for completeness.

This work builds off prior modeling conducted by ENVIRON (Vijayaraghavan et al, 2012) for the Coordinating Research Council (CRC, Project A-76-1) which included the simulation of a 2008 base case to establish satisfactory model performance in addition to the following four hypothetical 2022 g-LDV emissions scenarios:

1. 2022 Tier 1 scenario (assumed that only Tier 1 vehicle standards have been implemented in 2022); however, sulfur levels were reduced from Tier 1 levels per the MOVES representation of Tier 2 sulfur implementation
2. 2022 Tier 2 scenario (assumed that no standards beyond Tier 2 have been implemented in 2022)
3. 2022 LEV III scenario (assumed that the California LEV III standards have been adopted nationwide; however, pre-LEV III vehicles were assumed to be operated on Tier 2 sulfur levels)
4. 2022 LDV zero-out scenario (assumed there are no g-LDV emissions in 2022)

In the CRC effort, the future year fuel sulfur in all scenarios complied with a standard of 30 ppm sulfur except in California where the counties used lower sulfur. The scenarios listed above did not synchronize the fuel sulfur assumptions within MOVES with the vehicle technology assumptions. The purpose of the current study is to update the 2022 LEV III and Tier I scenario exhaust emissions from the CRC effort so that they reflect a gasoline sulfur level appropriate to the emission control technology, model effects on ground-level $PM_{2.5}$ and compare incremental changes relative to the 2022 Tier 2 scenario. As in the case of the ozone study (ENVIRON, 2012), two 2022 scenarios were modeled here for a summer month (July):

1. 2022 Tier 1 scenario with gasoline sulfur level reflecting that typical of the time period during which the Tier 1 vehicle emissions standards were in effect.
2. 2022 LEV III scenario with gasoline sulfur level reflecting the LEV III standard.

The Tier 2 scenario already matched the vehicle technology and fuel sulfur assumptions and therefore did not require further modeling.

The July 1999 gasoline sulfur levels as represented in the MOVES database were used for the 2022 Tier 1 scenario. The g-LDV VMT-weighted average gasoline sulfur in the MOVES database in July 1999 over counties in the lower 48 states was 228 ppm. Sulfur dioxide (SO_2) and particulate sulfate (PM SO_4) emissions from g-LDVs in the CRC Tier 1 scenario were increased by a factor of 228/21 in the on-road inventory to obtain SO_2 and PM SO_4 emissions for the Tier 1 scenario (the VMT-weighted average gasoline sulfur content in the MOVES database for the CRC Tier 1 scenario was 21 ppm). For the LEV III scenario, gasoline sulfur levels were modeled as 1/3 of the county-specific sulfur values in the MOVES database used to represent Tier 2 gasoline fuels. This approach was deemed to best approximate the reduction in gasoline sulfur content from a Tier 2 average of 30 ppm to a potential future federal "Tier 3" 10 ppm average standard. For this scenario, the California Air Resources Board (ARB) Predictive Model was used to develop adjustments reflecting the impact of gasoline sulfur by technology group for total hydrocarbons (THC), oxides of nitrogen (NOx) and carbon monoxide (CO). SO_2 and PM SO_4 emissions from g-LDVs in the Tier 2 scenario were scaled by a factor of 1/3 in the on-road inventory to reflect the reduction in gasoline sulfur content from the Tier 2 to LEV III scenarios.

Nationwide (continental US) g-LDV emissions of volatile organic compounds (VOCs), CO and NOx in the July 2022 Tier 2 scenario are lower by 62%, 51% and 80%, respectively, than those for the Tier 1 case. The corresponding reductions are much smaller (8%, 7% and 11%, respectively) when comparing the LEV III to the Tier 2 scenario. Nationwide g-LDV emissions of SO_2 were reduced by 92% in the Tier 2 scenario from Tier 1 and by 64% in the LEV-III scenario from Tier 2. Emissions from g-LDVs of $PM_{2.5}$ were reduced by 19% in the Tier 2 scenario when compared with Tier 1 and by 5% in the LEV-III scenario when compared with Tier 2.

The modeling results show that large benefits in ground-level $PM_{2.5}$ concentrations will have accrued in 2022 as a direct result of the transition from Tier 1 to Tier 2 g-LDV emissions standards and lower gasoline sulfur levels. These benefits include up to 5.8 $\mu g/m^3$ reductions in the summertime monthly maximum 24-h $PM_{2.5}$ concentrations and up to 2.7 $\mu g/m^3$ reductions in the monthly mean of $PM_{2.5}$ concentrations. However, nationwide implementation of more stringent LDV emissions standards similar to LEV III along with further reductions in gasoline sulfur content would yield relatively small additional improvements in 2022 summertime $PM_{2.5}$ concentrations, even when considering the in-use fleet emissions impact of the lower gasoline sulfur content. Peak monthly 24-h $PM_{2.5}$ concentrations would be reduced by no more than 0.2 $\mu g/m^3$, with reductions in the monthly mean of 24-h $PM_{2.5}$ concentrations of no more than 0.1 $\mu g/m^3$. Some further reductions in $PM_{2.5}$ would be realized in the post-2022 timeframe due to additional phase-in of vehicles meeting LEV III emission and gasoline sulfur standards in the vehicle fleet. In addition, this modeling study does not consider wintertime $PM_{2.5}$ benefits.

1.0 INTRODUCTION

This study examines the effect of historical, current and potential future gasoline-fueled light-duty vehicle (g-LDV) emission standards including mandated gasoline fuel sulfur reductions on ambient summertime ground-level ambient concentrations of fine particulate matter ($PM_{2.5}$, particulate matter with diameter smaller than 2.5 micrometers) in the eastern United States (US). The study builds upon prior work conducted by ENVIRON for the Coordinating Research Council (CRC, Project A-76-1) and for the American Petroleum Institute (API). Information on data and methods applied in those two studies is reproduced in this report for completeness.

In the prior CRC work (Vijayaraghavan et al., 2012), ENVIRON modeled a 2008 base case for air quality model performance evaluation and four 2022 emissions scenarios with increasingly stricter emission standards for g-LDVs to estimate the incremental and cumulative effect of g-LDV emissions controls on ambient air quality. The four 2022 scenarios modeled were:

1. 2022 Tier 1 scenario (assume that only US Federal Tier 1 standards are implemented through 2022)
2. 2022 Tier 2 scenario (assume that the current emissions standards, up to US Federal Tier 2 standards, are implemented through 2022)
3. 2022 LEV III scenario (assume that the California LEV III standard is adopted nationwide)
4. 2022 g-LDV zero-out scenario (assume there are no g-LDV emissions in 2022)

All four scenarios were modeled for a winter month (February) and summer month (July). The 2022 Tier 1 scenario in the CRC study aimed to answer the question: “what if the US had not switched from Tier 1 to Tier 2 standards by 2022?” The 2022 Tier 2 case reflects a scenario with current Tier 2 emissions standards that are not revised through 2022. The 2022 LEV III scenario addressed the potential impact of further tightening g-LDV emission standards from Tier 2 to a nationwide LEV III standard.

The g-LDV emission differences among the 2022 scenarios for the CRC study were due solely to technology changes in the g-LDV fleet. Gasoline sulfur content was set to the default value from the MOVES model database in all scenarios as discussed below. The purpose of the current study is to update the 2022 LEV III and Tier I scenario g-LDV exhaust emissions so that they reflect a gasoline sulfur level appropriate to the emission control technology, model effects on ground-level ambient $PM_{2.5}$ and compare incremental changes relative to the 2022 Tier 2 scenario. A similar modeling study was conducted earlier for summertime ozone for API (ENVIRON, 2012) and is now extended here for $PM_{2.5}$.

2.0 METHODS

2.1 Modeling Domain and Scenarios

The air quality simulations were conducted with the Comprehensive Air Quality Model with Extensions (CAMx) (ENVIRON, 2011) using on-road emissions inventories derived using the Motor Vehicle Emission Simulator (MOVES) (EPA, 2010) and other model inputs as discussed below. We applied version 5.40 of CAMx with the Carbon Bond 5 (CB05) chemical mechanism and version 2010a of MOVES. The CAMx modeling domain (see Figure 1) extends over the continental US (CONUS) at 36 km horizontal resolution with an inner nested domain at 12 km resolution over part of the eastern US. The domain has a pressure-based vertical structure with 26 layers with the model top at 145 mb or approximately 15-18 km above mean sea level.

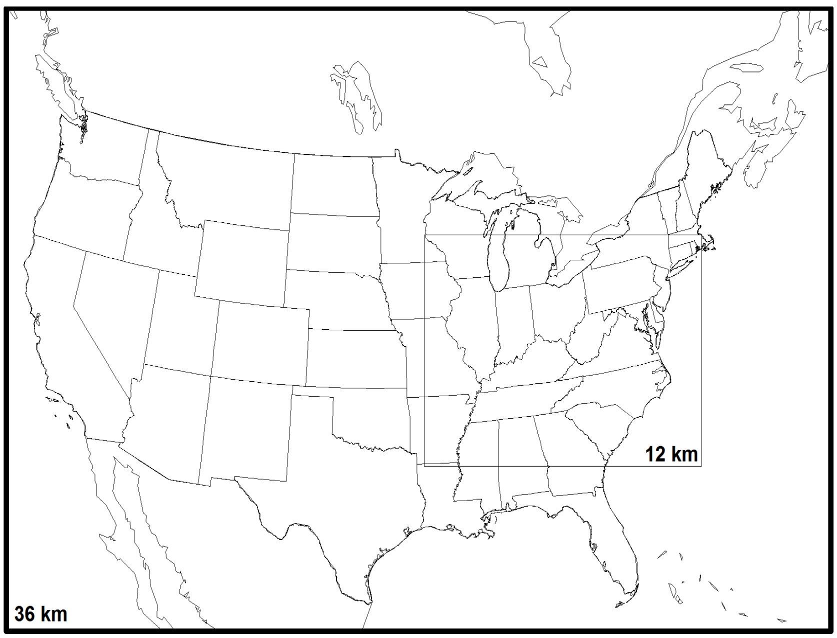


Figure 1. Air quality modeling domain.

Two emissions scenarios were modeled:

1. 2022 Tier 1 scenario with gasoline sulfur level reflecting that typical of the time period during which the Tier 1 standard was in effect, as described below.
2. 2022 LEV III scenario with appropriate gasoline sulfur level as discussed below.

Both scenarios were modeled for a summer month (July).

2.2 Meteorology

CAMx modeling for the 2022 scenarios was driven by year 2008 meteorological fields from the Weather Research and Forecast (WRF) model – Advanced Research WRF (ARW) core

(Skamarock et al., 2008). WRF output meteorological fields at 12 km horizontal resolution over the continental US were obtained from the EPA (Gilliam, R., personal communication, 2011). The CAMx input meteorological files for the nested 36 and 12 km resolution domains developed from the WRF files in the CRC study were used in the current work. Data in 34 WRF vertical layers extending up to 50 mb altitude are mapped to 26 layers in CAMx extending up to 145 mb (approximately 15-18 km). A performance evaluation of the WRF meteorological outputs and CAMx-ready meteorology showed satisfactory performance (Vijayaraghavan et al., 2012).

2.3 Emissions Inventories

The two scenarios modeled for the current work apply partial modifications of the on-road mobile emissions inventories developed under CRC A76-1 (Vijayaraghavan et al, 2012). All other emissions sources, biogenic and anthropogenic besides on-road mobile, are identical between the CRC effort and the current work. For on-road mobile sources, the portion of the inventories modified includes only exhaust VOC, CO, NOx, SO_2 and particulate sulfate (PM SO_4) emissions from gasoline light duty vehicles (g-LDVs). Emissions from heavy duty gasoline vehicles, motorcycles, and all diesel vehicles did not change.

2.3.1 Overview of on-road mobile emissions

The MOVES model-based on-road mobile emissions inventories from the CRC effort were all built on the assumption that g-LDVs in 2022 operated on gasoline in compliance with Tier 2 gasoline sulfur standards with the exception of California. The purpose of the following sections is to document the data and assumptions used to develop emissions inventories that reflect different sulfur levels than Tier 2 in-use by g-LDVs in the two scenarios. The group of vehicle types collectively referred to as g-LDV includes three categories:

1. Light-duty gasoline vehicles (LDGV)
2. Light-duty gasoline trucks weighing less than 6,000 lbs (LDGT1)
3. Light-duty gasoline trucks weighing between 6,001 and 8,500 lbs (LDGT2)

The Tier 1 program instituted standards for Total Hydrocarbons (THC), carbon monoxide (CO), oxides of nitrogen (NOx), and particulate matter (PM) for 1994-2003 model year vehicles with a phase-in for the early years (the prior standard was the federal Tier 0 program that applied to 1981-1993 model year vehicles). The Tier 2 program instituted gasoline sulfur and vehicle emission standards for model years 2004 onwards and phased in completely in 2007 for the three categories of g-LDVs considered in this study. The California LEV III standards apply to vehicle model years 2015 to 2028, with the phase-in for NOx and volatile organic compounds (VOCs) completed by 2025 and the phase-in for PM completed by 2028. In the LEV III phase-in schedule, by year 2022 the expected LEV III sales percent would be 73%. The Tier 1 and LEV III scenario g-LDV technology distributions in the 2022 fleet are summarized below in Tables 1 and 2, respectively.

Table 1. Tier 1 scenario 2022 g-LDV fleet technology composition by model year.

Model Year Group	Tier 1	Tier 0
2022 – 1996	100%	
1995	80%	20%
1994	40%	60%
1993 – 1992		100%

Table 2. LEV III scenario 2022 g-LDV fleet technology composition by model year.

Model Year Group	LEV III	Tier 2	LEV	TLEV	Tier 1	Tier 0
2022	73%	27%				
2021	64%	36%				
2020	55%	45%				
2019	45%	55%				
2018	36%	64%				
2017	27%	73%				
2016	18%	82%				
2015	9%	91%				
2014 – 2007	0%	100%				
2006		75%	25%			
2005		50%	50%			
2004		25%	75%			
2003		0%	100%			
2002			80%	20%		
2001			60%	40%		
2000 – 1996					100%	
1995					80%	20%
1994					40%	60%
1993 – 1992						100%

2.3.2 Gasoline sulfur levels

When EPA unveiled the Tier 2 vehicle emission standards, they also mandated cleaner, lower-sulfur gasoline fuel on a similar implementation schedule. The reason for coupling the fuel sulfur standards alongside vehicle emission standards is that sulfur is known to impede the performance of catalytic converters. The MOVES gasoline sulfur content data underlying the previous 2022 on-road emissions inventories used in the CRC study for all scenarios represent, with some exceptions, compliance with the current Tier 2 nationwide 30 ppm average standard. The exceptions include California as well as some areas in Arizona and Texas which have lower than 30 ppm standard gasoline sulfur contents. The MOVES database contains sulfur values on a county-by-county basis that are based on survey data, shown in Table 3. The lower-48 state, weighted average gasoline sulfur content in the MOVES database which underpinned the previous three July 2022 scenarios in the CRC effort was 21 ppm.[1] Gasoline sulfur levels were substantially higher prior to the implementation of the Tier 2 emission standards starting in 2000. During the 1990s, when g-LDVs certified to Tier 1 standards dominated the in-use fleet, the average sulfur content of regular grade gasoline typically fell within the range of 200 to 360 ppm according to semiannual survey reports of motor vehicle gasoline properties published by the National Institute for Petroleum and Energy Research (Dickson et al., 1994). EPA has proposed regulations that lower gasoline sulfur from the current Tier 2 average of 30 ppm down to 10 ppm. Since it was desired to model the emissions from g-LDVs under both a Tier 1 scenario with higher gasoline sulfur and an LEV III scenario with lower gasoline sulfur, adjustment factors were required in order to appropriately translate the MOVES Tier 2 based emissions estimates.

Table 3. July 2022 gasoline sulfur content in MOVES2010a database.

Gasoline Sulfur (ppm)	Number of Counties
7.8	51
16.9	22
21.6	115
22.3	27
22.6	692
22.9	563
23.3	1,320
26.5	320

The county-specific sulfur levels for the LEV III and Tier 1 scenarios were selected in the following manner.

For the LEV III scenario, the gasoline sulfur level was assumed to be 1/3 of the Tier 2 sulfur value shown in the underlying MOVES2010a database, i.e. the reduction from a 30 ppm average to a 10 ppm average sulfur standard. As refiners would likely produce sulfur below 10 ppm and that margin of compliance is unknown, one third of the existing (2022 Tier 2) gasoline sulfur is a realistic estimate for a LEV III scenario gasoline fuel. The exception to this is California which has the 7.8 ppm gasoline sulfur content; thus, LEV III scenario emissions from California counties were not adjusted.

For the Tier 1 scenario, two historic years were available in the MOVES model database to represent in-use gasoline sulfur levels during the Tier 1 era: 1999 and 2000. In 2000 the U.S. EPA was already beginning to provide incentives for early compliance to the Tier 2 fuel sulfur standard (EPA, 2008). Therefore, the year 1999 MOVES gasoline sulfur data was used to select an appropriate gasoline sulfur level as the basis for developing the factors to adjust the 2022

[1] The weighting factors were July 2022 g-LDV relative VMT fractions by county in the lower-48 states.

Tier 1 scenario g-LDV emissions. The weighted average gasoline sulfur in the MOVES database in July 1999 over the lower-48 states including California was 228 ppm.

2.3.3 Sulfur effects on LDV emissions

2.3.3.1 LEV III sulfur effects

Under API auspices, the California Air Resources Board (ARB) Predictive Model was used to develop the adjustment factors for translating the MOVES emissions estimates from a 30 ppm S basis to a 10 ppm S basis; these adjustment factors were provided to ENVIRON (J. Uihlein, Chevron, personal communication, 2011). Emissions estimates were obtained from a copy of the spreadsheets used for compliance with the ARB gasoline regulations. All Predictive Model gasoline properties were set at the ARB flat limits except for sulfur, which was varied from 5 ppm to 30 ppm in 5 ppm increments. The other property values do not affect the results because 1) sulfur does not interact with any other gasoline property in the Predictive Model and 2) the relationships are ultimately used to calculate an emissions ratio rather than absolute emissions. The predicted THC, NOx, and CO emissions rates in g/mi (“EXP(PREDICTION)” on the spreadsheets) were recorded for Tech Groups 4 and 5 at each sulfur level. A regression of the predicted emissions rates on sulfur content was then performed in order to generate a set of linear equations for each pollutant emission for each Tech Group. The Predictive Model-based adjustment factors are the ratio of the emissions prediction at 1/3 the input sulfur level divided by the emissions prediction at the input sulfur level, valid over the range of 15 to 30 ppm input sulfur. Figure 2 shows the regressions for Tech 5 (left) and Tech 4 (right) vehicles.

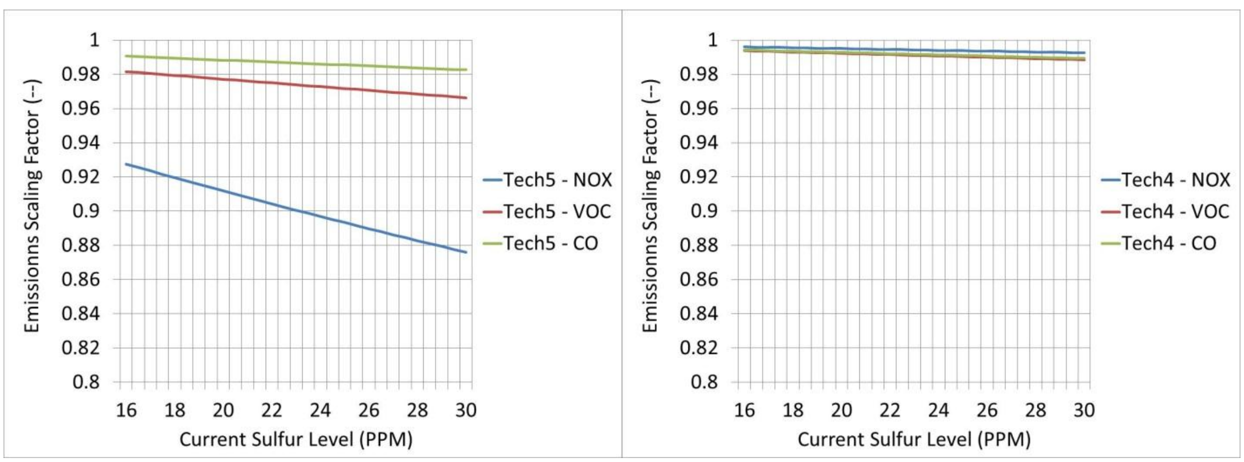


Figure 2. ARB Predictive Model-based emissions scaling factors for Technology Group 5 (left) and Technology Group 4 (right).

The adjustment factors from Figure 2 were used to scale the MOVES model estimates of g-LDV running and start exhaust VOC, CO, and NOx emissions on the basis of vehicle model year. Tech 5 adjustments were applied to model years 1996-2022 while Tech 4 adjustments were applied to 1992-1995. For consistency, the SO_2 and PM SO_4 emissions from g-LDVs also were scaled by a factor of 1/3 directly in the on-road inventory reflecting the reduction from a 30 ppm average gasoline sulfur standard to a 10 ppm average sulfur standard.

2.3.3.2 Tier 1 sulfur effects

For the Tier 1 scenario, ENVIRON used MOVES2010a to model sulfur effects on emissions from Tier 0 and Tier 1 g-LDVs corresponding to a sulfur increase from 21 to 228 ppm. The MOVES model's sulfur effect algorithms are the same as in MOBILE6, and they are based on relevant test data for pre-Tier 2 vehicles and higher sulfur fuel. To determine the emissions effects on running and start exhaust VOC, CO, and NOx, MOVES was run at 228 and 21 ppm sulfur holding all other fuel parameters constant. The ratios of emissions at 228 to 21 ppm are shown in Table 4 for running and start exhaust, respectively.

Table 4. MOVES2010a ratio of g-LDV emissions at 228 ppm over emissions at 21 ppm.

Technology	Running Exhaust			Start Exhaust		
	CO	VOC	NOx	CO	VOC	NOx
Tier 1	1.2176	1.383	1.174	0.9272	1.0314	1.2139
Tier 0	1.2475	1.2453	1.088	0.9320	1.0244	1.1147

Tier 1 emissions adjustments apply to model year 1994-2022 vehicles while Tier 0 adjustments apply to model years 1992 and 1993. For consistency with the modeled increase in gasoline sulfur content, SO_2 and PM SO_4 emissions from g-LDVs in the CRC Tier 1 on-road inventory were also increased by a factor of 228/21 to derive the Tier 1 emissions inventory for the current study.

2.3.4 LDV emissions adjustment methodology

The application of sulfur-based emissions adjustments to the LEV III and Tier 1 inventories was similar between the two scenarios. The low-sulfur adjustments in LEV III and the high-sulfur adjustments in Tier 1 scenarios apply to individual model years of g-LDVs but the original scenario inventories to be updated have a fleetwide average age level of detail. Thus the first step was to aggregate the "by model year" adjustments to fleetwide adjustment factors.

2.3.4.1 LEV III Scenario Fleetwide Adjustments

Equations 1 through 3 explain how the "by model year" low-sulfur emissions effects from Figure 2 were incorporated into the LEV III scenario inventory. Predictive Model emissions ratios applied to by-model-year emissions of the pollutants according to technology type (Tech 4 or Tech 5) are shown below in Equations 1a and 1b.

For $1992 \leq i < 1996$ (Tech 4) [Eqn. 1a]

$$Emissions_{i,j,k,l\ \sim 10\ ppm\ S} = \left(Emissions_{i,j,k,l\ \sim\ 30\ ppm\ S}\right) \times \left(R_{\text{Tech 4}}\right)_k$$

For $1996 \leq i \leq 2022$ (Tech 5) [Eqn. 1b]

$$Emissions_{i,j,k,l\,\sim\,10\,ppm\,S} = \left(Emissions_{i,j,k,l\,\sim\,30\,ppm\,S}\right) \times (R_{\text{Tech 5}})_k \times (P_{non\,LEV\,III}) + \left(Emissions_{i,j,k,l\,\sim\,30\,ppm\,S}\right) \times (P_{LEV\,III})$$

Where *i* = Model Year
j = Vehicle Class: LDGV, LDGT1, LDGT2
k = Pollutant: NOx, VOC, CO
l = Emissions Process: running exhaust, start exhaust
~ = The approximate sulfur level: county levels reflect sub-30ppm compliance levels (vis-a-vis sub-10ppm)
$R_{Tech4/5}$ = Emissions ratio adjustment factor for pollutants *k* from Figure 2
$P_{non\,LEV\,III}$ = Percent of fleet as sum of Tier 2, Tier 1, LEV, TLEV, and Tier 0 in Table 2
$P_{LEV\,III}$ = Percent of LEVIII fleet.

Equations 2 and 3 show how the by model year emissions using Equation 1a and 1b sum from by model year to the fleetwide level. Equation 2 shows how the by model year emissions are combined using a travel fraction weight. We note that the unadjusted MOVES inventory for the July 2022 LEV III Scenario already contains fleetwide emissions by SCC and county; these fleetwide emissions reflect the exact same travel fractions used in Equation 2 and shown in Figure 3. The by model year detail was necessary to incorporate sulfur effects by technology group, which is the only reason the travel fractions must be applied externally, as shown here.

$$Emissions_{j,k,l\,\sim\,10\,ppm\,S} = \sum_{i=1992}^{2022}\left\{\left(Emissions_{i,j,k,l\,\sim\,10\,ppm\,S}\right) \times TF_{i,j}\right\} \quad \text{[Eqn. 2]}$$

Where *i* = Model Year
j = Vehicle Class: LDGV, LDGT1, LDGT2
k = Pollutant: NOx, VOC, CO
l = Emissions Process: running exhaust, start exhaust
~ = The approximate sulfur level: county levels reflect sub-30ppm compliance levels (vis-a-vis sub-10ppm).
TF = Travel Fraction

Equation 3 shows the calculation of travel fractions, which are fractions that sum to 1 over the 31 model years for each vehicle class for the 2022 calendar year. A travel fraction simply represents model year contribution to the overall vehicle class VMT activity. They are calculated as the product of annual mileage accumulation and registration fraction, normalized by vehicle class.

$$TF_{i,j} = \frac{MAR_{i,j} \times ADF_{i,j}}{\sum_i\left(MAR_{i,j} \times ADF_{i,j}\right)} \quad \text{[Eqn. 3]}$$

Where *i* = Model Year
j = Vehicle Class: LDGV, LDGT1, LDGT2

MAR = Mileage Accumulation Rate, the annual miles driven by model year *i*, vehicle *j*
ADF = Age Distribution Fraction, the fraction of registered vehicles in model year *i*

The travel fractions for LDGV, LDGT1, and LDGT2 are shown visually below in Figure 3. We note that LDGT1 and LDGT2 have identical VMT distributions to each other and that LDGVs have a higher relative proportion of VMT in the 2015-2022 model years compared to the trucks.

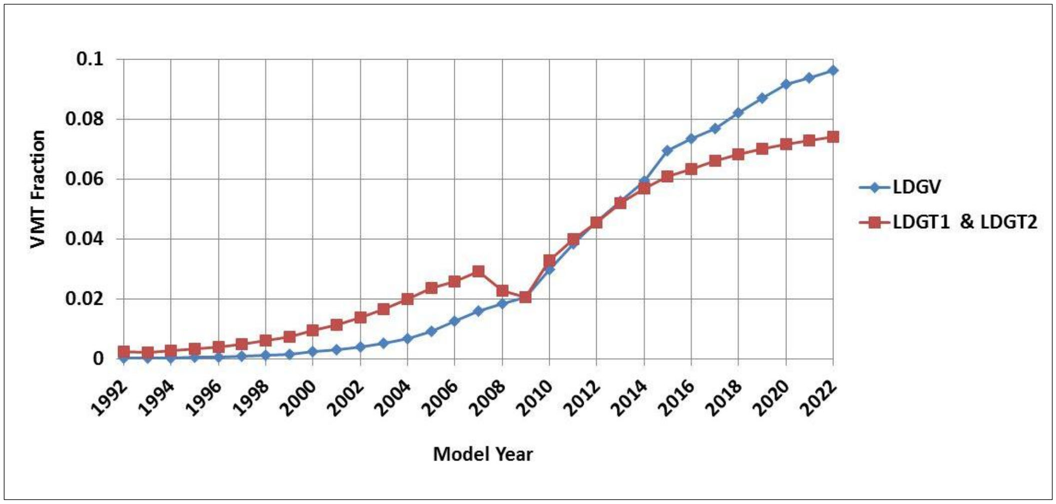


Figure 3. Year 2022 travel fractions for LDGV, LDGT1, and LDGT2 vehicles.

Equation 2 was applied twice—to sum the sulfur-adjusted emissions (~10 ppm) and also to sum the original unadjusted emissions (~30 ppm). The ratio of these two applications of Equation 2 produced fleetwide scaling factors that were multiplied directly with g-LDV emissions in the July 2022 LEV III scenario inventory. This final step to determine VOC exhaust, CO and NOx adjustments is shown in Equation 4.

$$Final\ Adjustment\ Factor_{j,k,l} = \frac{Emissions_{j,k,l\sim 10\ ppm\ S}}{Emissions_{j,k,l\sim 30\ ppm\ S}} \qquad \text{[Eqn. 4]}$$

Where *j* = Vehicle Class: LDGV, LDGT1, LDGT2
k = Pollutant: NOx, VOC, CO
l = Emissions Process: running exhaust, start exhaust
$Emissions_{j,k,l\sim 10\ ppm\ S}$ = Emissions adjusted for ~1/3 sulfur
$Emissions_{j,k,l\sim 30\ ppm\ S}$ = Unadjusted emissions

The fleetwide adjustments were multiplied on the basis of representative county[2,3] (except California where no adjustments are applied), g-LDV type, pollutant, and emission process (start

[2] A representative county is a county representing a group of counties with similar motor vehicle emission factors, as determined by fuel properties, inspection maintenance programs, fleet age distributions, and other parameters.
[3] Representative county basis is required for applying adjustments for consistency with original inventory development efforts for the CRC.

or running exhaust). Table 5 shows the range of fleetwide sulfur adjustments by representative county applied to the unadjusted LEV III scenario inventory to arrive at the final adjusted LEV III inventory.

Table 5. Representative County ranges of fleet average emissions scaling factors, LEV III scenario.

Vehicle	CO	VOC	NOx
Running			
LDGV	0.9868 - 0.9915	0.9731 - 0.9826	0.9027 - 0.9339
LDGT1	0.9862 - 0.9911	0.9733 - 0.9827	0.9043 - 0.935
LDGT2	0.9862 - 0.9911	0.9733 - 0.9827	0.9043 - 0.935
Starts			
LDGV	0.9869 - 0.9916	0.9733 - 0.9827	0.9019 - 0.9334
LDGT1	0.9861 - 0.9910	0.9718 - 0.9817	0.8969 - 0.9300
LDGT2	0.9861 - 0.9910	0.9718 - 0.9817	0.8969 - 0.9300

The adjustments to the SO_2 and SO_4 inventory are not a function of model year so they were performed in a later stage of emissions processing than adjustments to VOC, CO and NOx. Equation 5 shows the fleetwide emissions adjustments for SO_2 and SO_4 to account for the reduction in gasoline sulfur.

$$Emissions_{j,k,l\ \sim 10\ ppm\ S} = \frac{1}{3}\left(Emissions_{j,k,l\ \sim 30\ ppm\ S}\right) \quad \text{[Eqn. 5]}$$

Where *j* = Vehicle Class: LDGV, LDGT1, LDGT2

k = Pollutant: SO_2, PM_{10} SO_4, $PM_{2.5}$ SO_4

l = Emissions Process: running exhaust, start exhaust

~ = The approximate sulfur level: county levels reflect sub-30ppm compliance levels (vis-a-vis sub-10ppm).

2.3.4.2 Tier 1 Scenario Fleetwide Adjustments

The methodology described above in the LEV III scenario is generally applicable to the Tier 1 scenario. We provide below the corresponding equations and fleetwide scaling factors. The by model year high-sulfur emissions adjustments to g-LDVs are shown below in Equations 6a and 6b. These are analagous to the low-sulfur adjustments in Equations 1a and 1b.

For *i* = {1992, 1993} (Tier 0) [Eqn. 6a]

$$Emissions_{i,j,k,l\ at\ 228\ ppm\ S} = \left(Emissions_{i,j,k,l\ at\ 21\ ppm\ S}\right) \times \left(R_{\text{Tier 0}}\right)_k$$

For $1994 \geq i \geq 2022$ (Tier 1) [Eqn. 6b]

$$Emissions_{i,j,k,l\ at\ 228\ ppm\ S} = \left(Emissions_{i,j,k,l\ at\ 21\ ppm\ S}\right) \times (R_{\text{Tier 1}})_k$$

Where *i* = Model Year
j = Vehicle Class: LDGV, LDGT1, LDGT2
k = Pollutant: NOx, VOC, CO
l = Emissions Process: running exhaust, start exhaust
$R_{Tier\ 0/1}$ = Emissions ratio adjustment factor for pollutants *k* shown in Table 4

The next step was to sum the high-sulfur adjusted emissions from Equations 6a and 6b over model year using travel fractions as shown in Equation 7. This equation was also applied to unadjusted emissions by model year to determine the overall fleetwide scaling factors shown in Equation 8.

$$Emissions_{j,k,l\ at\ 228\ ppm\ S} = \sum_{i=1992}^{2022}\left\{\left(Emissions_{i,j,k,l\ at\ 228\ ppm\ S}\right) \times TF_{i,j}\right\} \qquad \text{[Eqn. 7]}$$

Where *i* = Model Year
j = Vehicle Class: LDGV, LDGT1, LDGT2
k = Pollutant: NOx, VOC, CO
l = Emissions Process: running exhaust, start exhaust
TF = Travel Fraction (previously defined in Equation 3 and illustrated in Figure 3)

$$Final\ Adjustment\ Factor_{j,k,l} = \frac{Emissions_{j,k,l\ 228\ ppm\ S}}{Emissions_{j,k,l\ \sim\ 30\ ppm\ S}} \qquad \text{[Eqn. 8]}$$

Where *j* = Vehicle Class: LDGV, LDGT1, LDGT2
k = Pollutant: NOx, VOC, CO
l = Emissions Process: running exhaust, start exhaust
$Emissions_{j,k,l\ 228ppm\ S}$ = Fleetwide emissions adjusted for 228 ppm sulfur
$Emissions_{j,k,l\ \sim\ 30\ ppm\ S}$ = Fleetwide emissions, unadjusted

The same fleetwide adjustments were applied to every county (including California) in the lower-48 states. The adjustments were applied on the basis of g-LDV type, pollutant, and emission process (start or running exhaust). Table 6 shows the fleetwide sulfur adjustments applied to the unadjusted Tier 1 scenario inventory to arrive at the final adjusted Tier 1 inventory.

Table 6. Fleet average emissions scaling factors, Tier 1 scenario.

Vehicle	CO	VOC	NOx
Running			
LDGV	1.2177	1.3810	1.1730
LDGT1	1.2187	1.3738	1.1700
LDGT2	1.2187	1.3738	1.1700
Starts			
LDGV	0.9273	1.0314	1.2131
LDGT1	0.9274	1.0312	1.2092
LDGT2	0.9274	1.0313	1.2092

The effect of increasing the nationwide gasoline sulfur content from 21 ppm to 228 ppm increases running exhaust g-LDV emissions of CO, VOC, and NOx by 22%, 37-38%, and 17% respectively. For g-LDV start exhaust, the CO decreases by 7%, and the VOC and NOx increase by 3% and 21% respectively. The somewhat unexpected decrease in CO start emissions with increasing sulfur content is noted in EPA's on-road emissions modeling documentation as being counterintuitive but supported by real-world data (EPA, 2001).

Equation 9 shows the fleetwide adjustments to the SO_2 and PM SO_4 emissions inventories that were made to account for the higher Tier 1 gasoline sulfur levels.

$$Emissions_{j,k,l\ at\ 228\ ppm\ S} = \frac{228}{21}\left(Emissions_{j,k,l\ \sim 30\ ppm\ S}\right) \qquad \text{[Eqn. 9]}$$

Where *j* = Vehicle Class: LDGV, LDGT1, LDGT2
k = Pollutant: SO_2, PM_{10} SO_4, $PM_{2.5}$ SO_4
l = Emissions Process: running exhaust, start exhaust
$Emissions_{j,k,l\ \sim 30\ ppm\ S}$ = Unadjusted emissions

2.3.5 Conversion of on-road emissions to CAMx-ready emissions files

The on-road emissions for July from MOVES for both emissions scenarios were speciated to CAMx model species, temporally allocated to hourly emissions, and spatially allocated to grid cells using version 2.7 of the Sparse Matrix Operator Kernel Emissions (SMOKE) model. Average day emissions were adjusted to account for day-of-week and hour-of-day effects based on SCC codes. Emission estimates for total VOC were converted to the CB05 chemical mechanism in CAMx using VOC speciation profiles derived from EPA's SPECIATE database, version 4.3 (EPA, 2011). On-road mobile sources generated using MOVES at the county level were allocated to CAMx 36 km and 12 km grid cells using spatial surrogates derived with the Spatial Surrogate Tool (http://www.epa.gov/ttn/chief/emch/spatial/spatialsurrogate.html).

2.4 Other model inputs

Other model inputs (e.g., boundary concentrations of $PM_{2.5}$ and other pollutants for the 36 km domain, landuse/ landcover data, photolysis rates) required for CAMx modeling were obtained from the CRC study and were held the same across the 2022 scenarios.

3.0 RESULTS AND DISCUSSION

3.1 Emissions and Air Quality in 2022 Scenarios

3.1.1 Emissions

The total CONUS anthropogenic emissions and the relative contributions of the major source sectors in the CRC 2022 Tier 2 scenario are shown in Figure 4.

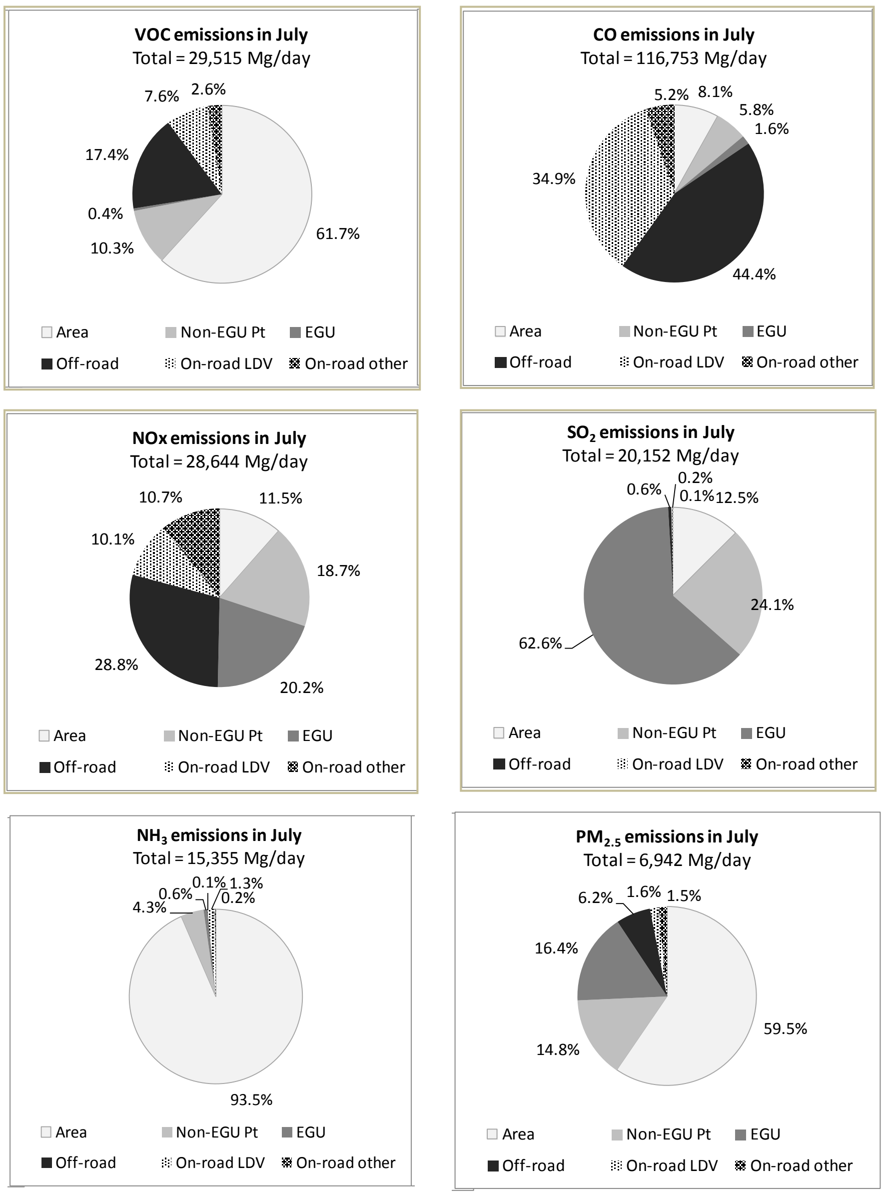


Figure 4. Estimated summertime anthropogenic emissions in the continental US in the 2022 Tier 2 scenario (source: Vijayaraghavan et al., 2012).

The on-road LDV emissions of $PM_{2.5}$ precursors VOC, CO, NOx, SO_2, NH_3 and primary $PM_{2.5}$ constitute approximately 8%, 35%, 10%, 0.2%, 1.3% and 1.6%, respectively, of the total US anthropogenic inventory in 2022. Emissions from source sectors other than on-road sources are held constant between this scenario and the other 2022 scenarios. The emissions inventories are described in detail in Vijayaraghavan et al., 2012.

A comparison of average day g-LDV emissions of VOC, CO, NOx, SO_2, NH_3 and $PM_{2.5}$ emissions between the Tier 1, Tier 2, and LEV III scenario inventories is presented in Table 7. The benefit by 2022 from advancing to Tier 2 controls in 2004 rather than remaining at Tier 1 is reflected by large decreases in g-LDV emissions of 62%, 51%, and 80%, for VOC, CO and NOx, respectively. There are reductions of 92%, 64% and 19% in SO_2, NH_3 and $PM_{2.5}$ emissions, respectively; however, these pollutants constitute a very small portion of the total US anthropogenic inventory as discussed above and hence their contribution to reductions in ambient $PM_{2.5}$ concentration is expected to be minor. The additional benefits expected by 2022 with partial LEV III technology penetration are further reductions of 8%, 7%, 11%, 64% and 5% in VOC, CO, NOx, SO_2, and $PM_{2.5}$ emissions, respectively, from CONUS emissions of g-LDVs.

Table 7. July 2022 emissions in the continental US from gasoline light-duty vehicles.

Pollutant	Tier 1 Scenario (Mg/day)	Tier 2 Scenario (Mg/day)	Tier 2 Benefit (Tier2-Tier1) / Tier1	LEV III Scenario (Mg/day)	LEV III Benefit (LEVIII-Tier2) / Tier2
VOC	6,061	2,275	-62%	2,096	-8%
CO	83,585	40,813	-51%	37,755	-7%
NOx	14,221	2,879	-80%	2,553	-11%
SO_2	620.3	48.4	-92%	17.5	-64%
NH_3	568.3	206.8	-64%	206.8	0%
$PM_{2.5}$	132.9	107.6	-19%	101.9	-5%

These benefits are smaller when looking at the emissions reductions in the context of total on-road emissions. For example, while g-LDVs make up 88% of the nationwide total 2022 July day VMT of 10.5 billion miles, they comprise less than half of the on-road NOx and about half the on-road $PM_{2.5}$ inventory in summer. Table 8 summarizes the total on-road emissions from the three scenarios and the incremental benefit of Tier 2 over Tier 1 and LEV III over Tier 2.

Table 8. July 2022 emissions in the continental US from all on-road motor vehicles.

Pollutant	Tier 1 Scenario (Mg/day)	Tier 2 Scenario (Mg/day)	Tier 2 Benefit (Tier2-Tier1) /Tier1	LEV III Scenario (Mg/day)	LEV III Benefit (LEVIII-Tier2)/ Tier2
VOC	6,826	3,040	-55%	2,861	-6%
CO	89,670	46,898	-48%	43,840	-7%
NOx	17,277	5,935	-66%	5,609	-5%
SO_2	633.5	61.6	-90%	30.7	-50%
NH_3	602.6	241.1	-60%	241.1	0%
$PM_{2.5}$	238.1	212.7	-11%	207.0	-3%

3.1.2 Air quality

Prior to air quality modeling of the 2022 scenarios, a 2008 CAMx scenario was run to evaluate the model performance (Vijayaraghavan et al., 2012). The 2008 CAMx predictions of $PM_{2.5}$ mass and components were compared to daily (24-hour) average measurements in the AIRS/AQS (EPA, 2002) and IMPROVE (IMPROVE, 1995) networks. Overall, model performance was good with the mean fractional bias (MFB) and mean fractional error (MFE) of simulated versus observed values for $PM_{2.5}$ mass and components meeting the model performance criteria recommended by Boylan and Russell (2006).

Model simulation results for total $PM_{2.5}$ in July 2022 are presented in Figures 5 and 6 and for $PM_{2.5}$ components in Figures 7 – 20. In each case (i.e., for the total $PM_{2.5}$ and for each component), we first present the spatial distributions of the monthly mean of $PM_{2.5}$ concentrations in the three 2022 scenarios and then differences in these monthly means between pairs of 2022 LDV scenarios.

If vehicle emissions standards and gasoline sulfur levels for new g-LDVs were no more stringent than those that had been in place during the timeframe of the Tier 1 requirements, then the monthly mean of $PM_{2.5}$ concentrations in July 2022 could be as high as 32.5 $\mu g/m^3$ in the eastern US with values exceeding 20 $\mu g/m^3$ in parts of Indiana, Ohio, Pennsylvania, Maryland, Virginia, North Carolina, Tennessee and Alabama (see Figure 5).

As seen in Figures 5 and 6, strengthening the new g-LDV emissions standards and introducing federal gasoline sulfur requirements as represented by the transition from Tier 1 to Tier 2 reduces the monthly mean of $PM_{2.5}$ concentrations by over 1 $\mu g/m^3$ in July 2022 in large parts of the eastern US, and by up to 2.7 $\mu g/m^3$ in eastern Pennsylvania. Switching from Tier 2 to a nationwide LEV III program in conjunction with a reduction in gasoline sulfur to a 10 ppm average yields less than 0.1 $\mu g/m^3$ reduction in the monthly mean $PM_{2.5}$ concentration anywhere in the eastern US domain in July 2022.

When considering the monthly peak of 24-h $PM_{2.5}$ concentrations, the largest benefit of the LEV III standard compared to the Tier 2 standard in the same model grid cell anywhere in the model domain is small (0.2 $\mu g/m^3$, in eastern Pennsylvania) compared to the Tier 2 benefit over Tier 1 (5.8 $\mu g/m^3$, also in eastern Pennsylvania).

Among the $PM_{2.5}$ components, the largest modeled benefit in July 2022 that results from the transition from Tier 1 to Tier 2 occurs for $PM_{2.5}$ nitrate (decreases of up to 1.8 $\mu g/m^3$) reflecting reductions in g-LDV NOx emissions. The additional $PM_{2.5}$ nitrate benefit from the implementation of a LEV III-like standard is less than 0.05 $\mu g/m^3$ over the entire modeling domain. Monthly mean concentrations of summertime $PM_{2.5}$ sulfate decrease by up to 0.3 $\mu g/m^3$ between the Tier 1 and Tier 2 scenarios. The additional decrease in $PM_{2.5}$ sulfate concentrations with the transition to LEV III is projected to be less than 0.02 $\mu g/m^3$ anywhere in the modeling domain despite the strengthening of the gasoline sulfur standard to 10 ppm. This is due to the fact that g-LDV SO_2 emissions constitute a small fraction (0.2%) of the total anthropogenic inventory. Improvements in other $PM_{2.5}$ components are less than that seen for $PM_{2.5}$ sulfate with the exception of $PM_{2.5}$ ammonium which show up to 0.6 $\mu g/m^3$ reductions from Tier 1 to Tier 2 (and no further reductions with LEV III because g-LDV NH_3 emissions do not change).

We note that the LEV III standard for PM emissions from new g-LDVs will not be fully phased in until model year 2028 and the LEV III standard for NOx + non-methane organic gas emissions will not be phased in until model year 2025. The results shown represent the air quality benefits achievable by 2022; approximately 27% of the g-LDV fleet would not have transitioned to the LEV III standard by this year (see Table 2). We expect some additional improvements in $PM_{2.5}$ to occur in the post 2022 time period as a result of the complete phase-in of the LEV III standard. Also, modeling was performed only for summertime $PM_{2.5}$ because inputs for prior summertime ozone modeling conducted for API were applied in the current study.

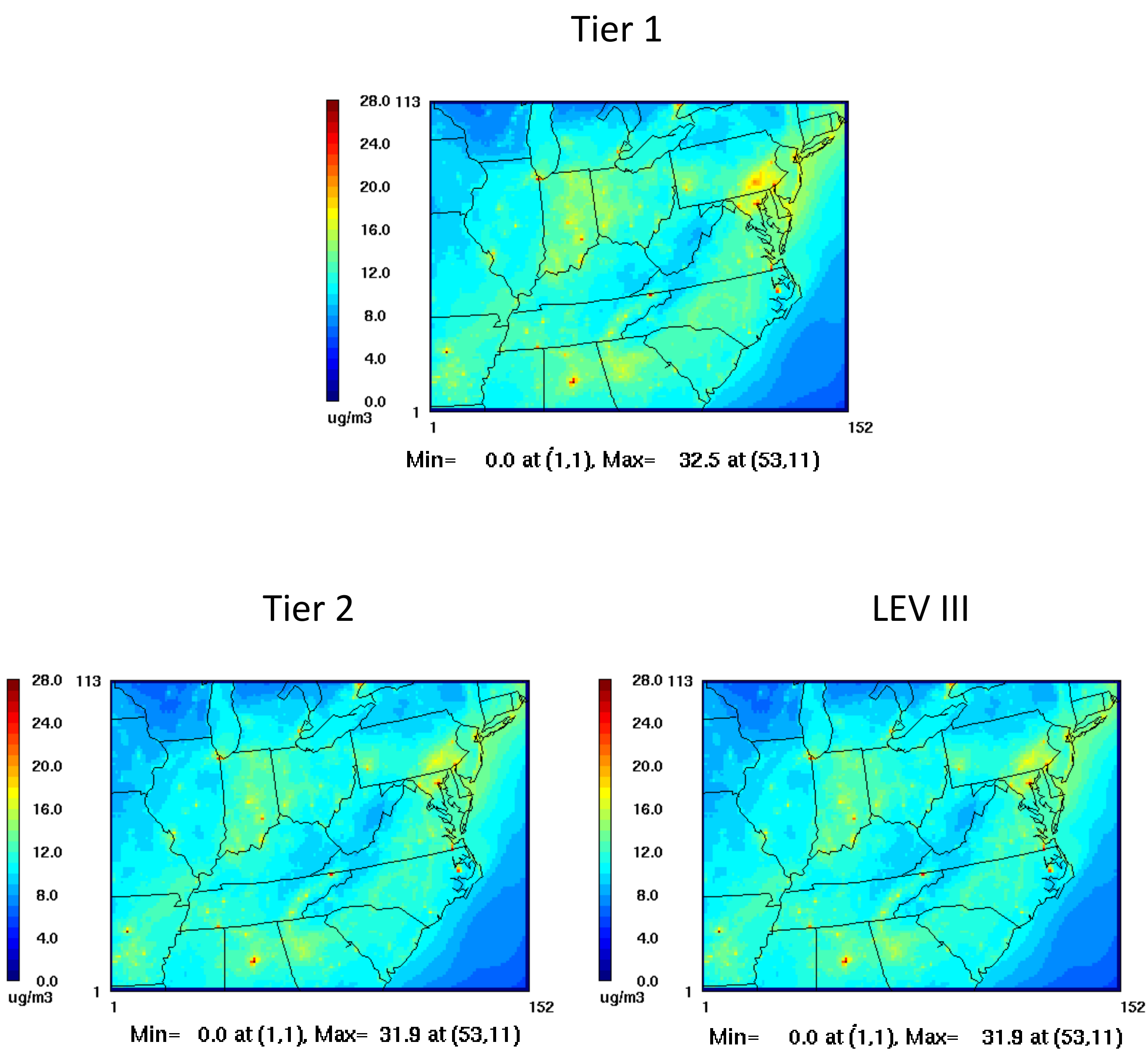


Figure 5. Monthly mean of $PM_{2.5}$ concentrations in July 2022 scenarios: Tier 1, Tier 2, LEV III.

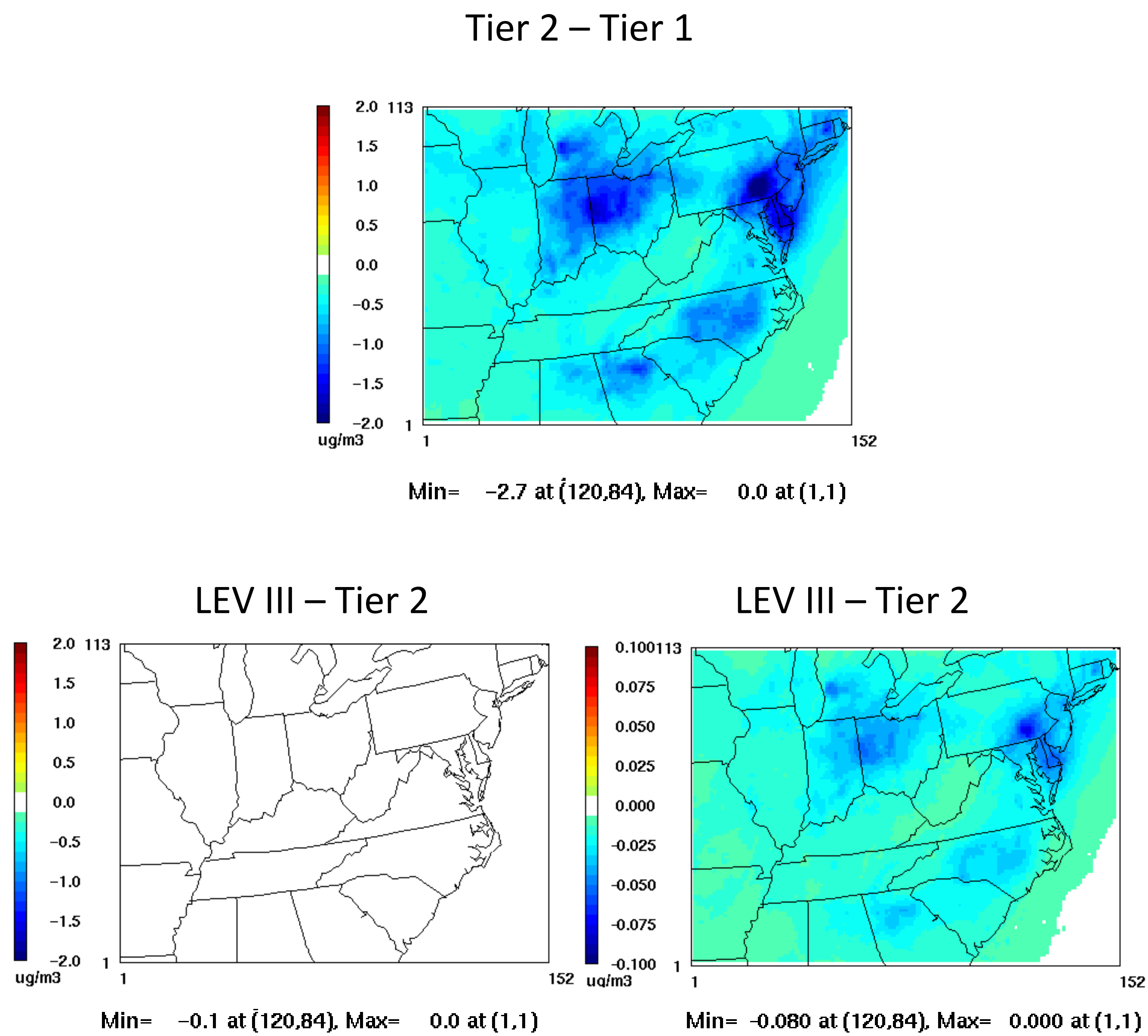


Figure 6. Differences in monthly mean of $PM_{2.5}$ concentrations in July 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two color scales).

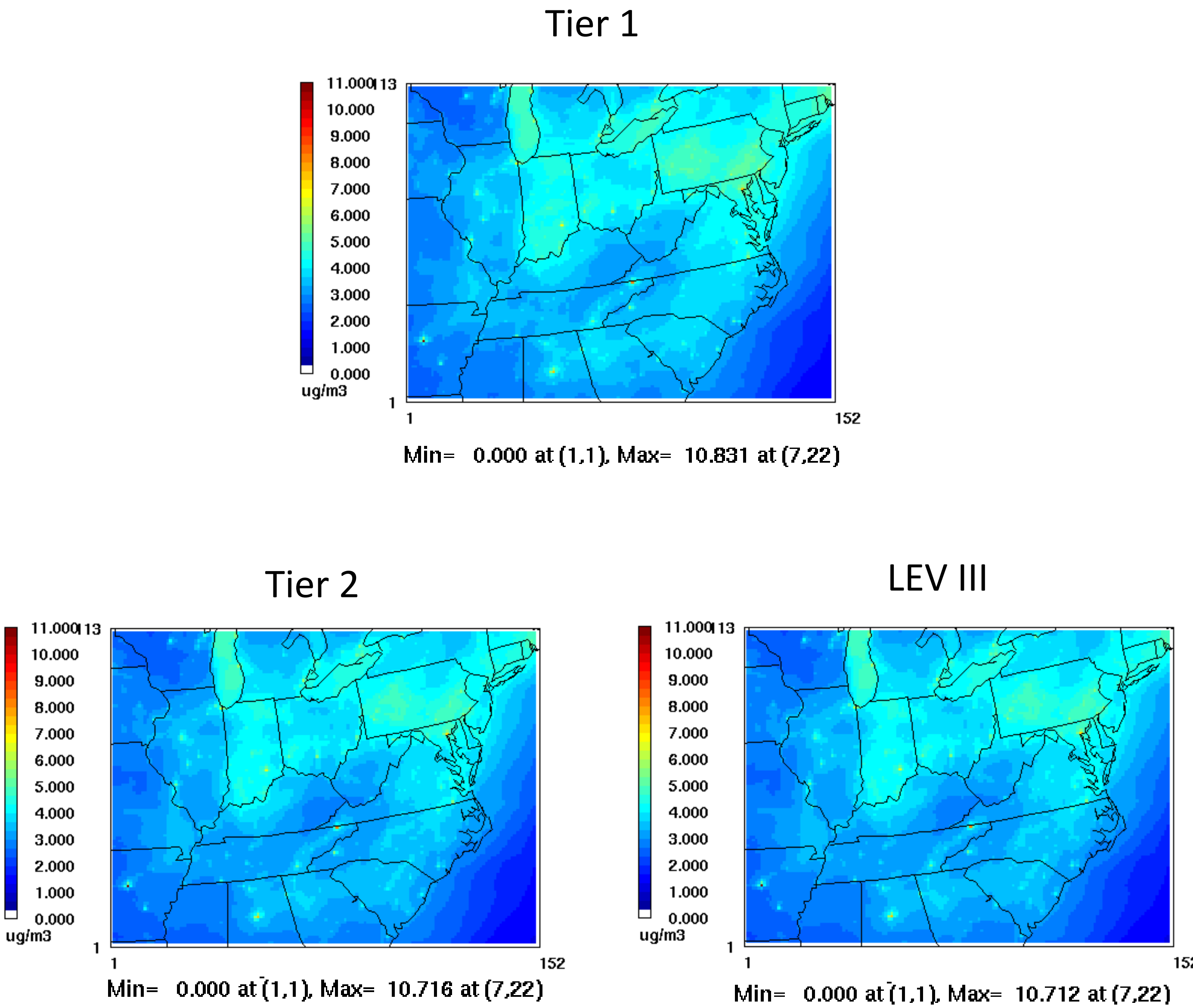


Figure 7. Monthly mean of $PM_{2.5}$ sulfate concentrations in July 2022 scenarios: Tier 1, Tier 2, LEV III.

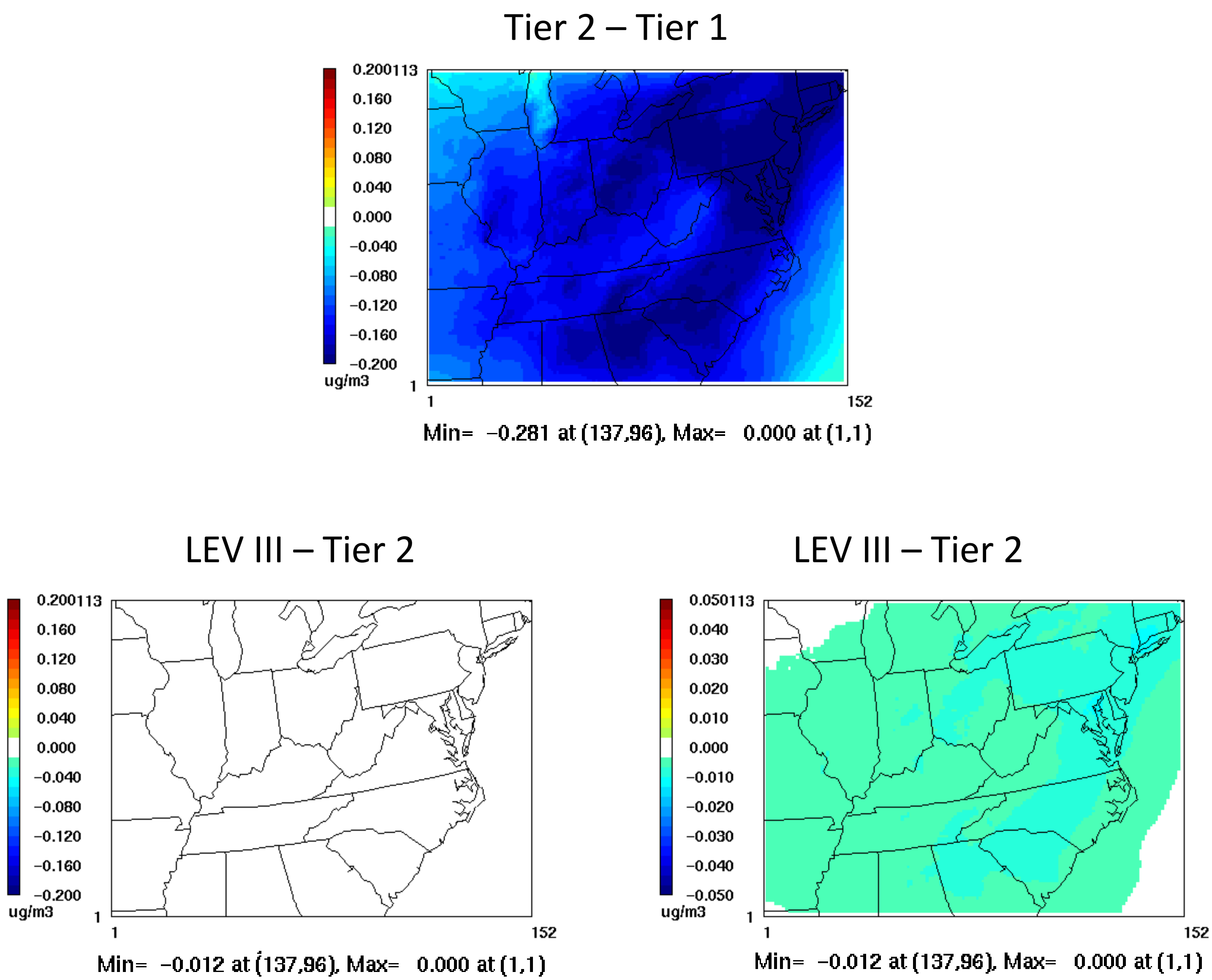


Figure 8. Differences in monthly mean of PM2.5 sulfate concentrations in July 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two color scales).

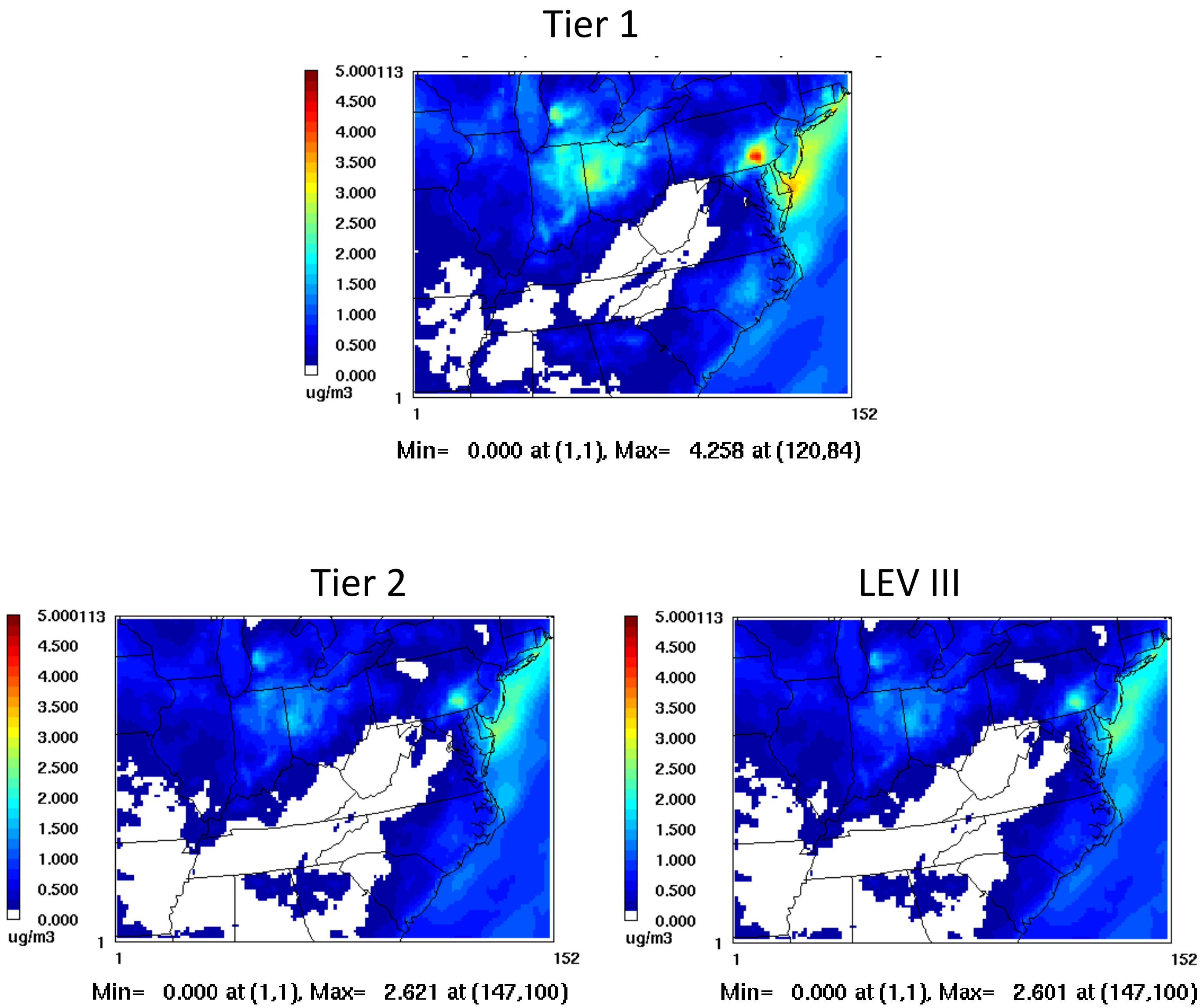


Figure 9. Monthly mean of $PM_{2.5}$ nitrate concentrations in July 2022 scenarios: Tier 1, Tier 2, LEV III.

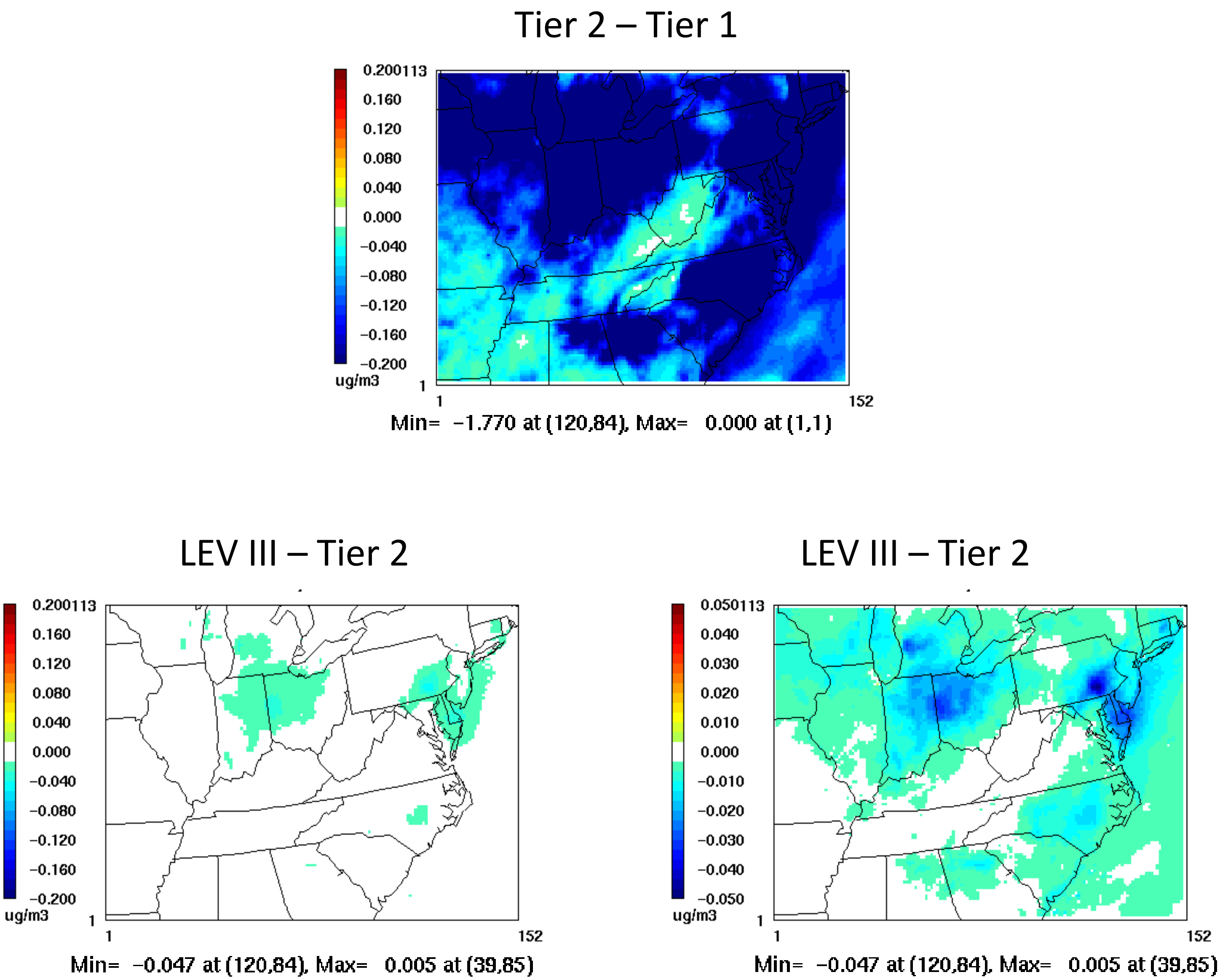


Figure 10. Differences in monthly mean of $PM_{2.5}$ nitrate concentrations in July 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two color scales).

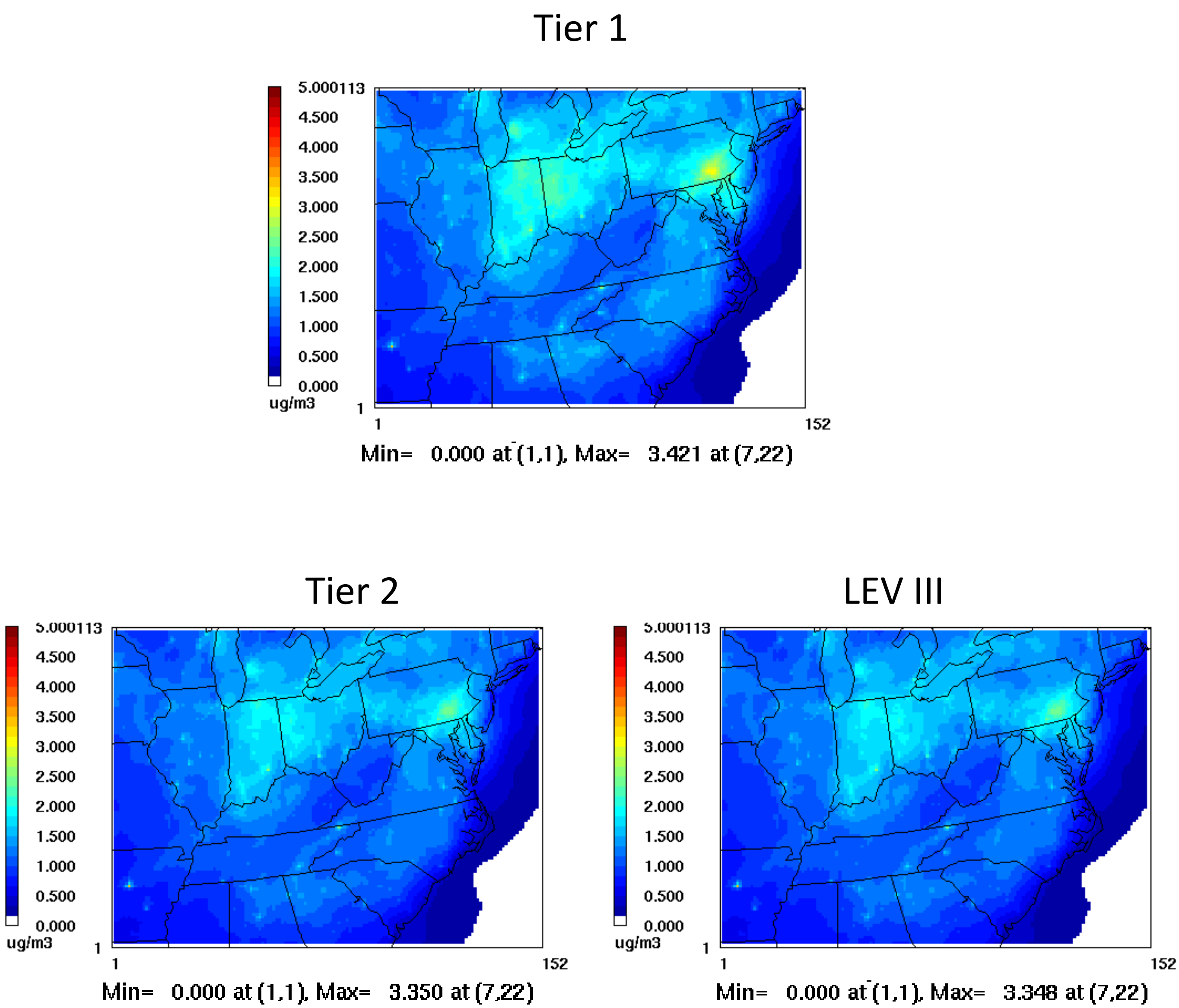


Figure 11. Monthly mean of $PM_{2.5}$ ammonium concentrations in July 2022 scenarios: Tier 1, Tier 2, LEV III.

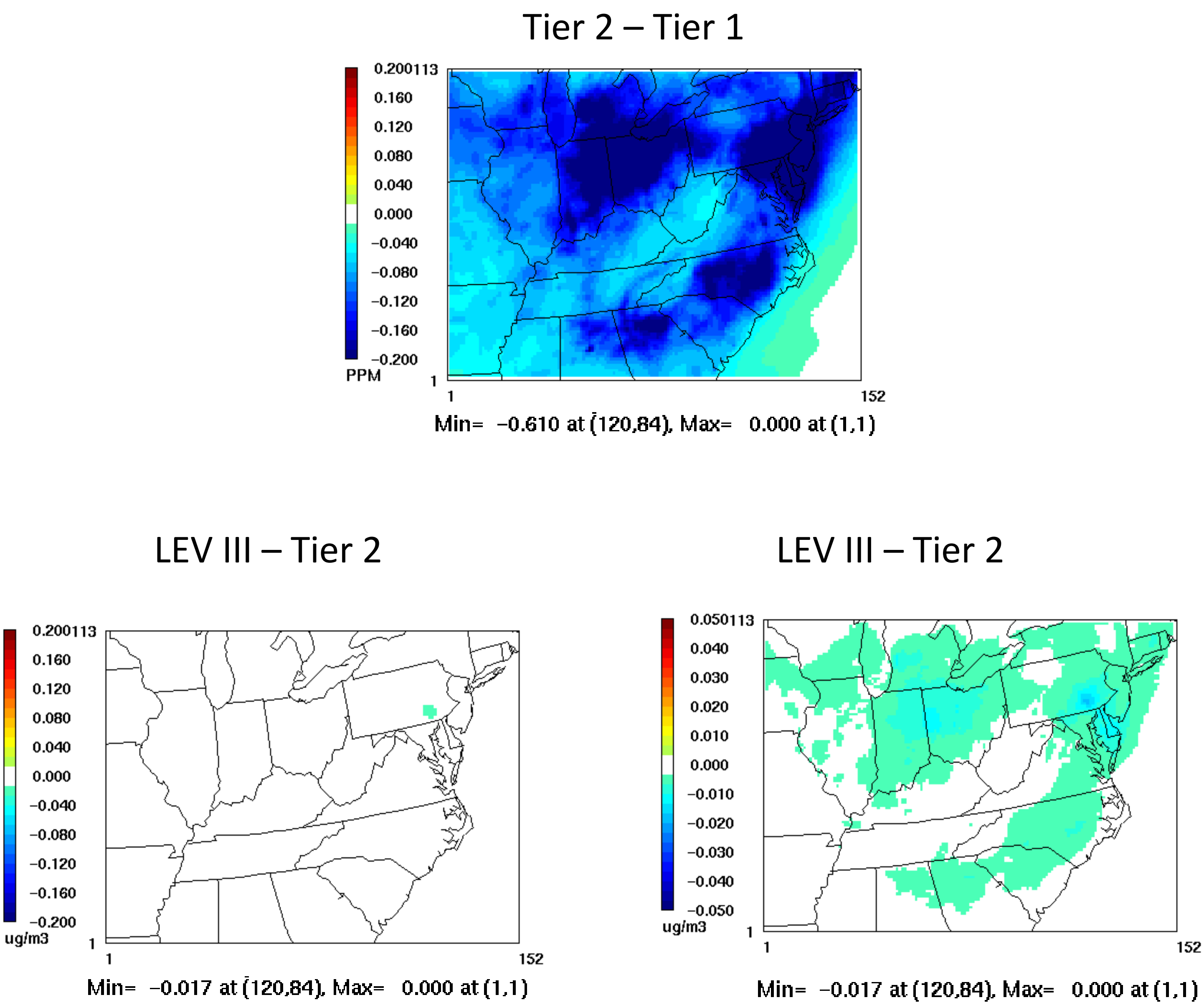


Figure 12. Differences in monthly mean of $PM_{2.5}$ ammonium concentrations in July 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two color scales).

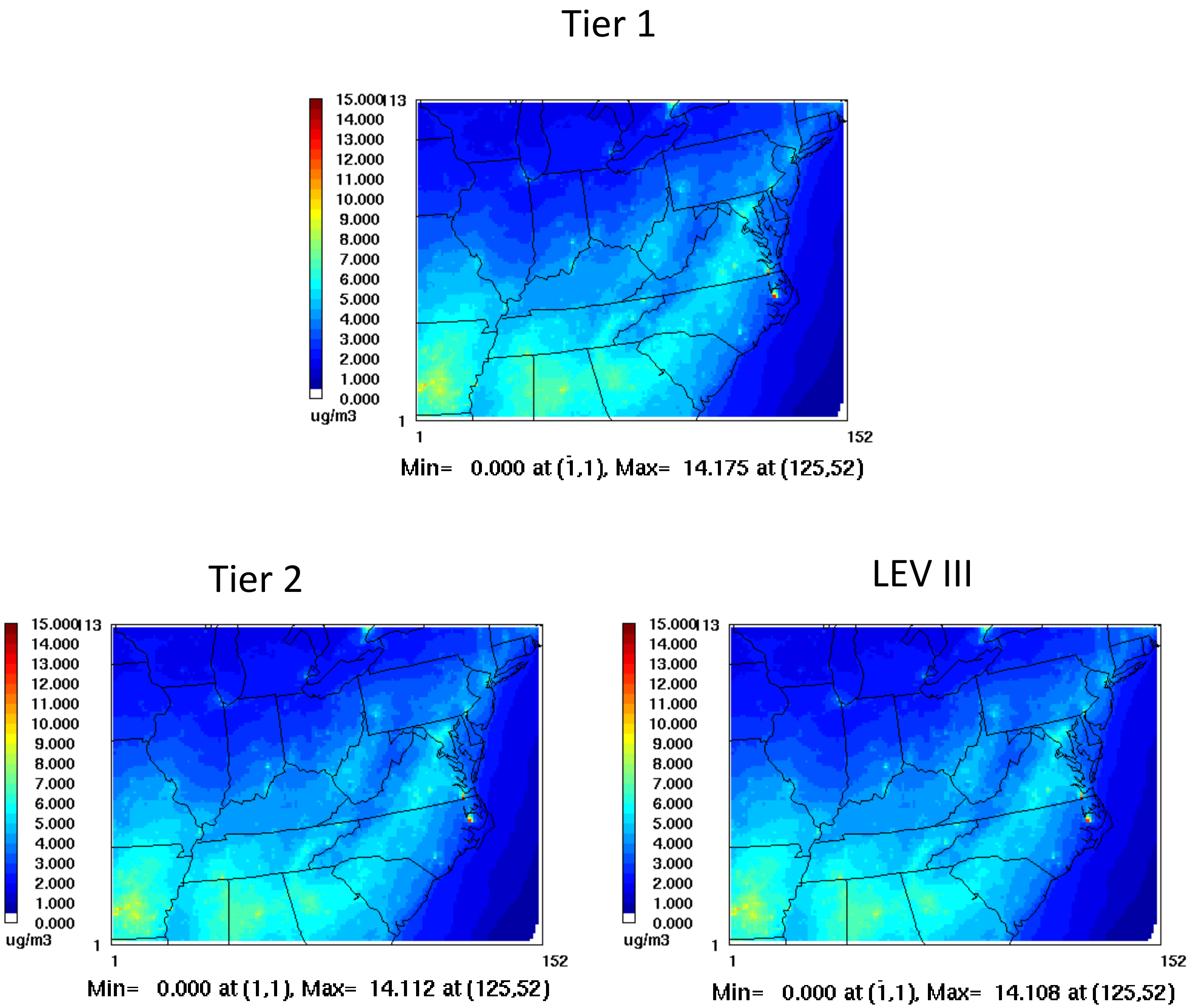
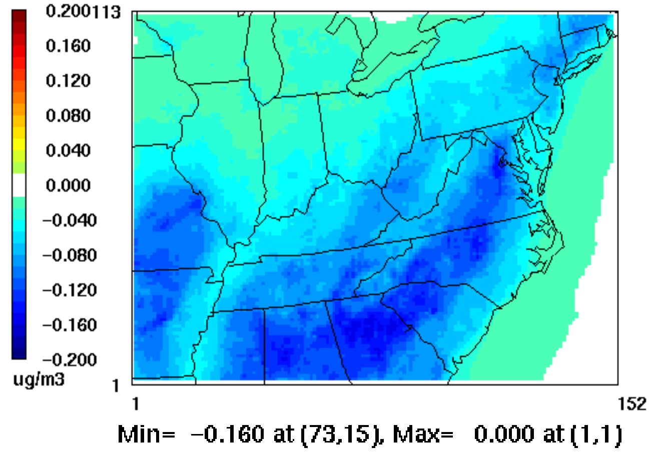
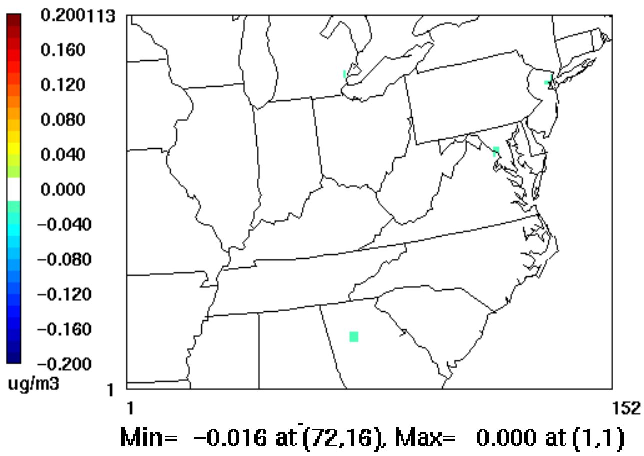


Figure 13. Monthly mean of $PM_{2.5}$ organic carbon concentrations in July 2022 scenarios: Tier 1, Tier 2, LEV III.

Tier 2 – Tier 1



LEV III – Tier 2



LEV III – Tier 2

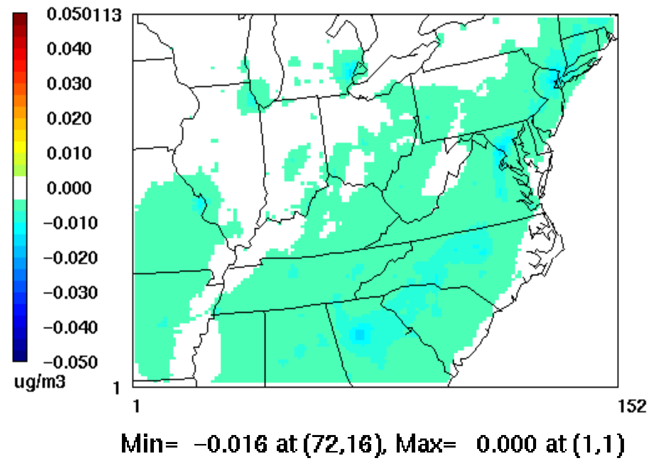


Figure 14. Differences in monthly mean of $PM_{2.5}$ organic carbon concentrations in July 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two color scales).

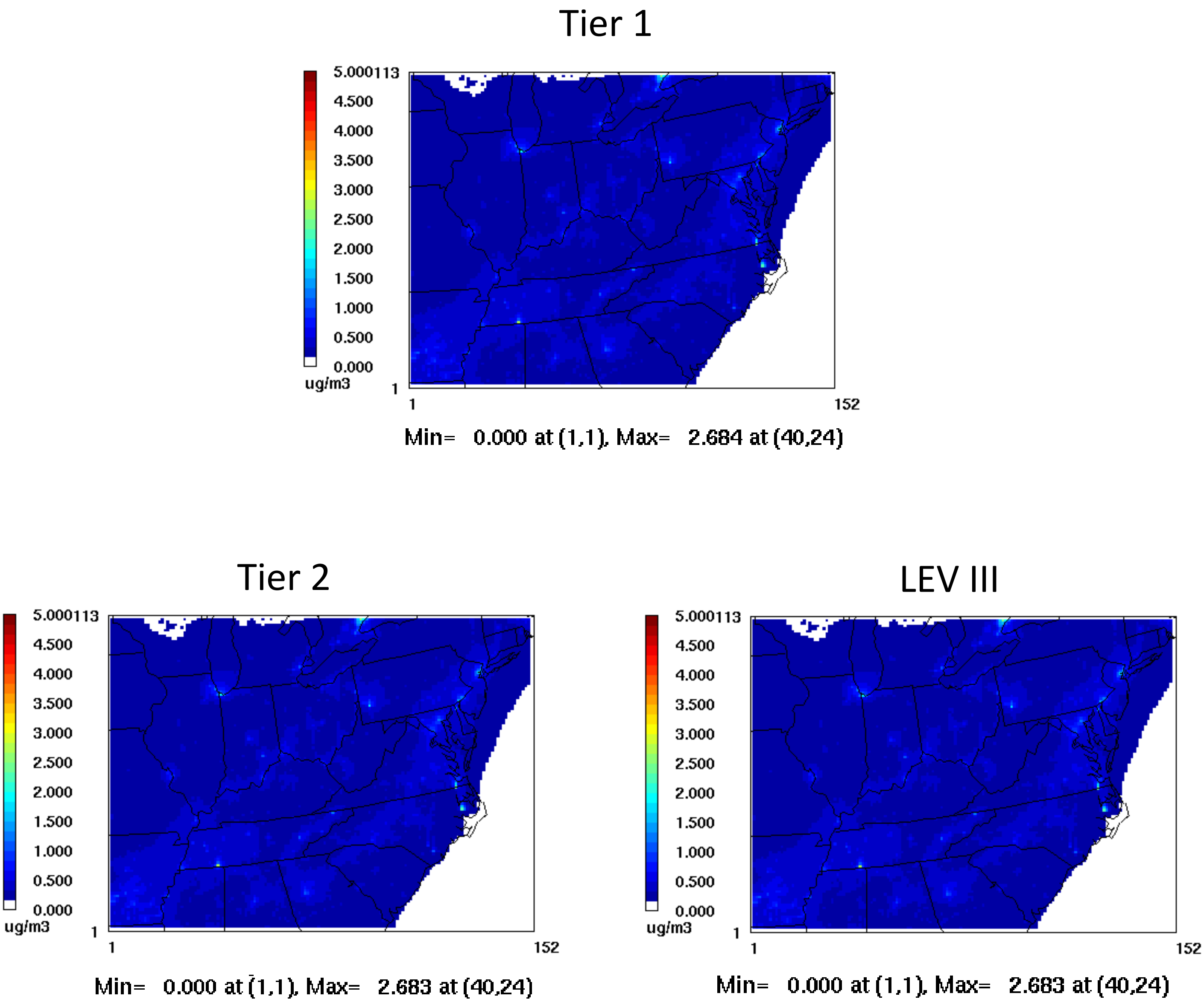


Figure 15. Monthly mean of $PM_{2.5}$ elemental carbon concentrations in July 2022 scenarios: Tier 1, Tier 2, LEV III.

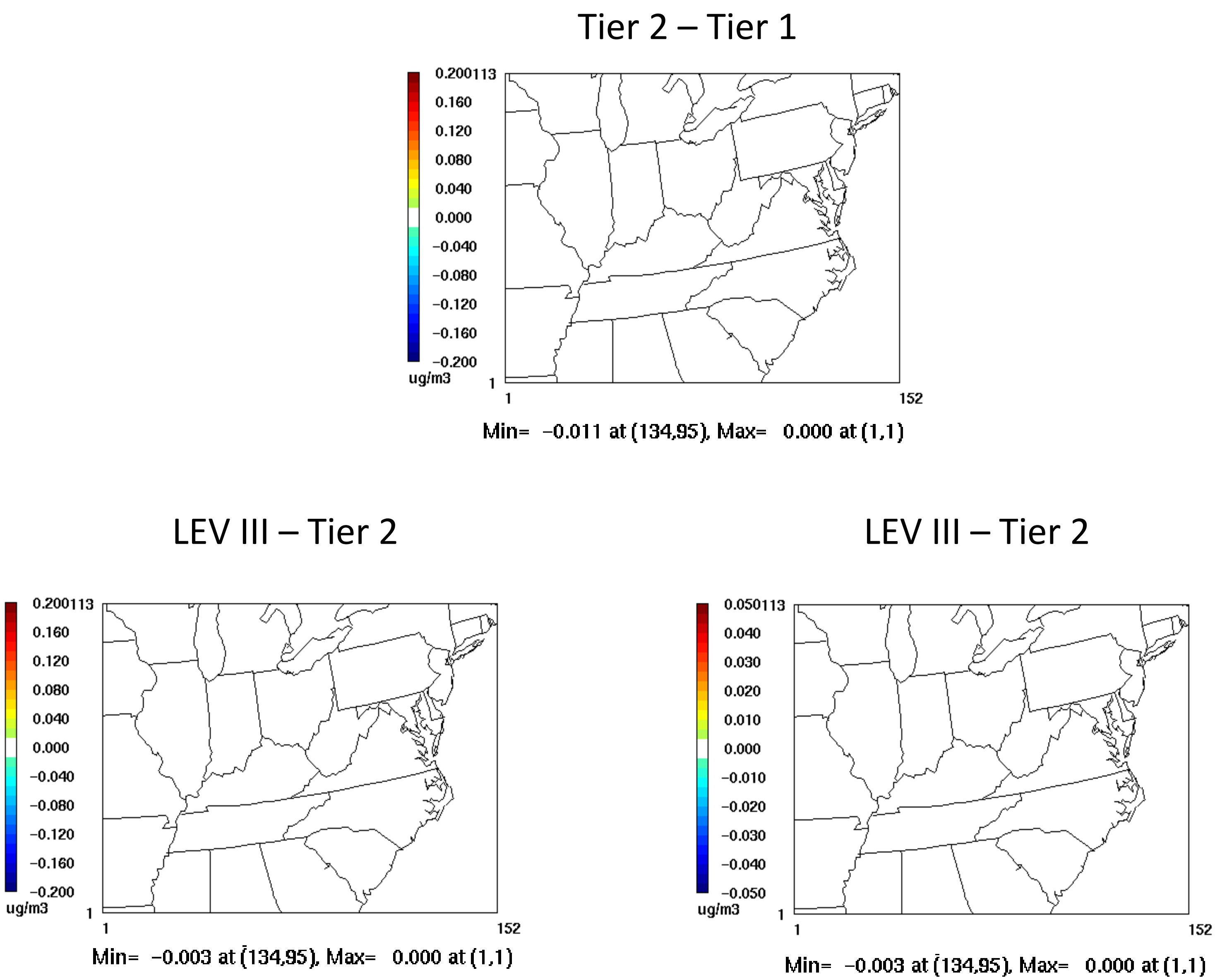


Figure 16. Differences in monthly mean of $PM_{2.5}$ elemental carbon concentrations in July 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two color scales).

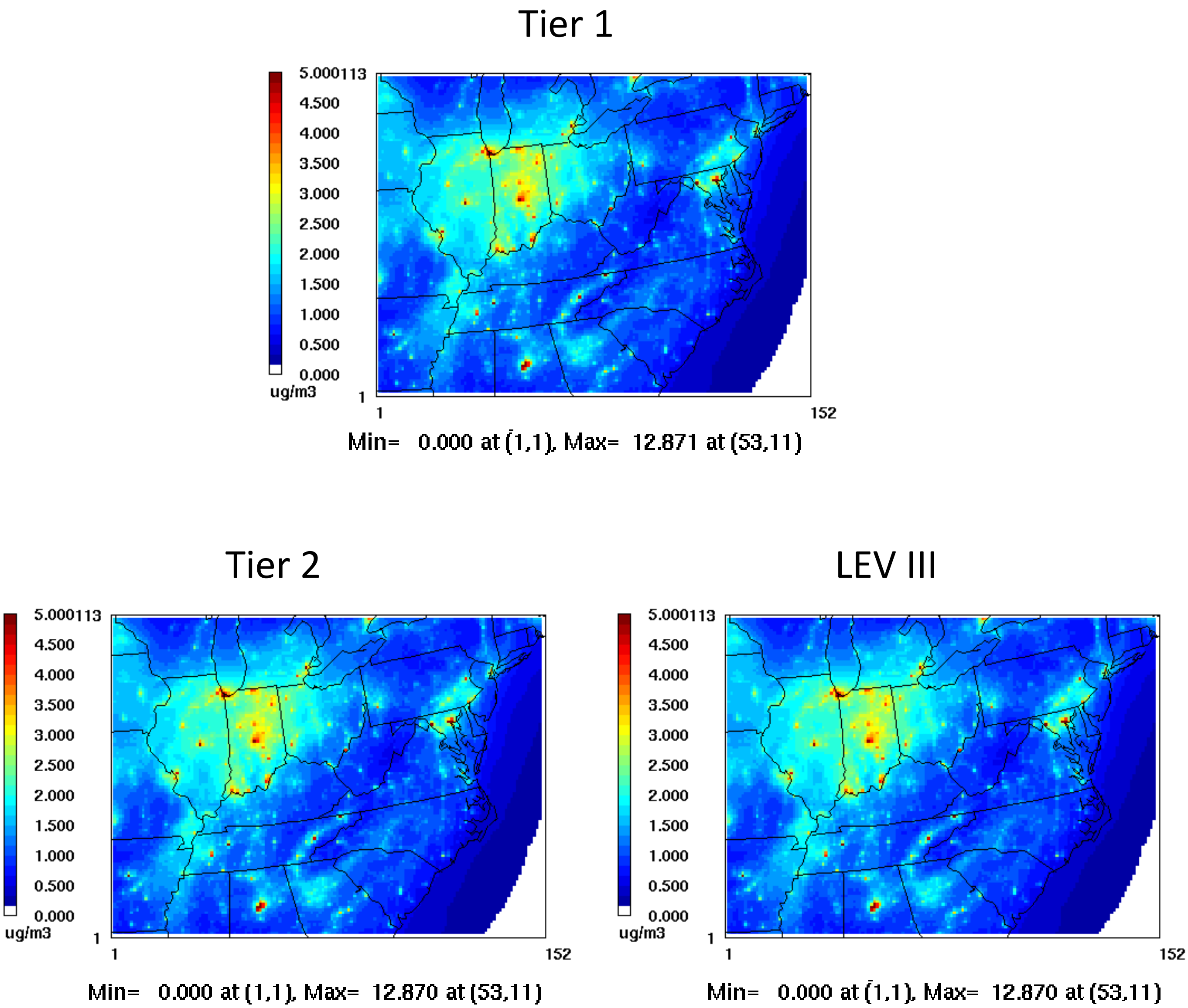
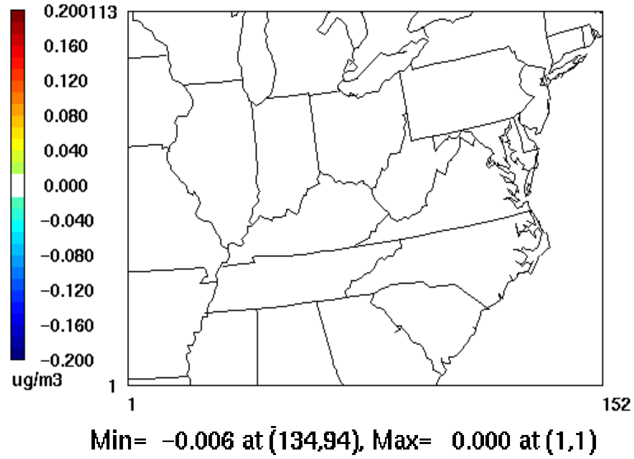
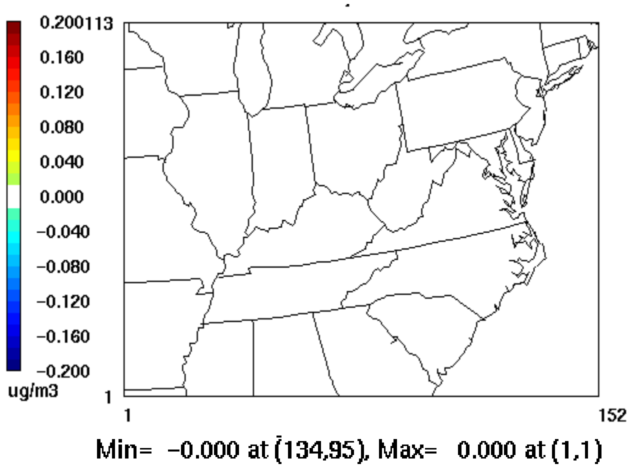


Figure 17. Monthly mean of crustal and other primary $PM_{2.5}$ concentrations in July 2022 scenarios: Tier 1, Tier 2, LEV III.

Tier 2 – Tier 1



LEV III – Tier 2



LEV III – Tier 2

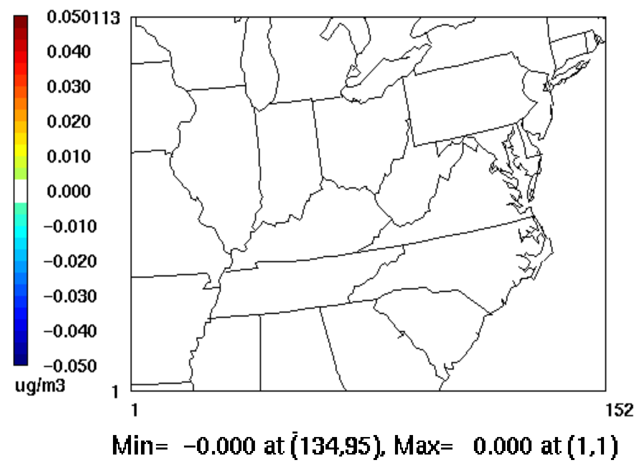


Figure 18. Differences in monthly mean of crustal and other primary $PM_{2.5}$ concentrations in July 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two color scales).

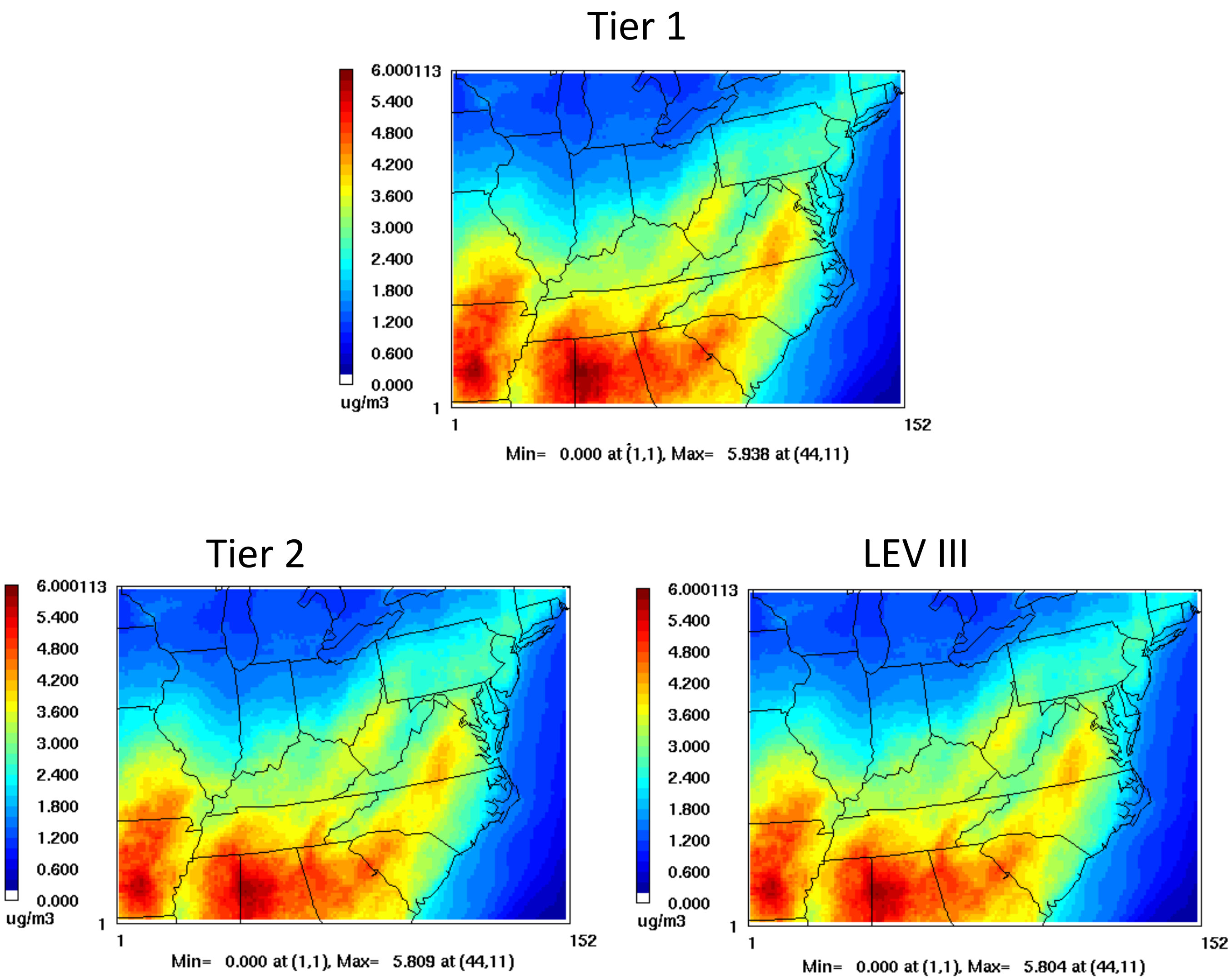


Figure 19. Monthly mean of secondary organic $PM_{2.5}$ concentrations in July 2022 scenarios: Tier 1, Tier 2, LEV III.

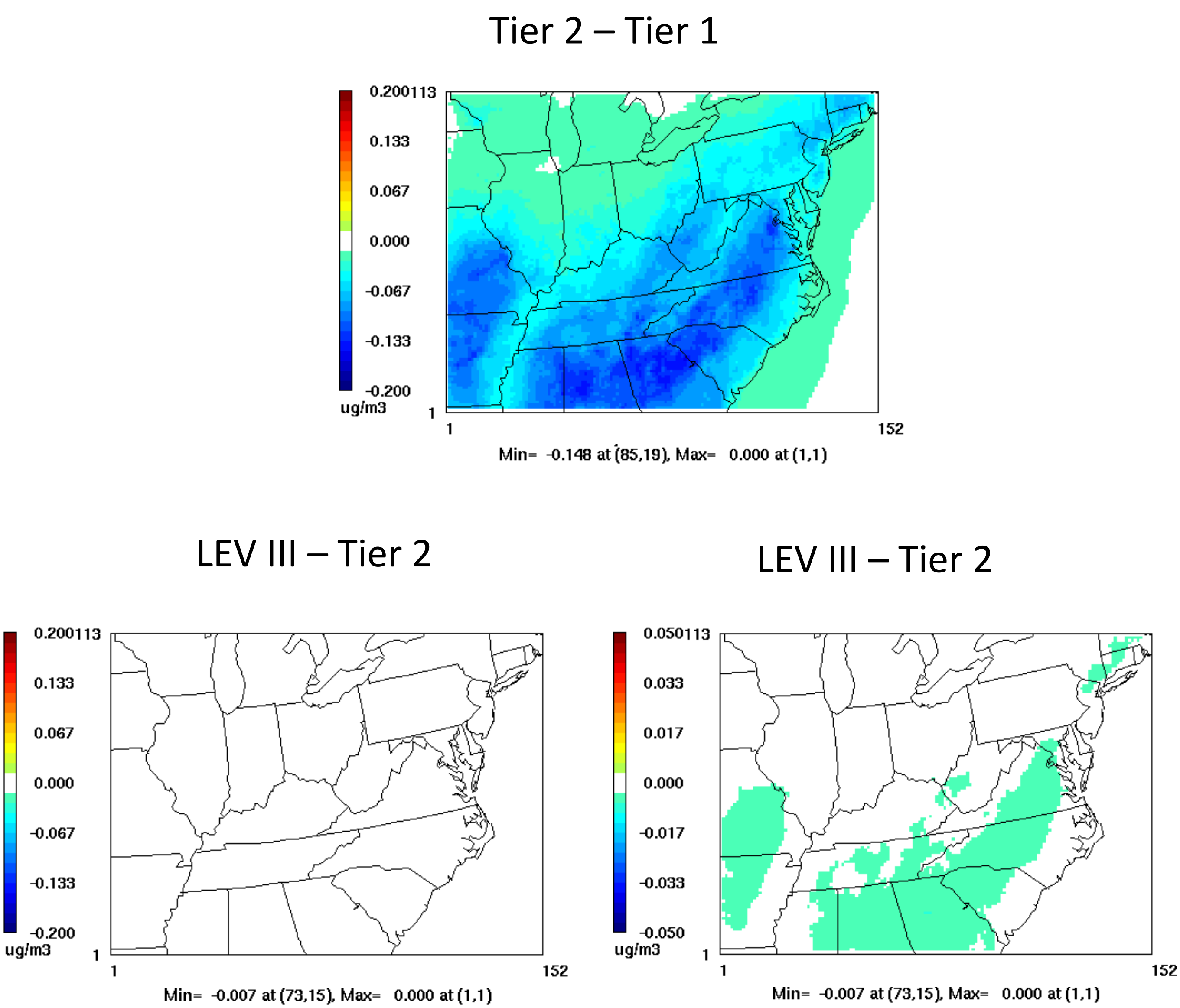


Figure 20. Differences in monthly mean of secondary organic $PM_{2.5}$ concentrations in July 2022 scenarios: Tier 2 – Tier 1 (top), LEV III – Tier 2 (bottom, two color scales).

3.2 Conclusion

Overall, the modeling results suggest that large improvements in summertime ambient ground-level $PM_{2.5}$ concentrations occur in the eastern US as a result of the switch from Tier 1 to Tier 2 standards. However, relatively small additional reductions in 2022 $PM_{2.5}$ concentrations are predicted to result from the transition to a Federal standard similar to the California LEV III standard, even when considering emissions reductions due to a lower gasoline sulfur content in the LEV III scenario. These results are due to one or both of the following factors depending on pollutant: (1) the change in emissions between the Tier 2 and LEV III scenarios is relatively small compared to the change between Tier 1 and Tier 2 scenarios, and (2) the Tier 2 LDV emissions of $PM_{2.5}$ precursors constitute a relatively small fraction of the total inventory. In particular, in the case of the $PM_{2.5}$ precursor that experiences the largest relative reduction from the Tier 2 to LEV III scenarios, SO_2, on-road LDV emissions constitute only 0.2% of the total anthropogenic inventory and hence SO_2 LDV emissions reductions result in small ambient $PM_{2.5}$ benefits.

The main limitation of this study is introduced by the lack of complete phase-in of the LEV III standard by 2022, the basis year for comparing emission standards. Some additional improvements in $PM_{2.5}$ beyond 2022 are expected as the LEV III standard fully matures. In addition, this study does not address wintertime $PM_{2.5}$ benefits.

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