Final report: Vehicle Miles Traveled Review

Prepared for the Tahoe Science Advisory Council Threshold Update 2017-18

by

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1 Summary:

We present a review of vehicle emissions of nitrogen (N) and roadway dust from vehicles traveling in the Tahoe basin with an emphasis on the relationship between vehicle miles traveled (VMT) and the deposition of nitrogen and dust on Lake Tahoe. Six topic briefs have been prepared that summarize the state of knowledge in the peer-reviewed literature on the following questions: (1) VMT and roadway condition; how does VMT affect or correspond with roadway condition? (2) Roadway condition and fine sediment; how does roadway condition affect generation and transport of fine sediment particles? (3) Nitrogen emission sources (In-Basin); overview of current emissions, drivers, and seasonal and interannual variation; (4) Nitrogen emissions from automobiles (historic perspective and projected); how have emissions changed between 1982 to the present, and as projected through 2050? (5) Regional nitrogen transport; relative contribution of local vs. regional N sources, seasonal and interannual variation in transport and drivers; (6) Deposition; what drives deposition, what does the historic record tell us about seasonal patterns of deposition?

The literature suggests that some aspects of the problem remain unresolved, including the relative contribution to N deposited on the lake from local compared to remote sources, and quantitative estimates of net deposition trends resulting from VMT trends. Toward the goal of advancing modeling tools to address these knowledge gaps, a numerical modeling system based on the Weather Research and Forecasting (WRF) model coupled to the Community Multiscale Air Quality (CMAQ) model is used to conduct a sensitivity study of the impact of emission control strategies and weather conditions on mobile-related pollution in the Tahoe airshed. We ran WRF and CMAQ at high spatial resolution in order to capture the complex geometry and circulation of the Tahoe basin and the Sierra Nevada. A one-week simulation during August 2014 was performed as a demonstration of the modeling capability was completed and evaluated with the observational data. This is the first study that applies fine-resolution (1 km) state-of-the-art air-quality model simulations to examine this issue. This study focuses on the dry deposition of nitrogen and PM from non-exhaust emissions. Several sensitivity tests were completed to quantify the percentage contributions of the mobile controls (via VMT changes) and the impact of local emissions versus regional emissions to the N and PM concentrations.

Preliminary results from this initial demonstration study find that deposition rates of nitrogen species, specially NOx, has likely decreased over the Lake Tahoe likely proportional to the decrease VMT since the 1981. In these simulations, vehicles account for about 20% of total N deposited on Lake Tahoe, therefore the reduction in N deposition due to the decrease in VMT since 1981 is about -2.5%. Agricultural emissions from Central Valley of California have little impact on HNO_3 deposition on Lake Tahoe, but have an impact on NH_3 deposition rates that is comparable the impact of vehicles, highlighting some complexity in the relative impact of local and remote sources on deposition of N to the lake. Road dust transport to the lake has also likely declined in proportion to the reduction in VMT in recent decades. These results are based on a simulation of only one week during the summer season. An expanded study that captures the full variations in weather and seasons that impact N and dust deposition should be

performed. Further evaluations and validation of the modeling system is also required. While some particulate matter measurements are present in the Tahoe basin to compare against the model, and observations of some N species are available at some stations near the Tahoe basin, better sampling of N species within the Tahoe basin would improve confidence in modeling of deposition on Lake Tahoe.

2 Introduction and summary of topic briefs

Lake Tahoe, known for its clarity and beauty has experienced declining clarity in recent decades. Emissions of dust and nitrogenous aerosol particles from vehicle traffic in the Tahoe basin is believed to be an important contributor to the decline in lake clarity. In response, a threshold was set calling for a 10% reduction in VMT from the 1981 value. The decline in VMT since then has been greater than the goal, at roughly 15% since the 1980's and has remained below the threshold value for the past decade.

Approximately 140 Mg of PM_{10} (particles of diameter 10 μm and smaller) road dust is emitted each year from roads around Lake Tahoe. The most heavily traveled roads tend to be in the best condition while the unimproved roads and those in poorer condition are in the less-traveled areas of the basin. When accounting for traffic volume however, the highest emitting roads are relatively clean roads in the urban areas, particularly South Lake Tahoe. Roadway emissions of dust are much greater, by a factor 5, in winter because of the application of traction control materials, such as sand. In addition to traction control materials, many dirtier secondary and tertiary roads exhibit unimproved shoulders, trackout of dust from unpaved surfaces onto roads and degraded pavement that provides a steady source of suspendable materials to the cleaner and more heavily trafficked primary roads. Immediate sweeping of roads, including secondary and tertiary roads as soon as they are dry following snow events can be effective in reducing road emissions of PM that may deposit on Lake Tahoe.

Lake Tahoe is surrounded by a nitrogen-limited forest ecosystem which takes up most of the N before it reaches the lake. However, this also makes the lake very sensitive to direct atmospheric deposition of N. Recent estimates conclude that over half of the annual loading of N in the lake comes from direct atmospheric deposition. Recent assessments have found NH_3 (ammonia) to be the primary component of nitrogen deposition to the Lake Tahoe surface water with significant N contribution to the entire basin from HNO_3 (nitric acid). In-basin source categories that emit a significant percentage of the NH_3 as well as the NOx (nitrous oxides) needed for the chemical formation of HNO_3, include on-road motor vehicles, waste burning (e.g., prescribed burns), and to a lesser extent residential wood burning.

The most important nitrogenous materials emitted by vehicles are NH_3 (ammonia) and NOx (nitrous oxides). NOx is the dominant species of N in vehicle emissions and undergoes a photochemical (needing sunlight) transformation to form HNO_3, and NH_4NO_3. Data on historical trends for automobile emissions within the Tahoe basin are not available, however the national data on automobile emissions offer a strong suggestion that N emissions have likely declined substantially. Even if VMT remains at

or near the threshold level it is reasonable to presume that vehicle emission of N may continue to decrease given the national trends toward fewer emissions per mile traveled.

The range for total flux of N to the Lake Tahoe Basin from the combination of wet and dry deposition is 3.3-14 kg N ha^{-1} yr^{-1}, which is comparable to that at moderately polluted sites in southern California (5.09 kg N ha^{-1} yr^{-1}). As with other sites in the Sierra Nevada Mountains, dry N deposition dominates the transfer of N from the atmosphere to the watershed and the surrounding forest canopy. Airborne N deposited to Lake Tahoe could originate either within the basin or be transported from upwind sources outside the basin such as the metropolitan areas of Sacramento and San Francisco, both areas are significant sources of pollutant emissions. All of the studies looking at atmospheric deposition of N in the Lake Tahoe basin try to understand the main sources of the N. They seek to address the issues of what are the sources of N for the basin and whether the sources of N originate in-basin or out-of-basin. The limitations of these studies however, include a very limited study time period, limited measurement techniques, and the lack of vigorous, up-to-date, computer modeling techniques. In order to address the questions surrounding the atmospheric deposition of N in the Lake Tahoe basin, as well as understanding the long-term trends associated with N deposition, it has been suggested to set up a long-term N monitoring system in and around the basin. It is also suggested that several in-depth air quality computer modeling studies be performed to gain a better understanding on the interaction between the meteorology and chemistry of the Lake Tahoe basin.

3 Design of numerical modeling case study

3.1 Purpose

Here we present results from a brief case study of the deposition of nitrogen species and particulate matter (PM) from vehicle emissions on the surface of Lake Tahoe and surrounding basin. The purpose of this is not to perform a complete study of the problem, but rather to demonstrate that the modeling capability exists at DRI to perform a more thorough and comprehensive study in the future should it be deemed worthwhile.

We selected a week-long case study from August 10 to 15, 2014, which corresponds to the time of year when VMT peaks. This period overlaps with a study by Stevens et al. (2016). They investigated the potential trade-offs among fuel treatment strategies in the Sierra Nevada area, including impacts on air quality. In this study, we investigate the impact of emissions from most sectors that emit N and PM, while conducting a sensitivity study that isolates the impact of the recent trend of decreasing VMT in the Tahoe basin. The next step for future work is a season-long simulation for July to September 2016. Air quality in the area will depend of the flow and meteorological conditions that can vary seasonally and synoptically. A longer simulation will provide more robust statistics and smooth out some flow dependent results. While some preliminary work has been done to evaluate the model results against station data in the Tahoe basin and surrounding area, substantially more of such error characterization and validation is required as part of the next phase of research on this topic.

3.2 Model framework and simulated scenarios

Air quality simulations were conducted using a state-of-art community model system composed of elements that simulate meteorology, emissions, and dispersion gas and particle pollutants. Elements of this modeling framework were configured to simulate concentrations of airborne gases and particles over a domain centered over Lake Tahoe (figure 1) and the analysis is focused N and PM concentration and deposition. Preliminary results from this case study are described in the next section (section 4). Table 1 shows the components of this modeling framework used in this study. Description and configuration of each model component is described in section 5 below.

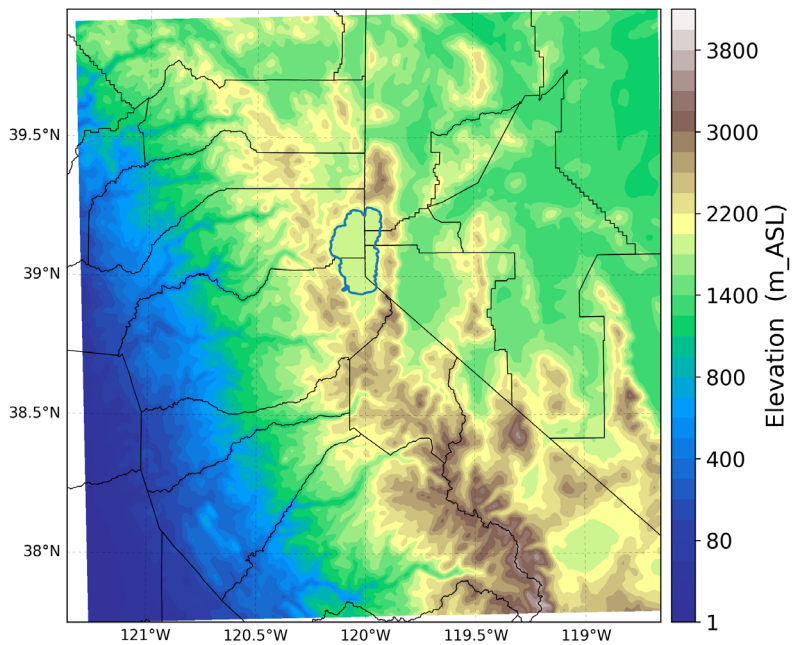

Figure 1: The domain for model simulations centered on Lake Tahoe and simulated at 1km grid size resolution.

Table 1- Air quality modeling framework model components.

Model Component	Version	Description
Weather and Research Forecast (WRF)	3.9.1.1	Numerical weather prediction modeling system
Meteorology-Chemistry Interface Processor (MCIP)	4.3	Post-processor of meteorological model
Spatial Allocator	4.3.1	Generator of data fields for emissions and air quality modeling
EPA National Emission Inventory (NEI)	2011ek-v6.3	Emission modeling platform and databases
Sparse Matrix Operator Kernel Emissions (SMOKE)	3.7	Emission inventory processing system
Community Multiscale Air Quality Modeling System (CMAQ)	5.2	Atmospheric dispersion modeling system

One of the main goals of this study was to explore how much vehicle traffic and mileage affect emissions over Lake Tahoe. The on-road sector represents emissions from vehicles that operate on public roadways in our modeling domain. Emissions of N species are mainly due to on-road mobile sources (Figure 2). We conducted one simulation over the week-long study period for each of the following emission scenarios:

1. Baseline emission scenario (henceforth "***2014 VMT***"): this scenario aims to simulate background air quality as a baseline to compare against other scenarios using present day emissions (e.g., NEI 2011). This scenario includes emission sectors in Table 2 and uses vehicle miles traveled (VMT) values as of 2014. Due to their episodic nature, we excluded the following emissions sources: agricultural fire (agfire), residential wood burning (rwc), and wildfires and prescribed fires (ptfire). Future work will consider a newer emissions inventory (NEI 2014), which was made available after the start of the performance period of this study.
2. Non-mobile emission scenario (henceforth "***No Mobile***"): this scenario aims to explore how much pollution from on-road mobile vehicles affect air quality over the modeling domain. This scenario includes all emissions as in 2014 VMT scenario except the "on-road" sector.
3. 1981 VMT emission scenarios (henceforth "***1981 VMT***"): this scenario aims to explore how much emission would be affected if vehicle miles traveled (VMT) of on-road mobile sources in the modeling domain would increase to VMT levels of 1981. We assumed increase of 15.1% for 1981 VMTs compared to 2014 VMT values and prepared on-road emissions based on this assumption. This scenario includes all emissions as in 2014 VMT scenario but for on-road sector VMT values were increased by 15.1% compared to 2014 VMTs. VMT changes are assumed to have a relatively linear relationship with emissions. The same present "baseline" vehicle speeds were kept. The effect of watercraft activity trends and emissions were neglected.
4. No agriculture emission scenario (henceforth "***No Agriculture***"): this scenario aims to explore how much regional agriculture emissions around Lake Tahoe (e.g. San Joaquin Central Valley) affects the concentration and deposition of N species at the lake. NH_3 agriculture-related emissions from fertilizer or animal feeding application is minimum within the Tahoe watershed. This scenario includes all emissions as in 2014 VMT scenario but excludes all emissions related to the agriculture sector. Hence, this scenario includes all sectors in Table 2 except agriculture "ag" sector. Table 3 compares emission of criteria pollutants by sector. Among mobile sources of NH_3 and PM10, on-road mobile sources are the main contributor. Overall, however, agriculture is a major source of NH_3 with 3,515,198 ton/yr of NH3 over US.
5. No biogenic emission scenario (henceforth "***No Biogenic***"): This scenario investigates the sensitivity of Nitrogen deposition and Particulate Matter due to natural vegetation, which emits organic nitrates and volatile organic compounds, among other pollutants.

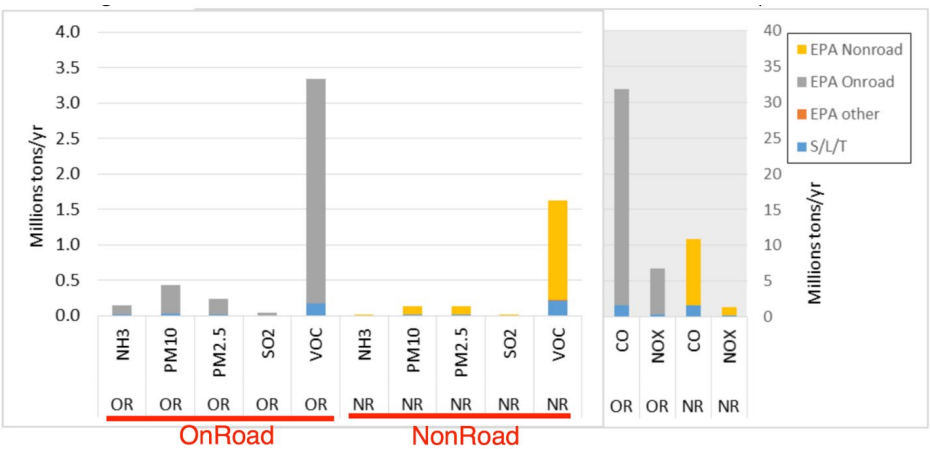

Figure 2: Data sources for on-road and non-road mobile emissions for criteria pollutants (EPA, 2016).

Table 2. list of emission types used as baseline emissions ("2014 VMT").

Emission type
afdust
ag
beis
rail
cmv
nonpt
np_oilgas
non-road
on-road
pt_oilgas
pt_egu
pt_nonipm

Table 3. National by-sector criteria pollutant emissions summaries for the 2011 evaluation case (EPA, 2016).

Sector	CO	NH_3	NO_X	PM_{10}	$PM_{2.5}$	SO_2	VOC
afdust_adj				6,732,941	923,590		
ag		3,515,198					
agfire	1,030,817	3,321	46,035	152,837	101,379	17,755	80,540
cmv	70,408	231.5019729	413,314	19,629	18,099	91,045	12,578
nonpt	1,645,989	94,242	720,454	491,825	404,258	276,332	3,671,898
np_oilgas	625,430	0	664,966	17,784	16,333	17,232	2,483,856
nonroad	13,951,020	2,627	1,630,301	162,417	154,657	4,031	2,024,419
onroad	**25,369,638**	111,881	5,608,800	325,704	187,869	27,458	2,656,899
rail	122,703	347.3226239	791,381	25,898	23,963	7,936	40,851
ptprescfire	10,063,500	161,999	167,599	1,060,130	900,546	83,082	2,313,404
ptwildfire	10,499,197	167,331	165,799	1,111,857	943,717	82,691	2,374,690
ptegu	792,397	25,066	2,081,762	283,072	208,129	4,650,841	38,062
ptnonipm	2,297,650	66,051	1,213,528	477,387	320,857	1,049,424	801,188
pt_oilgas	235,162	5,947	509,856	14,585	13,935	66,577	164,098
rwc	2,517,844	19,693	34,436	381,476	381,252	8,954	442,541
Con U.S. Total	**69,221,756**	**4,173,935**	**14,048,231**	**11,257,540**	**4,598,583**	**6,383,357**	**17,105,023**
Off-shore to EEZ*	175,353	185	899,986	26,247	24,544	139,169	81,602
Non-US SECA C3	17,184	0	202,432	17,206	15,828	127,579	7,294
Canada othafdust				779,674	112,523		
Canada othar	3,015,606	326,610	361,896	158,996	131,114	70,272	886,456
Canada othon	3,032,005	18,653	345,664	17,628	12,216	1,701	178,431
Canada othpt**	496,083	13,069	266,912	70,005	29,165	544,502	129,119
Mexico othar	277,810	163,040	182,869	98,812	50,158	10,679	410,734
Mexico othon	3,361,123	7,978	243,714	2,425	1,624	4,919	319,353
Mexico othpt	153,061	3,706	286,303	55,162	42,105	453,466	53,813
Non-US Total	**10,528,225**	**533,241**	**2,789,775**	**1,226,156**	**419,276**	**1,352,287**	**2,066,802**

4 Results of numerical modeling case study

4.1 Nitrogen Deposition rates

The model framework was used to estimate deposition rates of N-containing species for all scenarios over the Tahoe airshed (Table 4) during the August 2014 case study. There was no precipitation during the experiment period, so only dry deposition is considered here. A longer model integration is necessary to include robust statistics of the role of wet deposition processes into the lake. Results show that the contribution to net N dry deposition resulting from on-road mobile emissions is on average about 20% (all N species ***2014 VMT*** minus ***No Mobile***). Holding vehicle emissions constant over the simulation period, the net effect on N deposition rates into the Tahoe airshed due to the 15% VMT decreasing trend (1981-2014) is -2.5% and -2.8% over water and land, respectively. A longer simulation would be valuable to determine how much variability

there is in the net contribution of VMT to total deposition of N species and whether the relatively low percentage contribution of VMT in these simulations is robust.

Table 4: Deposition rates for N-containing species for different scenarios

Tahoe-Water	1981 VMT	2014 VMT	No Mobile	No Agriculture	No Biogenic	Difference due to VMT trend	Difference relative to No Mobile
Units	kg-N/Het/Year	kg-N/Het/Year	kg-N/Het/Year	kg-N/Het/Year	kg-N/Het/Year	%	%
All N species	0.865	0.844	0.688	0.854	0.892	-2.49	-13.48
NOY	0.798	0.778	0.626	0.799	0.824	-2.61	-13.42
NOX	0.00226	0.00223	0.00196	0.00226	0.00245	-1.34	-11.07
NHX	0.067	0.066	0.062	0.055	0.068	-1.04	-15.37
NH3	0.015	0.014	0.012	0.010	0.014	-3.12	-16.04
HNO3	0.443	0.436	0.391	0.444	0.675	-1.57	-14.97

Tahoe-Land	1981 VMT	2014 VMT	No Mobile	No Agriculture	No Biogenic	Difference due to VMT trend	Difference relative to No Mobile
Units	kg-N/Het/Year	kg-N/Het/Year	kg-N/Het/Year	kg-N/Het/Year	kg-N/Het/Year	%	%
All N species	3.237	3.149	2.503	3.208	4.151	-2.80	-13.63
NOY	3.013	2.928	2.305	3.016	3.895	-2.89	-13.57
NOX	0.203	0.192	0.096	0.203	0.229	-5.83	-11.64
NHX	0.224	0.221	0.198	0.191	0.255	-1.60	-15.30
NH3	0.028	0.027	0.020	0.021	0.028	-4.71	-17.66
HNO3	2.184	2.137	1.828	2.188	3.432	-2.17	-15.01

This case study shows that deposition rates of N-containing species over land are slightly higher than over the water surface (Figure 3). NOx, half of which is contributed by mobile sources (Table 4), is deposited near the sources and a very small proportion (20%) is dispersed over the water area. The striking differences between land and water surfaces in N deposition suggest that sources of NO_x are originate on land, mainly from on-road emissions and over urban areas (Figure 4).

Table 4 shows that HNO_3 contributes two thirds of the N deposition over land and half of the N deposition over water (Table 4). Figure 5 highlights these results and further shows that the HNO_3 deposition rate over water is more homogeneous in space. In agreement with Tarney et al. (2001, 2005), the most abundant N species in the Tahoe airshed is HNO3. A different study aiming to measure Nitrogen species in the Tahoe basin, the Lake Tahoe Atmospheric Deposition Study (2002-2004 LTADS; Dolislager et al. 2012), suggested that ammonia (NH_3) as the main contributor of N deposition into the lake. However, during the summer LTADS observations show that the mean NH_3 and HNO_3 concentrations are similar. Of note is that our results are only for a one-week period and therefore not representative of the entire summer season. HNO_3 can have lifetimes of weeks in the troposphere and therefore provide a secondary source of NOx far from the point of original emission (Staudt et al. 2003). On the other hand, HNO_3 is a secondary pollutant that is formed by biogenic and anthropogenic volatile organic compounds (VOCs) and NOx precursors by chemical reactions in the air, both of which are a strong function of the ambient temperature (Day et al. 2008).

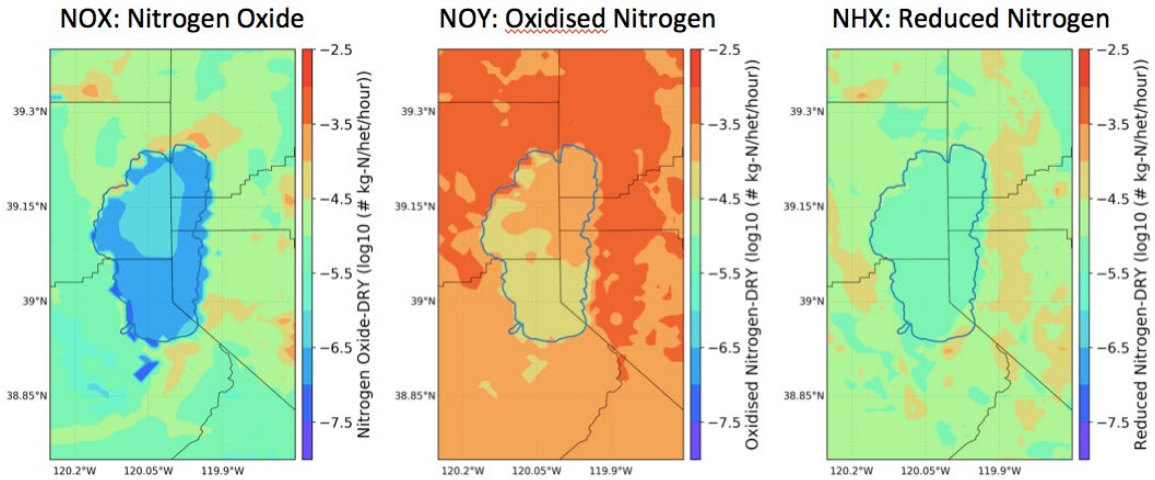

Figure 3: NOx, NOy, and NHx means during the simulation period. A logarithmic color table was applied to highlight the large magnitude and spatial differences between N species.

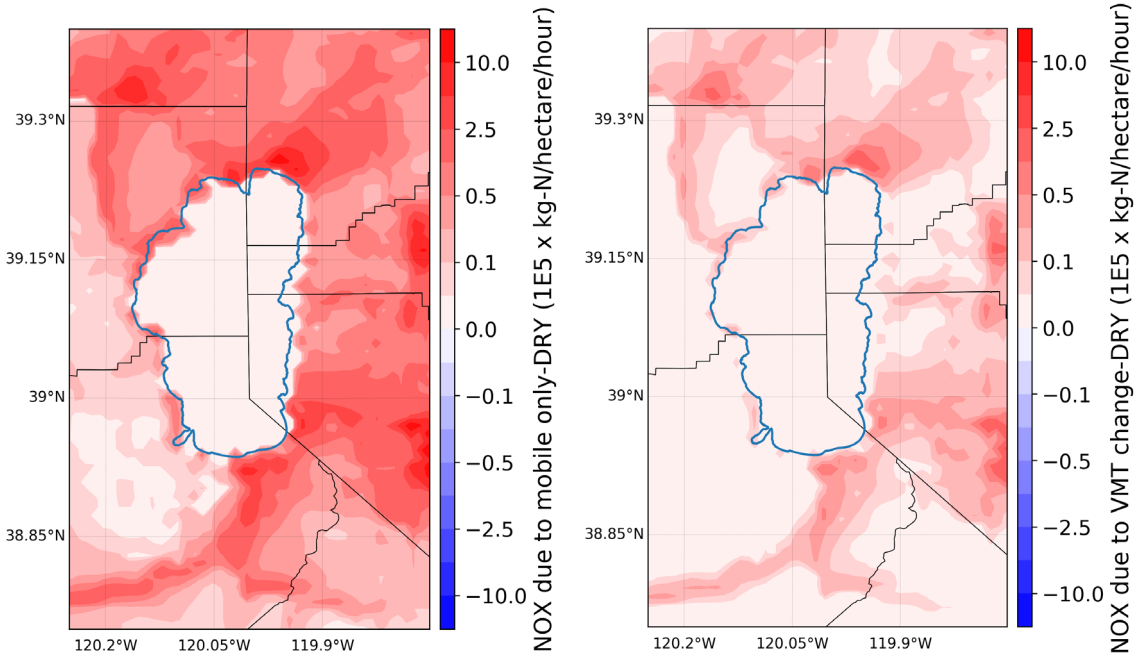

Figure 4: Spatial differences of NOx (1E5 kg-N/hectare/hour) between (left) 2014 VMT non-mobile and (right) 2014 minus 1981 VMT scenarios.

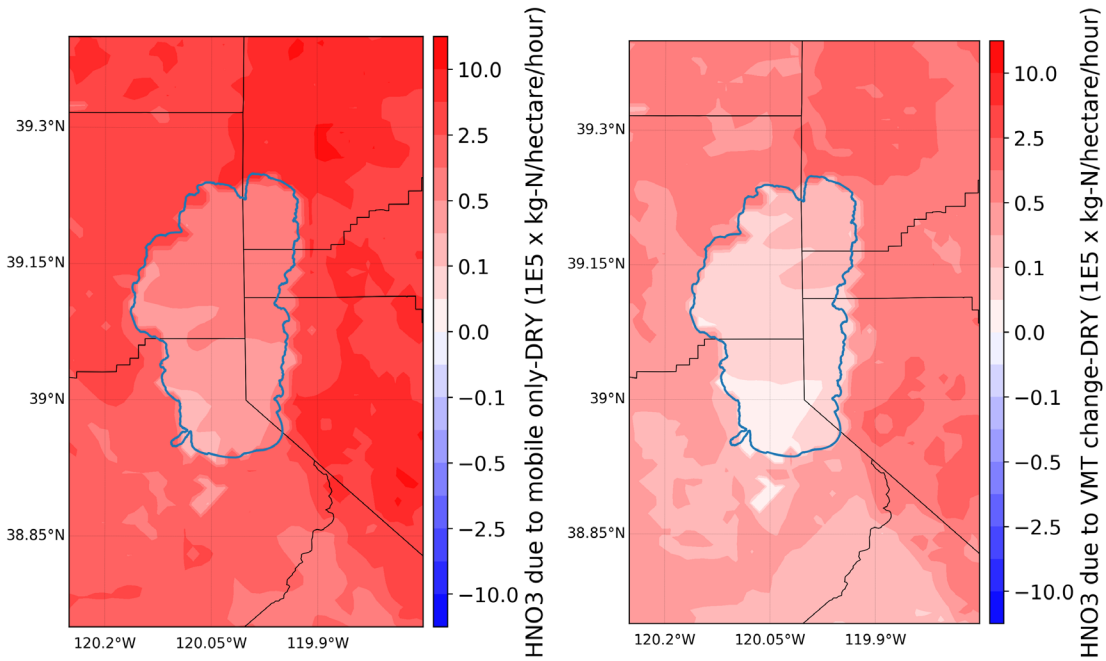

Figure 5: Spatial differences of NHO_3 (1E5 kg-N/hectare/hour) between (left) 2014 VMT non-mobile and (right) 2014 minus 1981 VMT scenarios.

4.2 On the role of local vs. regional sources

Concentrations of HNO_3 (and other N-containing species are found) in air masses coming from the west and the east, suggesting that some background HNO_3 inside Tahoe airshed can provide from other sources.

We developed the ***No agriculture*** scenario as an effort to examine the relative role of the regional agricultural emissions, mostly from Central Valley emissions into Tahoe airshed. The striking result shown in Figure 6 and Table 4 is that agriculture emissions have little impact on Lake Tahoe HNO_3 deposition rates but have similar impact on NH_3 levels as the No mobile scenario. Of note is that the Central San Joaquin Valley NH_3 concentrations are mostly modulated by agriculture (not shown). However, other N species in the Tahoe airshed slightly increase with the No Agriculture scenario, suggesting that secondary nitrogen in the airshed is NH_3 limited.

Results for deposition rates of N-containing species for the ***No mobile*** and ***No biogenic*** emissions suggest that HNO_3 deposition rates into the airshed are VOC and NO_x limited (Figure 6). However, model uncertainties may be contributed by non-linear interactions of VOC and NOx, and therefore distinguishing sources may be a challenging task. Removing biogenic emissions can increase the soil-surface to lower-atmosphere Nitrogen gradients, thus increasing the deposition fluxes (Phillips et al. 2006). On the other hand, a reduction in biogenic VOC (BVOC) helps reduce O_3 and likely reduce secondary organic aerosols. Basic chemistry would suggest that when VOC's are around they react with the OH (hydroxy radical). When BVOC's are removed in the ***No biogenic*** simulation, then the OH remains. The OH reacts with NO_2 forming more HNO_3.

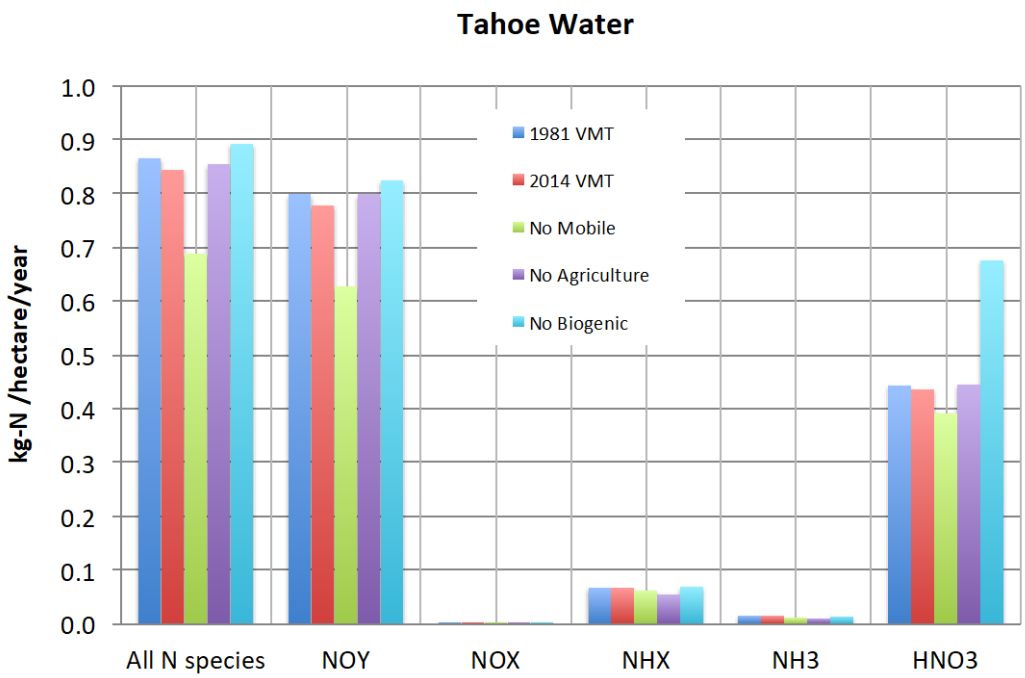

Figure 6 Deposition rates for N-containing species averaged over the Lake Tahoe water area. See values in Table Table 4.

4.3 Simulated road dust emissions and deposition

Non-exhaust sources contribute easily as much and often more than the tailpipe exhaust to the ambient air PM concentrations in cities (Timmers and Achten 2016). Non-exhaust mobile emissions depend on traffic, speed, as well as the condition of the road. Most of the PM mass from non-exhaust emissions, regardless of the type of traffic site (road, crossroad, or highway), is made of resuspension dust. This dust is originally created by aerosol re-suspension rates by vehicle movement and abrasion of car body, brake pad wear, brake disc wear, tire wear, and road surface abrasions, and is composed of particles with diameter ranging between 1 and 10 microns. For this reason, coarse PM (fraction of atmospheric particles with an aerodynamic diameter in the 2.5–10 µm range; coarse PM) usually makes up most of the PM mass close to crossroads and can include soil as well as particle elements originating from organic compounds.

CMAQ results show that coarse PM related to mobile emissions are produced over the main roadways and urban areas bordering the lake (Figure 7). During this case study, mean flow (Westerly-southwesterly) seems to carry most of the pollutant over the lake and to the northern and northeastern quadrants of the lake. Similar to N deposition, course PM deposition changes proportional to the VMT trends (~15%; not shown). Of note is that coarse PM deposition rates are not unchanged in the ***No agriculture*** and ***No biogenic*** scenarios, suggesting that most coarse PM emissions are both emitted and deposited within the basin.

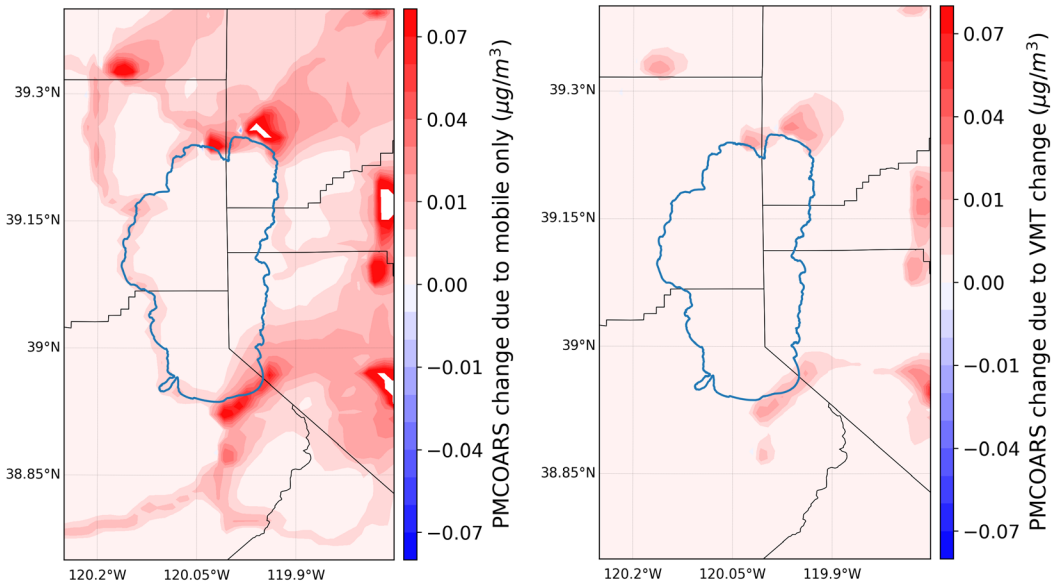

Figure 7: Spatial differences of PM-COARS (2.5 and 10micron/m^3) due to Mobile (2014 minus No Mobile; left) and VMT trend (1981 minus 2014; right).

5 Detailed description of modeling system components

5.1 The Weather and Research Forecasting Model

Regional Climate Models (RCMs) can be used in conjunction with reanalysis data or global climate models (~100km) to produce high-resolution numerical simulations (10 km or even 1 km) of the climate or specific events over a region of interest. RCMs are becoming important tools in evaluating detailed and realistic flow patterns due to their ability to simulate high spatial and temporal resolution (~kilometer and sub-hourly, respectively) in areas with complex topography and sparse observation networks (Silverman et al. 2013; Xue et al. 2014). For this project, we developed a fine-resolution meteorology simulation based on the Weather and Research Forecasting (WRF; Skamarock et al. 2008) model to simulate the Lake Tahoe local circulation and the regional flow around the Sierra Nevada (Fig. 1). Simulated output was used to feed into the dispersion and air quality models. The model domains consist in 9 km, 3 km, and 1km nested domains with the 3 km grid size domain covering the states of CA and NV and 1 km centered at Lake Tahoe (Fig. 1). All model results shown in this report are for the 1 km grid size domain.

Our RCM configuration follows the DRI-Regional Climate Modeling (RCM; Dorman at al. 2013) strategies with some modifications outlined below. The selection of model setup was designed through basic and common knowledge of the prevailing physical processes that dominate regional climate variations over Western United States (Leung et al. 2003; Rasmussen et al. 2011; Liou et al. 2013; Silverman et al. 2013; Zhang et al. 2013; Dorman et al. 2013). However, it is well known that the selection of optimal parameters and physics configuration within an RCM is a challenging task that depends on many factors, including: boundary conditions implemented reanalysis datasets-,

regional climate and its variability, and simulations grid size (Liang et al. 2012; Fernández-González et al. 2015). Controlling all these and other factors is out of our scope of work and requires time and resources not available for this project. A summary of the model configurations is shown in Table 5. We added a 3-hour period after the model initialization to allow model relaxation or "spin-up".

The RCM is driven by initial and lateral boundary conditions (LBC) provided by the North American Regional Reanalysis (NARR; Mesinger et al. 2006), while integrating the dynamic equations and physics parameterizations at the interior grids at finer spatial and temporal scales. NARR is produced and recurrently updated by the National Centers for Environmental Prediction (NCEP). The horizontal grid spacing for the NARR data is 32 km, and there are 30 vertical layers. It provides lateral boundary conditions of surface, atmosphere, and soil variables every three hours. The NARR data input includes all available surface and upper-air observations from various national and local networks. The NARR is currently the best available resource of LBC data as it is dynamically consistent in the atmospheric and hydrologic fields. The NARR has been rigorously evaluated in multiple studies (Mesinger et al., 2006; Kennedy et al. 2011; Li et al. 2010; Zhong et al. 2012; Walters et al. 2014).

Table 5: Model settings for WRF used in this study.

Settings	**Domain 1 9 km grid size**	**Domain 2 3 km grid size**	**Domain 3 1 km grid size**
Deep soil temperature	Fixed	Fixed	Fixed
Slope radiation	On	On	On
Topographic shading	On	On	On
Downscaling	One-way	One-way	One-way
Output time increments	hourly	hourly	hourly
Time step	54 seconds	9 seconds	3 seconds
Physics Parameterizations:			
Boundary Layer	MYJ-TKE (Janjic 1994)	MYJ-TKE (Janjic 1994)	MYJ-TKE (Janjic 1994)
Cumulus	Explicit	Explicit	Explicit
Microphysics	Thompson (Thompson et al. 2008)	Thompson (Thompson et al. 2008)	Thompson (Thompson et al. 2008)
Land Surface Model	Noah Multi-Physics (Niu et al. 2011)	Noah Multi-Physics-(Niu et al. 2011)	Noah Multi-Physics-(Niu et al. 2011)
Radiation (SW and LW)	Dudhia (Dudhia 1989) and RRTM (Mlawer et al. 1997)	Dudhia (Dudhia 1989) and RRTM (Mlawer et al. 1997)	Dudhia (Dudhia 1989) and RRTM (Mlawer et al. 1997)

5.2 Pre-Processing of meteorology fields by using MCIP

Meteorology-Chemistry Interface Processor (MCIP) is a meteorological post-processor for the air quality modeling framework. This program reads in and processes output meteorology fields from WRF to generate meteorology files in a format that is needed by other programs in the modeling framework. In addition, in the preprocessing step MCIP can calculate necessary meteorology variables and parameters such as cloud parameters from WRF fields and then generates model-ready meteorology input files for programs such as CMAQ and SMOKE.

5.3 Emission Inventory and source categories

EPA keeps records of amount of pollutants that are emitted through a specific year at the county level in the National Emission Inventory (NEI) platform (https://www.epa.gov/air-emissions-inventories). Emission sources are generally categorized into following four typical source groups based on their characteristics: point sources, area sources, mobile sources, and biogenic sources. For the purpose of preparing air quality model-ready emissions, NEI is split into finer grained sectors called "platform sectors" for emission modeling. Table 6 shows NEI sectors and major processing steps of each platform sector. The following source categories and major sectors are included in NEI 2011 emission platform:

1. Point sources: Emission sources that specific geographic coordinates are specified for them in the emission inventory. The following sectors are considered as point sources in NEI 2011:

1.1. Electric Generating Units (ptegu): This sector incorporates emissions from EGUs and Continuous Emissions Monitoring (CEM) hourly emissions for a majority of sources.

1.2. Point source oil and gas sector (pt_oilgas): emissions from oil and gas sources.

1.3. Non-IPM sector (ptnonipm): remaining non-EGU point source emissions from industrial activities that are not in the ptegu or pt_oilgas sectors. The ptnonipm sector contains a small amount of fugitive dust PM emissions from vehicular traffic on paved or unpaved roads at industrial facilities, coal handling at coal mines, and grain elevators.

Point source emissions were processed and prepared based on the time period and spatial resolution of the modeling domain.

2. Nonpoint sources (stationary area): sources of emissions that are considered as area sources.
NEI 2011 considers the following sectors as nonpoint sources:

2.1. Area fugitive dust sector (afdust): PM10 and PM2.5 emission estimates from fugitive dust sources, such as paved roads, unpaved roads and airstrips, construction (residential, industrial, road and total), agriculture production, and mining and quarrying.

2.2. Agricultural ammonia sector (ag): Agricultural ammonia emissions from livestock and agricultural fertilizer application emission.

2.3. Agricultural fire sector (agfire): this sector contains emissions from agricultural fires.

2.4. Nonpoint source oil and gas sector (np_oilgas): this sector contains onshore and offshore oil and gas emissions. The types of sources covered include drill rigs, workover rigs, artificial lift, hydraulic fracturing engines, pneumatic pumps and other devices, storage tanks, flares, truck loading, compressor engines, and dehydrators.

Table 6. NEI 2011v6.3 sectors and major processing steps (adapted from NEI 2011 technical support document https://www.epa.gov/air-emissions-inventories).

Platform sector	Spatial	Speciation	Inventory resolution	Plume rise
afdust	Surrogates	Yes	annual	
ag	Surrogates	Yes	annual	
agfire	Surrogates	Yes	monthly	
beis	Pre-gridded land use	in BEIS3.61	computed hourly	
rail	Surrogates	Yes	annual	
cmv	Surrogates	Yes	annual	
nonpt	Surrogates & area-to-point	Yes	annual	
nonroad	Surrogates & area-to-point	Yes	monthly	
np_oilgas	Surrogates	Yes	annual	
onroad	Surrogates	Yes	monthly activity, computed hourly	
othafdust	Surrogates	Yes	annual	
othar	Surrogates	Yes	annual	
othon	Surrogates	Yes	annual	
othpt	Point	Yes	annual	in-line
pt_oilgas	Point	Yes	annual	in-line
ptegu	Point	Yes	daily & hourly	in-line
ptfire	Point	Yes	daily	in-line
ptnonipm	Point	Yes	annual	in-line
rwc	Surrogates	Yes	annual	

2.5. Residential Wood Combustion (rwc): this sector includes residential wood burning devices such as fireplaces, fireplaces with inserts (inserts), free standing woodstoves, pellet stoves, outdoor hydronic heaters (also known as outdoor wood boilers), indoor furnaces, and outdoor burning in firepots and chimeneas.

2.5. Remaining nonpoint (nonpt): Area source emissions not included in other area sectors.

In order to process area sources for the spatial and temporal resolution of the modeling domain, we had to generate 1-km spatial surrogates for our modeling domain following and conforming to the meteorology grid. Spatial surrogates are spatial emission factors that allocate emission inventories at county level to grid cells in air quality models that cover the modeling domain. Figure 8 shows the schematics of this process. We collected GIS-based shape files from EPA and then used the "Spatial Allocator" tool and computed spatial surrogates for our modeling domain from available nationwide shapefiles. Table 7 shows a list of the spatial surrogates that were implemented for this study. Non-road emissions were also processed for the spatial and temporal resolution of the modeling domain and were spatially allocated by using spatial surrogates.

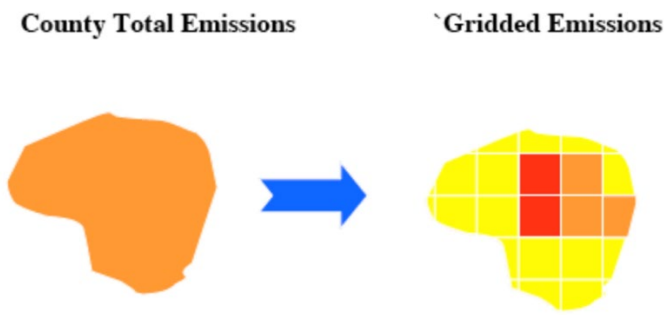

Figure 8: Emission allocation by spatial surrogates (EPA, 2016).

3. On-road mobile sources: this includes emissions from motorized vehicles that operate on public roadways and transport goods and people. This category includes emissions from processes in both parked vehicles (e.g., starts, hot soak, and extended idle) and in on-network vehicles moving along the roads. Some types of mobile sources included in this sector are passenger cars, motorcycles, minivans, sport-utility vehicles, light-duty trucks, heavy-duty trucks, and buses.

On-road mobile inventories can have two types of data. The data type can be either emissions or activity data. Emissions data includes precomputed mobile emissions from on-road mobile models such as MOBILE6 or MOVES. Activity data consists of information about vehicles miles traveled (VMT), vehicle population (VPOP), vehicle hoteling, and vehicles average speed. Based on the type of data available, SMOKE uses two approaches to process mobile source inventory data: emission approach and MOVES approach. Emission approach is the approach when inventory has precomputed emissions and SMOKE uses these emissions and allocate them to air quality modeling grids. In MOVES approach, emissions are computed inside SMOKE by using activity data, meteorology, and emission factor tables from a mobile model called MOVES. MOVES model computes emission factors for four major groups of processes such as rate per distance, rate per profile, rate per vehicle, and rate per hour. These groups include several processes such as running exhaust, start exhaust, hoteling, idling, on-road and off-network evaporative fuel leaks. One benefit of using MOVES approach compared to precomputed emissions approach is that in this approach SMOKE considers and calculates variations in mobile emissions caused by meteorological variables such as temperature and humidity.

On-road mobile sources are an important source of emissions in this study. EPA uses MOVES emission model to calculate on-road emission factor tables. In this study on-road mobile emissions were computed inside SMOKE by using 2011 NEI platform mobile activity data and EPA 2014 MOVES emission factor tables. This sector was processed with SMOKE-MOVES suite of programs for the modeling domain.

4. Non-road mobile sources: this includes emissions from mobile sources that do not operate on highways. This category consists of following sectors:

4.1. Category 1, 2 and 3 Commercial Marine Vessels (cmv): Emissions from C1, C2, and C3 commercial marine vessels, including ports and navigable waterways. Marine vessels are categorized based on their engine and are grouped into three engine categories: C1, C2, and C3 commercial marine vessels. C1 and C2 are vessels inside and around ports such as supply vessels, fishing vessels, tugboats, pushboats and other commercial vessels. C3 are very large marine diesel engines that are used on ocean-going vessels such as oil tankers, cruise ships, and container ships.

4.2. Railroad sources (rail): railway emissions.

4.3. Non-road mobile equipment sources (nonroad): Off highway mobile source emissions. Types of sources include recreational equipment engines and pleasure craft, construction, industrial, and agricultural equipment, airport support and underground mining.

5. Biogenic sources (beis): This sector includes emissions from biogenic sources. Biogenic emissions are computed by using Biogenic Emissions Inventory System, version 3.61 (BEIS3.61) model as part of the SMOKE processing system. BEIS model estimates volatile organic compound (VOC) emissions from vegetation cover and nitric oxide (NO) emissions from soils. Emissions are calculated based on land use category data and vegetation cover for each grid cell. In this study, we used Biogenic Emissions Landcover Data (BELD) v4.1 dataset which includes 230 land use types at 1 km grid size. In the first step, BEIS model reads in gridded land use data from BELD4 database and generates gridded land use fractions for each grid cell. In the next step, it reads in meteorology data such as 2-m temperature, solar radiation, soil texture type by USDA category, soil temperature, surface pressure, and calculates model ready biogenic emissions. BEIS model calculates emissions for mainly VOC such as isoprene and methanol, CO, and NO species.

6. Fires (ptfire): this sector is considered as a point source and includes emissions from fires. It does not include agriculture burning and any other burning sources. Forest wildfires and prescribed burning for forest management are sources that are included in this sector. In this study we removed any source related to fire emissions to exclude any fire emissions.

Table 7: List of spatial surrogates generated for this study (EPA, 2016).

REGION	SURROGATE	SURROGATE COD
USA	Population	100
USA	Population by State	105
USA	Housing	110
USA	Urban Population	120
USA	Rural Population	130
USA	Urban Housing	131
USA	Suburban Housing	132
USA	Exurban Housing	133
USA	Rural Housing	134
USA	Housing Change	137
USA	Housing Change and Population	140
USA	Residential Heating - Natural Gas	150
USA	Residential Heating - Wood	160
USA	0.5 Residential Heating - Wood plus 0.5 Low Intensity Residential	165
USA	Residential Heating - Distillate Oil	170
USA	Residential Heating - Coal	180
USA	Residential Heating - LP Gas	190
USA	Urban Primary Road Miles	200
USA	Rural Primary Road Miles	210
USA	Urban Secondary Road Miles	220
USA	Urban Unrestricted Roads	221
USA	Rural Secondary Road Miles	230
USA	Rural Unrestricted Roads	231
USA	Total Road Miles	240
USA	Urban Primary plus Rural Primary	250
USA	0.75 Total Roadway Miles plus 0.25 Population	255
USA	Off-Network Short-Haul Trucks	256
USA	Off-Network Long-Haul Trucks	257
USA	Total Railroad Miles	260
USA	NTAD Total Railroad Density	261
USA	Class 1 Railroad Miles	270
USA	NTAD Class 1 2 3 Railroad Density	271
USA	NTAD Amtrak Railroad Density	272
USA	NTAD Commuter Railroad Density	273
USA	ERTAC Rail Yards	275
USA	Class 2 and 3 Railroad Miles	280
USA	Low Intensity Residential	300
USA	Med Intensity Residential	301
USA	High Intensity Residential	302
USA	Open Space	303
USA	Total Agriculture	310
USA	Pasture Land	318
USA	Crop Land	319
USA	Forest Land	320
USA	Strip Mines/Quarries	330
USA	Land	340
USA	County Area	346
USA	Water	350
USA	Rural Land Area	400
USA	Commercial Land	500
USA	Industrial Land	505
USA	Education	506
USA	Heavy Light Construction Industrial Land	507
USA	Commercial plus Industrial	510
USA	Commercial plus Residential	512
USA	Commercial plus Institutional Land	515
USA	Commercial plus Industrial plus Institutional	520
USA	Golf Courses plus Institutional plus Industrial plus Commercial	525
USA	Residential - Non-Institutional	526
USA	Single Family Residential	527
USA	Residential - High Density	530
USA	Residential + Commercial + Industrial + Institutional + Government	535
USA	Retail Trade (COM1)	540
USA	Personal Repair (COM3)	545
USA	Retail Trade (COM1) plus Personal Repair (COM3)	550
USA	Professional/Technical (COM4) plus General Government (GOV1)	555
USA	Hospital (COM6)	560
USA	Medical Office/Clinic (COM7)	565
USA	Heavy and High Tech Industrial (IND1 + IND5)	570
USA	Light and High Tech Industrial (IND2 + IND5)	575
USA	Food, Drug, Chemical Industrial (IND3)	580
USA	Metals and Minerals Industrial (IND4)	585
USA	Heavy Industrial (IND1)	590
USA	Light Industrial (IND2)	595
USA	Industrial plus Institutional plus Hospitals	596
USA	Refineries and Tank Farms	650
USA	Oil and Gas Wells	680
USA	Airport Points	710
USA	Airport Areas	711
USA	Military Airports	720
USA	Golf Courses	850
USA	Mines	860
USA	Construction and Mining	861
USA	Quarries	862
USA	Wastewater Treatment Facilities	870
USA	Commercial Timber	890

5.4 Emission processing using SMOKE modeling system

The original resolution of emission inventories is different from the resolution that air quality models require. NEI has different sectors with annual, monthly, daily, and hourly temporal resolutions. Spatial resolution of NEI also varies by sector and differs from point resolution to area total emissions at county level. Also, pollutants in the inventory are not speciated and are almost course from air quality modeling perspective. Air quality models such as CMAQ need speciated chemicals as their input. For instance, NEI inventory has total emission of PM2.5 as inventory pollutant. On the other hand, CMAQ require emissions of chemical species of PM2.5 such as particulate black carbon and particulate nitrate at hourly and gridded resolutions. The process of transforming emission inventory resolutions to required air quality resolutions is called emission modeling. This task is done through SMOKE modeling system.

SMOKE is an emission inventory processor capable of processing gaseous and particulate pollutants. SMOKE processes criteria, particulate, toxics, and activity data inventories. It consists in several programs that import in the raw inventory data and process the data by performing temporal and spatial allocation of inventory data to the grid cells of modeling domain. SMOKE also performs chemical speciation of raw inventory pollutants and finally prepares emission files as inputs for air quality models in the prescribed format and resolution that we define. Emission files are inventory emissions that are spatially and temporally allocated to each model grid cell. Also, emissions are chemically speciated through this process for each grid cell. In order to prepare emissions for air quality modeling, each NEI sector was processed independently from the other sectors through all SMOKE programs except the final merge step. In the final step, SMOKE merges gridded, speciated, hourly emissions of specific sectors together to generate model-ready emission input files. This provides a flexible approach for air quality modelers when they need to exclude some sectors and combine other sectors to perform sensitivity studies. In this study SMOKE v3.7 was used. Output of SMOKE is gridded, speciated, temporally and spatially resolved emission files ready for air quality models such as CMAQ.

We used 2011 EPA NEI datasets for this study (ftp://ftp.epa.gov/EmisInventory/). We used Carbon Bond version 6 (CB6) chemical mechanisms to speciate inventory pollutants. Chemical mechanisms include reaction chemistry and chemical specification of model species. Carbon Bond is the name of a set of photochemical mechanisms and NEI 2011v6.3 platform supports CB6 chemistry. It includes updates and revisions to previous carbon bond version (CB05) and results in better treatment of chemistry in rural and remote environments. Recent version of CMAQ (5.2) is the first version that supports this mechanism. SMOKE3.7 also supports CB6 chemical mechanisms.

5.5 Community Multi-scale Air Quality (CMAQ)

Community Multi-scale Air Quality (CMAQ v5.2; EPA-CMAQ) model is a numerical air quality model that is able to simulate the formation, transport and dispersion, chemical evolution and deposition of airborne gases and particles matter. CMAQ requires hourly and gridded emissions of chemical species. CMAQ v5.2 supports CB6 chemical mechanism. So, emissions were speciated by using CB6 chemical

mechanism during processing steps in SMOKE. The horizontal grid used for CMAQ was based on the WRF innermost domain grid (domain 3). This grid also corresponds to the resolution of SMOKE grid, for which emissions were prepared for. The number of vertical layers in CMAQ grid was set according to the number of WRF vertical layers to 64 layers. Initial conditions (IC) and boundary conditions (BC) used in the simulations were the default CMAQ IC and BC profiles. Table 8 included the CMAQ model output parameters for Nitrogen containing species (N-containing) and particulate matter (PM) implemented this study. CMAQ generates eight PM2.5 species: crustal/unspeciated PM, sulfates (SO4), primary anthropogenic organic aerosols (PAOA), ammonia (NH4), secondary biogenic organic aerosols (SBOA), elemental carbon (EC), nitrates (NO3), and secondary anthropogenic organic aerosols (SAOA). However, CMAQ cannot split sulfates, nitrates, and ammonia between primary and secondary species. CMAQ also track unspeciated mass as crustal/other PM. According to speciation profiles in SMOKE, those crustal/other PM are sources such as road dusts, construction and open burning.

Table 8: species and Particulate Matter elements considered by CMAQ

Nitrogen containing Species	**CMAQ N-containing components**
Nitrogen oxide	NOX=NO+NO2
Oxidised nitrogen	NOY=NOX+NO3+2*N2O5+HONO+HNO3+PAN+PANX+PNA+NTR for concentration and NOY=NOY+ANO3J+ANO3I or NOY=NOY+ANO3J+ANO3I+ANO3K for deposition
Reduced nitrogen	NHX=NH3+ANH4J+ANH4I+ANH4K for deposition
PM Components	
PM2.5 total aerosol	PM2.5=PM2.5_SO4+PM2.5_NH4+PM2.5_NO3+PM2.5_EC+PM2.5_POC+PM2.5_SOAA+PM2.5_SOAB+PM2.5_CM+PM2.5_SS
PM10 total aerosol	PM10=PM2.5+ACORS+ASOIL+ASO4K or PM10=PM2.5+ACORS+ASOIL+PM10_SS+ANH4K+ANO3K
PM2.5 Components	
PM2.5 sulphate aerosol	PM2.5_SO4=ASO4J+ASO4I
PM2.5 ammonium aerosol	PM2.5_NH4=ANH4J+ANH4I
PM2.5 nitrate aerosol	PM2.5_NO3=ANO3J+ANO3I
PM2.5 elemental carbon aerosol	PM2.5_EC=AECJ+AECI
PM2.5 primary organic carbon aerosol	AORGPAJ+AORGPAI/1.2 or PM2.5_POC=AORGPAJ+AORGPAI
PM2.5 anthropogenic SOA	PM2.5_SOAA=AORGAJ+AORGAI or PM2.5_SOAA=AALKJ+AXYL1J+AXYL2J+AXYL3J+ATOL1J+ATOL2J+ATOL3J+ABNZ1J+ABNZ2J+ABNZ3J+AOLGAJ+AORGCJ/2.
PM2.5 biogenic SOA	PM2.5_SOAB=AORGBJ+AORGBI or PM2.5_SOAB=ATRP1J+ATRP2J+AISO1J+AISO2J+AISO3J+ASQTJ+AOLGBJ+AORGCJ/2.
PM2.5 crustal material aerosol	PM2.5_CM=A25J+A25I
PM2.5 sea salt aerosol	PM2.5_SS
PM2.5 total organic matter aerosol	PM2.5_TOM=PM2.5_POC+PM2.5_SOAA+PM2.5_SOAB
PM10 Components	
PM10 sulphate aerosol	PM10_SO4=PM2.5_SO4+ASO4K
PM10 ammonium aerosol	PM10_NH4=PM2.5_NH4+ANH4K
PM10 nitrate aerosol	PM10_NO3=PM2.5_NO3+ANO3K
PM10 sea salt aerosol	PM10_SS=ANAK*0.78+ACLK+ASO4K

6 Modeling system evaluation

In order to evaluate the performance of the modeling platform, we compared CMAQ simulations with observations of each pollutant at measurement sites over the region. The only station that measures nitrogen species close to Lake Tahoe is Reno3 station, which is located inside Reno. Figure 9 shows the location of air quality stations over the modeling domain that we used in this study. Information about stations and error indices are in table 9.

We used both visual and quantitative approaches to evaluate the model output. Two error metrics that we used to quantitatively inspect the model output are MBE and RMSE. MBE is the difference between model output and measurements. The negative value of MBE indicates that the model underestimates the concentrations and positive value of MBE indicates that the model overestimates predictions. RMSE is standard deviation of prediction errors. It tells us how spread out the errors are.

Table 9: Information of air quality stations used in this study.

Station name	latitude	longitude	State code	County code	Site ID
Incline Village	39.250409	-119.956738	"32"	"031"	"2002"
Carson	39.1447	-119.7661	"32"	"510"	"0020"
Reno3	39.525083	-119.807717	"32"	"031"	"0016"
South Reno	39.469219	-119.775354	"32"	"031"	"0020"
Sparks	39.540917	-119.746761	"32"	"031"	"1005"
Tahoe City	39.166017	-120.148833	"06"	"061"	"1004"
Echo Summit	38.81161	-120.033084	"06"	"017"	"0012"

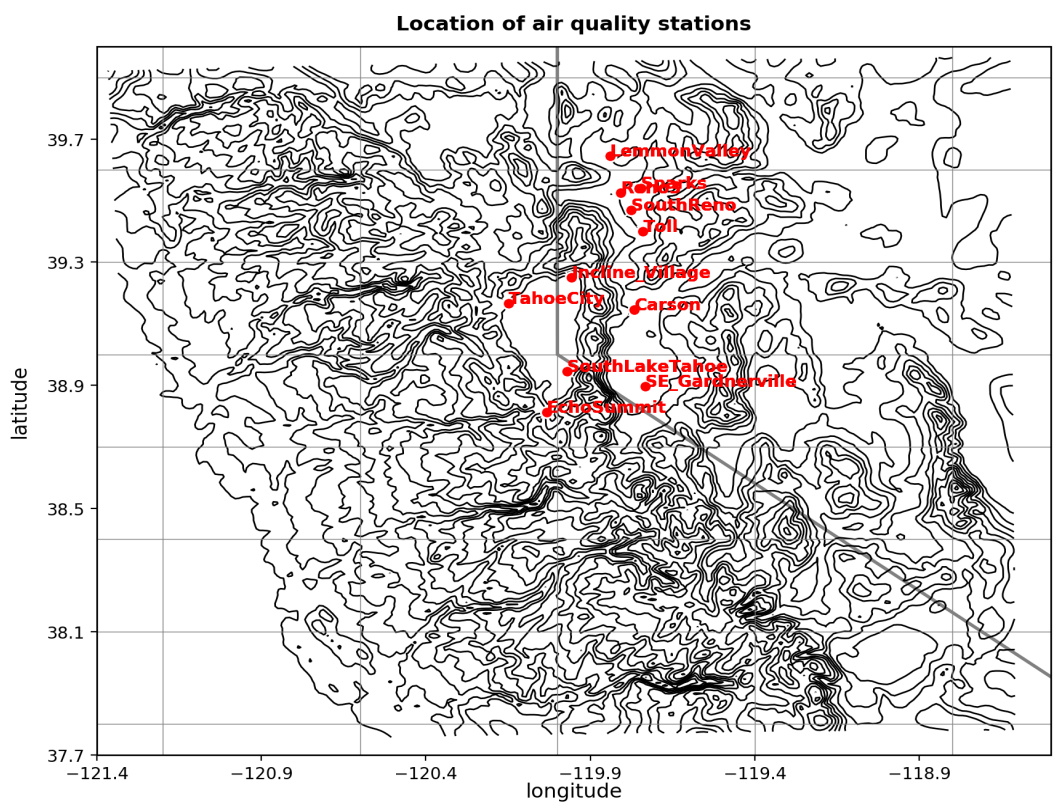

Figure 9: location of air quality stations in the modeling domain.

Figure 10: shows the comparison of diurnal cycle of NO_2 from observations and simulations at Reno3 station. at the plot shows, model has captured the diurnal cycle of

NO_2 at that station well.

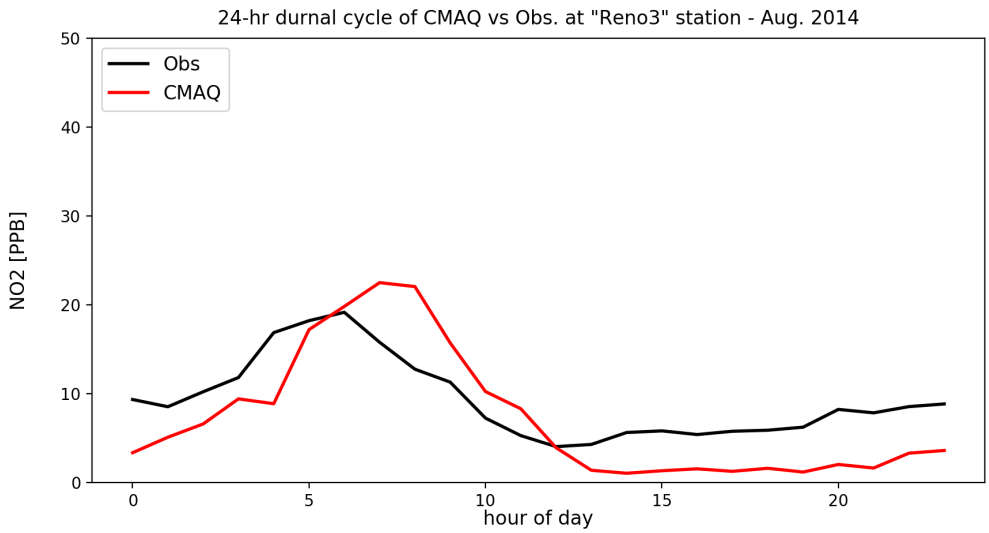

Figure 10 Comparison of diurnal cycle of NO2 from CMAQ and measurements at Reno3 station.

Table 10 provides a quantitative data to compare CMAQ simulations against observations. Two error metrics are calculated to compare observations and model simulations. Positive MBE indicates that predictions are bigger than observations. Although O_3 predictions follow the same diurnal cycle of observations at urban areas, they do not capture the peaks very well and night-time O_3 values are also higher than observations which make the MBE positive.

Figure 11 shows the diurnal pattern of PM2.5 at Reno3 station. PM2.5 predictions follow the diurnal pattern, but concentrations are not predicted well by the model. One reason for this difference might be because we did not include fire emissions in our simulations. MBE also shows that the model underestimates observations by about -5.6 micrograms per cubic meter at Reno3 station.

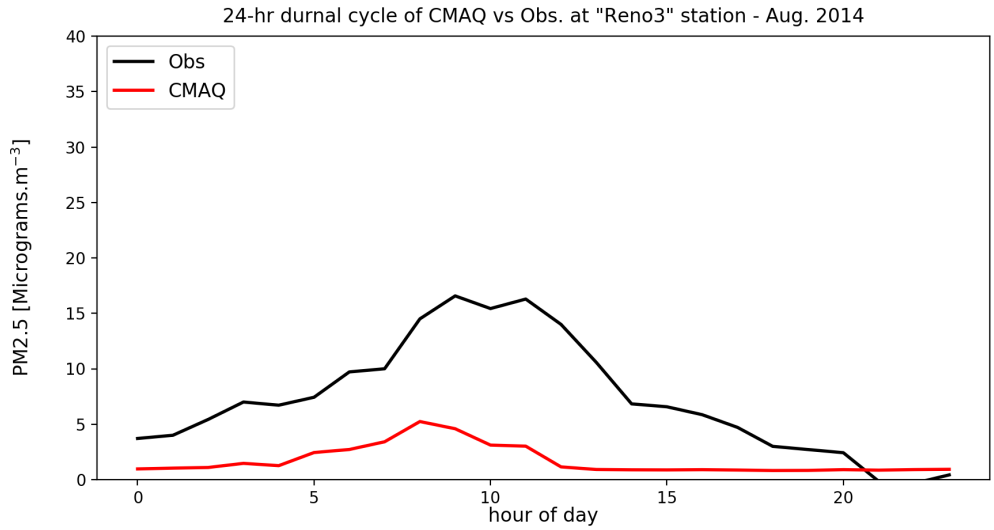

Figure 11 Comparison of diurnal cycle of PM2.5 between CMAQ and measurements at Reno3 station.

Table 10 error values in predictions vs observations ate different measurement sites.

	Station name	MBE	RMSE
Ozone	Incline Village	0.00494	0.01034
	Carson	0.00312	0.01259
	Reno3	0.00085	0.01336
	South Reno	0.00151	0.01337
	Sparks	0.00336	0.01611
	Tahoe City	0.00827	0.01662
	Echo Summit	-0.004911	0.01052
Nitrogen Dioxide	Reno3	-2.2074	6.9721
PM2.5	Reno3	-5.615	8.778

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