Modeling the Effects of Local Air Pollution Control Measures on Air Quality in the Shenandoah Valley

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Abstract

Air quality in the Shenandoah Valley has deteriorated in recent years. The valley exceeds the National Ambient Air Quality Standards for ozone (O_3) a few days each year, and with stricter fine particulate matter ($PM_{2.5}$) standards coming into effect, the valley risks exceeding those as well. Visibility is poor in the valley region, and the haze obscures the spectacular vistas from the Shenandoah National Park. To solve the growing problem local governments in the valley joined forces to find economically and politically feasible ways to reduce air pollution. In this study we aim to provide the scientific basis for air quality management strategies through modeling the sensitivity of various pollutants to changes in emissions. We distinguish between locally generated versus regionally transported air pollution as well as assess the impacts of proposed local air pollution control measures on ambient air quality in the valley.

The first part of this thesis assesses air pollutant emissions in the Shenandoah Valley. Emissions were assigned to one of 14 source categories and allocated by county or city. Biogenic sources were responsible for 56% of the volatile organic compounds (VOCs) emitted in the valley. VOCs are important because they, together with nitrogen oxides (NO_x) react to form O_3 in the presence of sunlight. On-road and off-road mobile sources were the largest anthropogenic sources of VOCs as well as 63% of the NO_x. $PM_{2.5}$ emissions were not dominated by any single source, but fuel combustion, dust, and agriculture were important contributors.

The second part of this thesis focuses on modeling ambient air pollution concentrations in the Shenandoah Valley based on the emissions generated in the first portion. We developed a set of three alternative emissions scenarios for comparison to the base case. We first zeroed anthropogenic emissions in the valley, allowing us to determine how much pollution was produced by local sources versus transported into the valley from upwind areas. We then developed a scenario that contained nine different pollution reduction strategies being considered by local governments. Finally we modeled a similar scenario in which we predicted the impact of ten proposed greenhouse gas reduction strategies on concentrations of O_3 and $PM_{2.5}$. We found that $PM_{2.5}$ concentrations fell when emissions in the valley were reduced, but O_3 did not. $PM_{2.5}$ concentrations fell by 26-57% for the Zero Case and by 10-27% for the other two cases, depending on the time of year and location. Conversely for O_3 there was either no change in most seasons or a small increase in concentrations in the fall. These results suggest that $PM_{2.5}$ in the valley can be controlled with local measures but O_3 is a more geographically wide problem.

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1. Introduction

Air pollution is the one of the leading causes of death in the US. It is responsible for 64 deaths out of every 100,000 people in the US [1]. In terms of direct medical costs, this amounts to $800 per year per adult in America. In Virginia air pollution related health costs total $4.8 billion, about 1.6% of the state's gross domestic product (GDP) [1]. Many studies have found direct relationships between ambient air quality and hospital visits. For example, one study found that if ambient ozone (O_3) and particulate matter (PM) were reduced by 33%, respiratory illnesses in children would decrease by a third, and premature deaths would fall by 21 per 100,000 people, resulting in $1.6 billion in medical cost savings per year [1]. Another study found that adding 29 proposed fossil-fuel burning power plants in Virginia would increase PM concentrations in 272 counties across the eastern US by 0.01-0.16 $\mu g\ m^{-3}$, which would lead to more hospital visits, increase premature deaths, and raise medical costs [2].

Although hazardous air pollutant concentrations in Virginia fell during the 1990s and early 2000s, the trend started to reverse in the middle of the decade [1]. Since 2004 ambient O_3 and PM concentrations increased by 5-12% statewide. The Shenandoah Valley, a mountainous region in the western part of the state, also had numerous days in which PM and O_3 concentrations violated the United States Environmental Protection Agency's (USEPA) air quality standards. In order to tackle this problem the Shenandoah Air Quality Project (SHENAIR) was begun in 2005. This project focuses on improving air quality through coordinated actions by local governments.

1.1 Shenandoah Valley Characteristics

The Shenandoah Valley consists of a strip of 20 counties and independent cities in the states of Virginia and West Virginia. The region starts at the southern end in Roanoke County and it continues northeastward in Virginia close to the West Virginia border. At its northeastern end the Shenandoah Valley region spills out of Virginia and into the two counties that make up the West Virginia panhandle. The entire valley makes up slightly over nine percent of the combined Virginia and West Virginia area. In terms of topography the valley is surrounded by the Blue Ridge Mountains on the east and the Valley and Ridge region on the west. Within the valley itself, elevation tends to increase southward. The lowest points, in the north, range between 100-200 m above sea level while the highest areas, in the south, reach close to 900 m above sea level.

Population densities in the valley are not as high as in the urbanized eastern and northern portions of Virginia but they are greater than in sparsely populated West Virginia and southern Virginia. Figure 1.1 shows a joint Virginia and West Virginia population density map with the

Shenandoah Valley circled. Table 1.1 presents demographic data about the counties and cities that make up the valley.

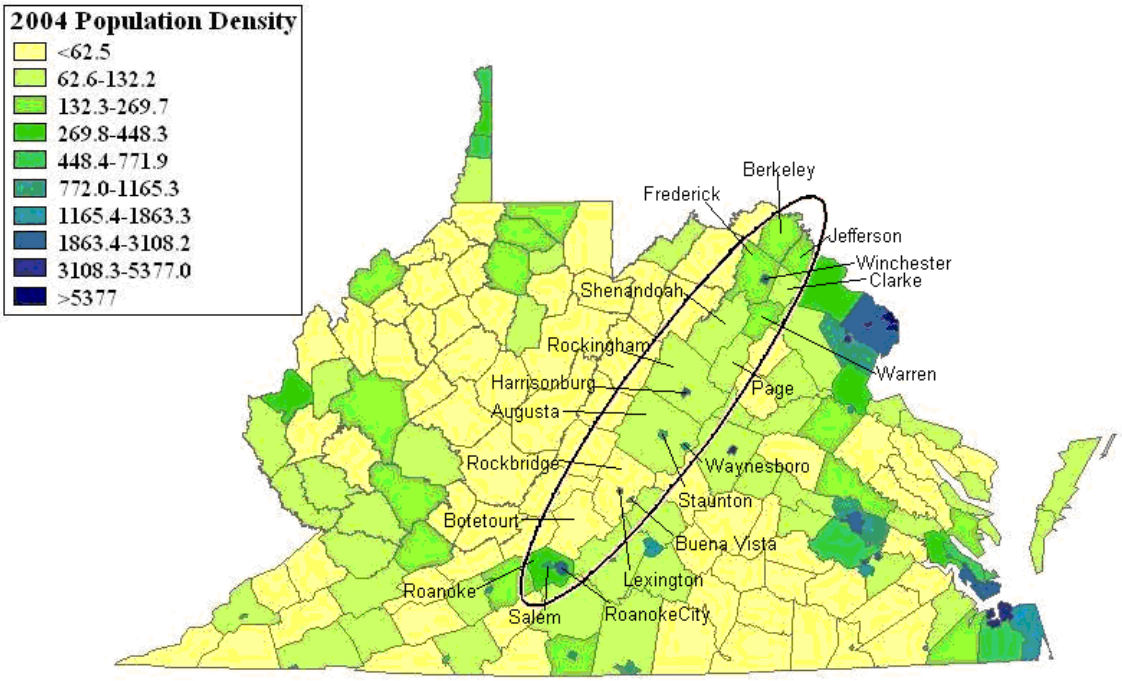


Figure 1.1: Map of population densities of Virginia and West Virginia. The black oval encircles the counties and cities of the Shenandoah Valley.

Table 1.1: Demographic statistics of the Shenandoah Valley.

City/County/State (north to south)	Pop.	Area (km^2)	% Pop.	% Area
Virginia	7,078,515	110,862	-	-
West Virginia	1,808,344	62,809	-	-
Berkeley County	93,394	833	11.57%	5.83%
Jefferson County	42,190	548	5.23%	3.83%
Frederick County	59,209	1,076	7.33%	7.53%
Winchester City	25,119	24.2	3.11%	0.17%
Clarke County	12,652	462	1.57%	3.23%
Shenandoah County	35,075	1,327	4.34%	9.29%
Warren County	31,584	560	3.91%	3.92%
Page County	23,177	813	2.87%	5.69%
Rockingham County	67,725	2,210	8.39%	15.47%
Harrisonburg City	40,468	45.6	5.01%	0.32%
Augusta County	65,615	2,515	8.13%	17.60%
Staunton City	23,853	51	2.95%	0.36%
Waynesboro City	19,520	39.8	2.42%	0.28%
Rockbridge County	20,808	1,557	2.58%	10.90%
Lexington City	6,867	6.4	0.85%	0.04%
Buena Vista City	6,349	17.7	0.79%	0.12%
Botetourt County	30,496	1,405	3.78%	9.83%
Roanoke County	85,778	650	10.63%	4.55%
Salem City	24,747	37.8	3.07%	0.26%
Roanoke City	92,631	111.4	11.47%	0.78%
Shenandoah Region	807,257	14,290	9.08%	8.23%
Virginia Shenandoah Region	671,673	12,909	5.86%	5.81%
West Virginia Shenandoah Region	135,584	1,381	7.50%	2.20%

[1]Percentages reflect the Shenandoah region out of Virginia and West Virginia together.
[2]Percentages reflect the Virginia Shenandoah region out of Virginia only.
[3]Percentages reflect the West Virginia Shenandoah region out of West Virginia only.

1.2 Shenandoah Valley Air Quality in Recent Years

The USEPA is responsible for defining the National Ambient Air Quality Standards (NAAQS) for six criteria pollutants: O_3, PM, carbon monoxide, nitrogen dioxide, sulfur dioxide, and lead. Among them the O_3 and PM standards have been routinely violated in the Shenandoah Valley. For O_3 the USEPA 8-hour standard of 0.08 ppm was established in 1997 and was lowered to 0.075 ppm in 2008. The PM standards have tightened considerably as the evidence linking PM exposure to health effects has accumulated. In the late 1980s the USEPA started focusing on PM_{10} (particulate matter 10 μm in diameter or smaller) instead of total suspended particulate matter and set a 24-hour standard of 150 μg m^{-3} and an annual standard of 50 μg m^{-3}. In the late

1990s new $PM_{2.5}$ (particles 2.5 μm in diameter or smaller) standards of 65 μg m^{-3} and 15 μg m^{-3} were introduced for 24-hour and annual averages, respectively. Finally in 2005 the USEPA invoked a more stringent 24-hour $PM_{2.5}$ standard of 35 μg m^{-3} and in 2006 revoked the PM_{10} annual standard.

The number of O_3 monitoring sites the Virginia Department of Environmental Quality (VDEQ) maintains within the Shenandoah Valley region has increased from just one in 1980 to four at present. Roanoke County was initially the lone O_3 site while today monitoring sites exist in Roanoke, Frederick, Rockbridge, and Page Counties. Monitoring sites also existed in Augusta and Warren Counties from 1985 through 1994 but were shut down thereafter. The number of PM_{10} monitoring sites has also increased from one to four since 1985. Initially present just in Roanoke County, they now exist in Roanoke, Warren, Winchester, and Rockingham Counties. $PM_{2.5}$ measurements in the Shenandoah Valley, on the other hand, started in 2005, and currently $PM_{2.5}$ monitoring sites exist in the cities of Roanoke and Salem and in Page County.

Summary measurements of these three pollutants in the valley are shown in Figures 1.2-1.5 and Table 1.3. Figure 1.2 shows maximum 8-hour average O_3 concentrations between 1980 and 2007 while Figure 1.3 shows the number of days that violated the NAAQS. Violations of the standard are known as “exceedances”. Figure 1.4 shows maximum 24-hour averages, and Figure 1.5 shows annual average PM_{10} concentrations between 1985 and 2007, while Table 1.3 displays $PM_{2.5}$ 24-hour maximum and annual average concentrations between 2005 and 2007.

Figures 1.2 and 1.3 show that since the 1980s a few ozone exceedances have been common each year in the Shenandoah Valley, though there has not been a consistent trend over time. There was however, good correlation between the number of exceedances and the reported maximum 8-hour concentration, as expected. In the early to mid-1980s three to five exceedances were typical for Roanoke. When O_3 measurements started in Augusta and Warren Counties in 1985, there was only one exceedance in Augusta County but nine in Warren County. The following year exceedances were low in all three counties but rose sharply in 1987 and 1988. From 1989 to 1997 exceedances per year remained low in all counties. In 1992 a monitoring site was added in Frederick County while in 1995 the O_3 monitoring sites in Augusta and Warren Counties were taken offline. In 1998 another sharp increase in O_3 exceedances was recorded in all counties, but exceedances came down the following year. In 2001 Rockbridge and Page Counties received O_3 monitoring sites as well. In 2003 the number of exceedances started dropping in all counties, and by 2005 no exceedances were reported. While Augusta, Frederick and Roanoke Counties have had relatively significant emissions of the ozone precursors, volatile organic compounds (VOC) and NO_x, Warren and Page Counties have not, suggesting their O_3 concentrations may be due to

pollutant influx from other areas. Table 1.2 below shows the four days of 2002 in which O_3 concentrations were the highest at various locations in the Shenandoah Valley [3]. The year 2002 is important because it is the base year we used in our research. The anomalies in exceedances over the last 25 years suggest that meteorology plays an important role in O_3 concentrations. Wind patterns may also explain why counties with similar VOC and NO_x emissions have different O_3 concentrations. In this case it is likely that pollutants are being transported from one place to another.

Table 1.2: 2002 dates of the four highest O_3 concentrations in the Shenandoah Valley.

Location	1st Max	2nd Max	3rd Max	4th Max
Rockbridge Co.	8/11	6/11	8/23	8/10
Frederick Co.	9/10	7/2	8/11	8/13
Page Co.	9/10	8/11	9/13	8/14
Roanoke Co.	8/13	7/17	8/11	6/11

Figures 1.4 and 1.5 show that PM_{10} concentrations in the Shenandoah Valley never exceeded the NAAQS over the last 20 years and were fairly constant from year to year. There was also a slight overall reduction in PM_{10} concentrations between 1985 and 2007. The annual arithmetic mean (AAM) and the maximum 24-hour PM_{10} concentration were not strongly correlated. Throughout this time the AAM PM_{10} concentrations measured in Roanoke were in the 40-60 $\mu g\ m^{-3}$ range in the mid to late 1980s and over the next 20 years fell to 15-30 $\mu g\ m^{-3}$, where they currently stand. The other PM_{10} monitoring sites in Warren County, Winchester City, and Rockingham County, came online in 1988, 1989, and 1997, respectively. These sites always reported AAM concentrations below 31 $\mu g\ m^{-3}$. Maximum 24-hour PM_{10} concentrations varied more than AAM concentrations from year to year. These measurements also showed unusually high concentrations in 1987 and 1997, the same years O_3 concentrations were high. Aside from these years, in which maximum 24-hour concentrations exceeded 110 $\mu g\ m^{-3}$ in Roanoke, levels did not exceed 100 $\mu g\ m^{-3}$ in Roanoke or 75 $\mu g\ m^{-3}$ in other places. The year-to-year anomalies in 24-hour PM_{10} concentration further support the hypothesis that meteorology influences pollutant concentrations in the Shenandoah Valley.

When the national $PM_{2.5}$ standards were introduced, Salem and Roanoke exceeded the annual standards in 2005 (Table 1.3). Roanoke City and County had relatively large $PM_{2.5}$ emissions in 2002, mainly from dust and vehicles, and these emissions may have been responsible for the high $PM_{2.5}$ concentrations in nearby Salem. But the next year both Roanoke

and Salem had fallen below the national annual standards. A new $PM_{2.5}$ measuring station was installed in 2006 in Page County, and this station reported no exceedances for that year.

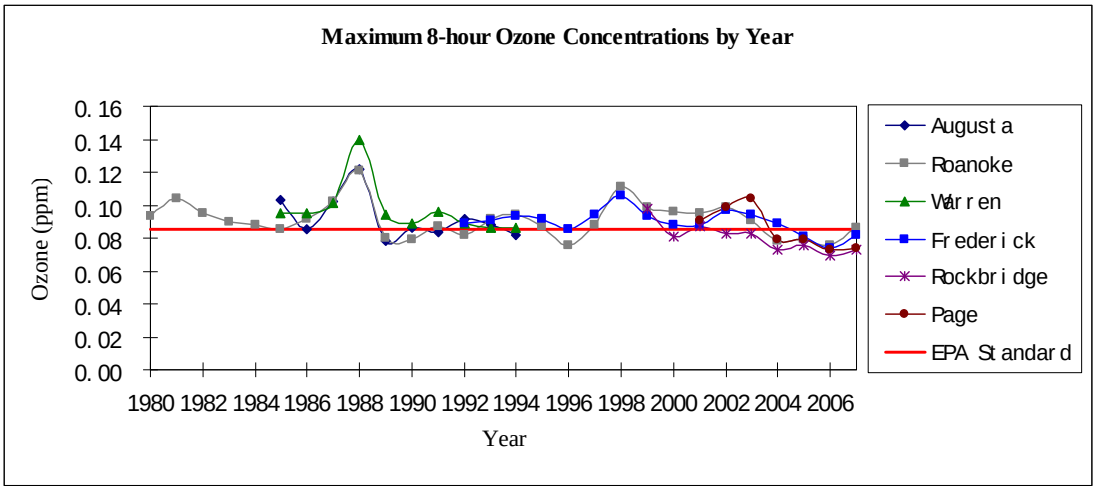


Figure 1.2: Maximum 8-hour average O_3 concentrations from 1980 to 2007.

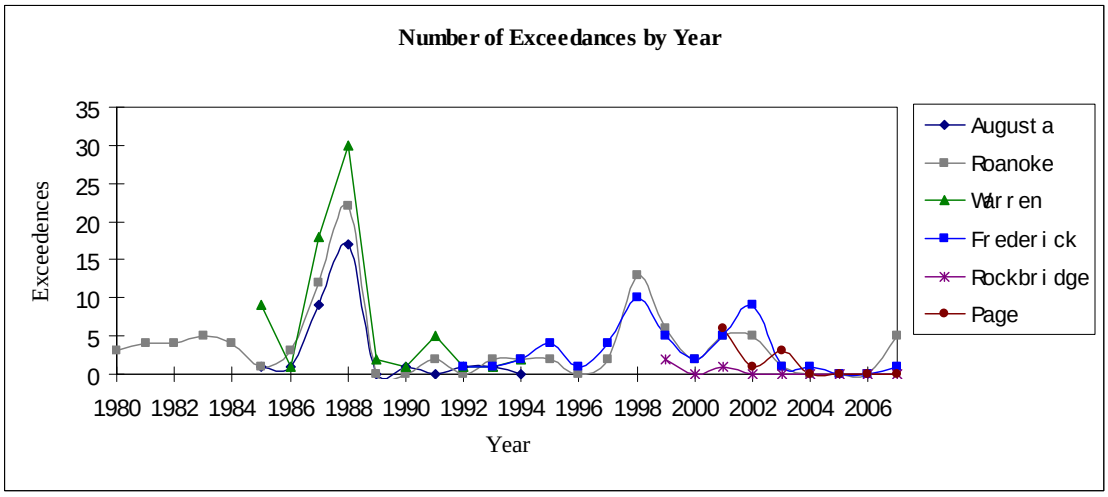


Figure 1.3: O_3 exceedances for the years 1980 through 2007.

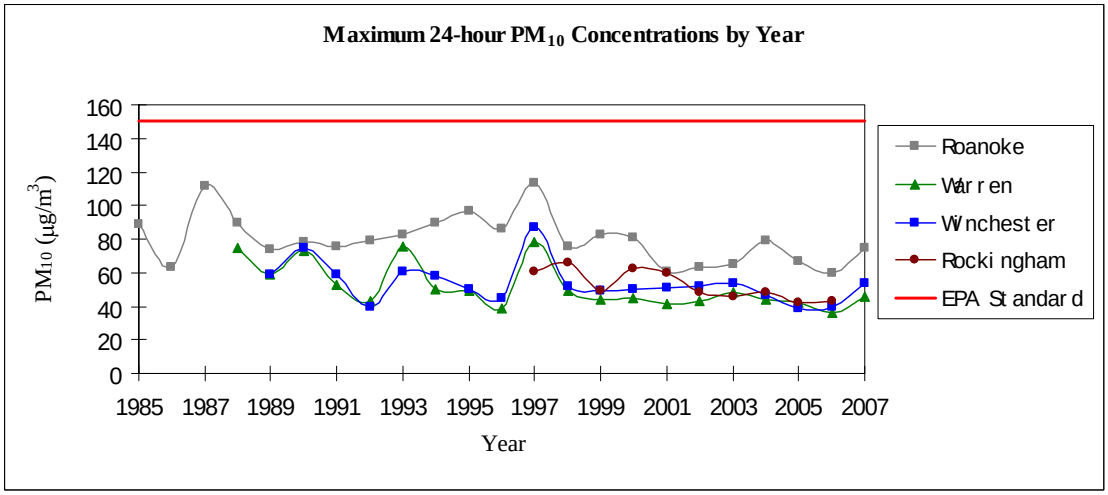


Figure 1.4: Maximum 24-hour average PM_{10} concentrations from 1985 to 2007.

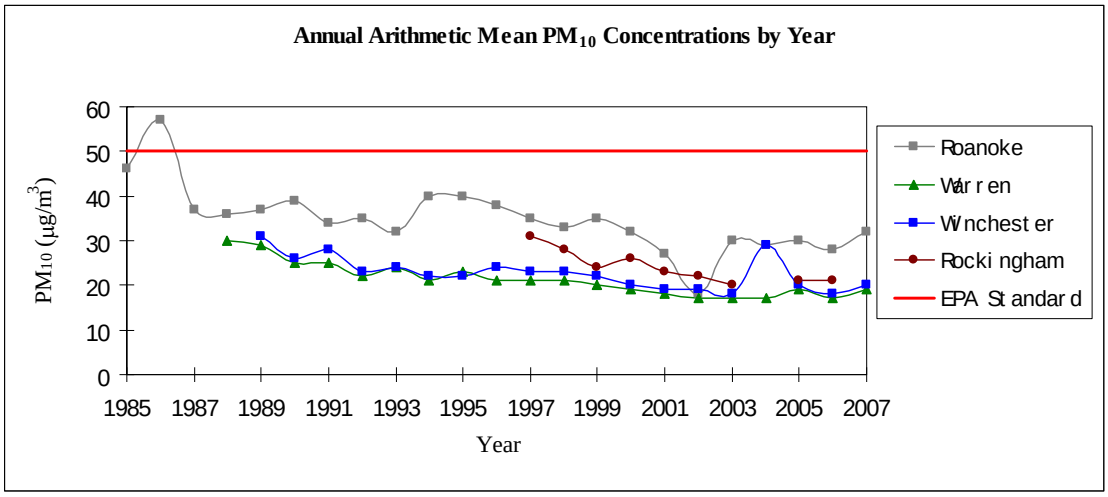


Figure 1.5: Maximum annual average PM_{10} concentrations from 1985 to 2007.

Table 1.3: Maximum 24-hour and annual arithmetic mean $PM_{2.5}$ concentrations between 2005 and 2007. Exceedances of the NAAQS are in bold.

Year	Roanoke		Salem		Page	
	24-Hour ($\mu g/m^3$)	AAM[a] ($\mu g/m^3$)	24-Hour ($\mu g/m^3$)	AAM ($\mu g/m^3$)	24-Hour ($\mu g/m^3$)	AAM ($\mu g/m^3$)
2005	35.4	**15.1**	37	**16**	**41.2**	14
2006	29.9	14.2	21.9	12	28.3	12.1
2007	**45.2**	14.2	NA	NA	33.2	12.5

[a]Annual arithmetic mean.

1.3 O_3 and PM Formation

O_3 is a secondary pollutant created by reactions between VOCs and NO_x. Its formation is controlled by a complex relationship between sunlight, temperature, VOC and NO_x concentrations, and the exact species of VOCs that are present. Figure 1.6 is an ozone isopleth diagram that shows the ozone concentration resulting from certain initial concentrations of VOCs and NO_x [4]. The isopleths are lines of constant O_3 concentration; multiple combinations of VOCs and NO_x can result in the same O_3 concentration. Ozone formation falls into one of two regimes: VOC-limited or NO_x-limited, separated by the diagonal line running from the origin to the upper right corner. In the VOC-limited regime, reductions in VOC concentrations are needed to achieve reductions in O_3 concentrations, and in the NO_x-limited regime, the opposite is true. Under certain conditions in the VOC-limited regime, holding VOCs constant and reducing NO_x may actually increase the level of O_3 in the air. This situation presents a special challenge to air quality managers. O_3 in the Shenandoah Valley is worst in the summer because of high biogenic VOC emissions and because of ample sunlight to catalyze O_3 forming reactions [5, 6]. On the other hand ambient O_3 concentrations are low during winter months.

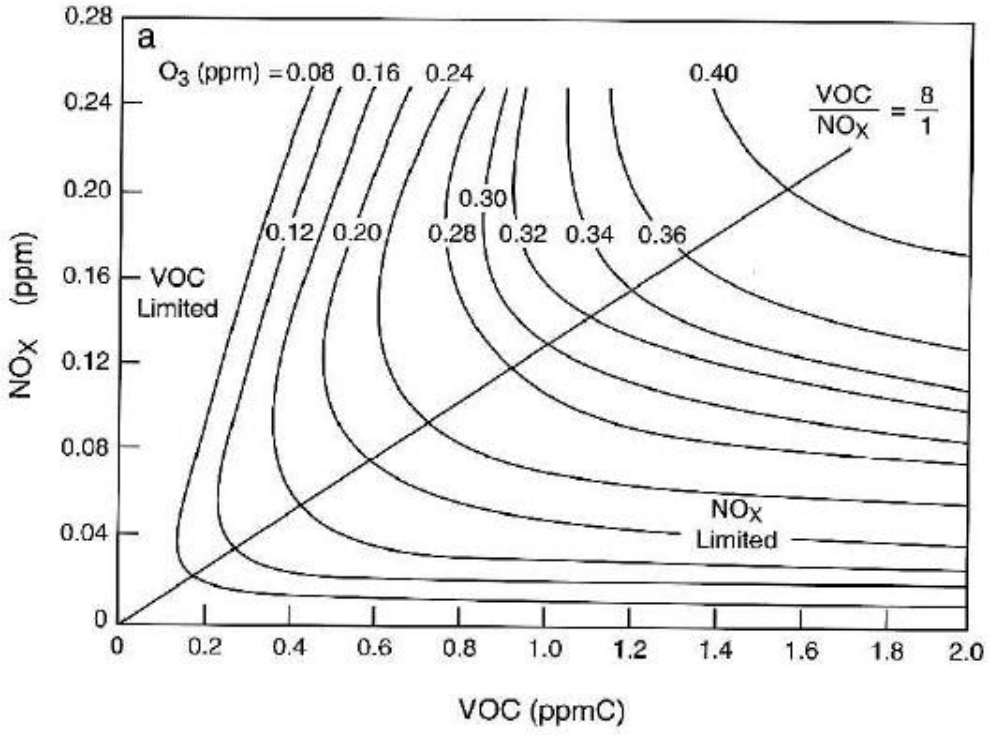


Figure 1.6: O_3 isopleth chart. The curved lines represent constant O_3 concentrations [4].

Many studies have attempted to predict O_3 concentrations using various models [7, 8]. Measurements and model predictions indicate that local emissions are chiefly responsible for O_3 and other secondary pollutant formation in the Shenandoah Valley [8]. But studies have also found that prevailing westerly and northwesterly winds in the eastern US lead to pollutants, including VOCs and NO_x, being transported into the Shenandoah Valley from other areas [9, 10]. Evidence for this comes from the fact that peak O_3 times in urban areas in eastern Tennessee and western North Carolina were earlier than peak O_3 times in mountainous regions east and downwind of these cities [9, 10]. This observation indicates that pollutant transport from upwind areas is partially responsible for the high O_3 and possibly also the high PM levels in Shenandoah Valley farther downwind.

PM is both a primary and secondary pollutant. It is divided into two size categories: coarse (particle diameter (D_p) between 2.5-10 μm) and fine (D_p < 2.5 μm). The fine category is often further subdivided into an ultrafine or Aitken mode (D_p < 0.1 μm) and an accumulation mode (0.1 μm < D_p < 2.5 μm). Apart from being emitted as primary pollutants, accumulation and coarse mode particles can also arise from the coagulation of smaller particles [11].

Primary sources of PM include combustion processes, mechanically generated particles, and wind blown dust and sea salt [11]. Studies have shown that dust from northern Africa has reached

the southeastern US and significantly affected PM concentrations during the summer months [12]. Secondary particles are usually formed by gas-to-particle reactions. Some precursor gases that may become particles or react with other gases to do so include NH_3, SO_2, NO_x, and VOCs. Usually when VOCs form the backbone of PM it is categorized as secondary organic aerosol (SOA), while secondary inorganic aerosols (SIAs) have a non-carbon backbone. In the eastern US sulfate (SO_4^{2-}) is the most prevalent SIA, representing between 44-56% of all $PM_{2.5}$ [11]. Sulfate is followed by nitrate (NO_3^-), which makes up 1-5% [11]. In the Shenandoah Valley ammonium nitrate (NH_4NO_3) is also most likely an important PM constituent due to the high ammonia emissions. SOAs in the valley chiefly derive from VOC reactions. Two studies showed that small amounts of hydrogen peroxide in the atmosphere can react with isoprene, a major biogenic VOC pollutant in the valley, to form SOAs [13]. Though SOA yields from isoprene usually represent no more than 4% of the total PM in a given area, this can mean the difference between attainment and nonattainment [14]. In the Shenandoah Valley this percentage may be even higher due to biogenic sources, primarily isoprene, being responsible for 55% of VOC emissions.

1.4 Problems Associated With O_3 and PM

Both PM and O_3 have adverse effects on human health, the environment, and visibility. Airborne particles, especially those smaller than 2.5 μm in diameter which can be inhaled more deeply into the lungs, can cause respiratory and heart problems [15]. A variety of health complications have been linked to PM exposure such as decreased lung function, increased coughing, asthma, chronic bronchitis, heart problems, and even premature death among people with heart or lung problems [15]. In addition to health, PM also deleteriously affects the environment. Transport and deposition of PM can lead to acidification and changes in the nutrient balance of soils and bodies of water, forest damage, changes in biodiversity of ecosystems, and the staining and damaging of buildings, statues and monuments [15]. Airborne PM is also a major cause of visibility reduction [15]. Visibility problems have led the USEPA to form several regional planning organizations (RPOs) which focus on returning visibility across the country to natural levels.

O_3 also has many of the same negative health effects as PM. It has been shown to cause or aggravate a host of respiratory problems and lung diseases such as asthma, wheezing, coughing, breathing difficulty, pneumonia, and bronchitis [16]. O_3 is also responsible for degrading plant life, reducing crop yields, making plants more susceptible to diseases and insects, reducing biodiversity, and even damaging materials such as rubber and furniture [16].

1.5 Shenandoah Air Quality (SHENAIR) Project

Repeated violations of the 8-hour O_3 standard in Frederick County and the city of Winchester and their subsequent designation by the USEPA as non-attainment areas led to the creation of the SHENAIR project in 2005. Local governmental officials realized that air pollution was a regional and multi-pollutant issue and that the problem needed to be solved through a larger effort than what their localities alone could provide [17].

The objective of the SHENAIR project is to improve overall air quality in the Shenandoah Valley by providing a strong scientific basis for environmental policy decisions [17]. Also referred to as the SHENAIR Institute, it is a conglomeration of local governments, universities, and various agencies. In order to work towards its goals, the project is gathering, maintaining, and modeling data on meteorology, air pollution emissions, and concentrations; researching the effects of local and regionally transported air pollution; and studying the relationships between air quality, public health, ecological health, and economic growth [17].

The SHENAIR project also aims to incorporate and educate stakeholders in its effort [17]. To meet this objective the project educates teachers, students, landowners, and the general public about the benefits of good air quality [17]. Three SHENAIR programs, Valley AIRNow, Global Learning and Observations to Benefit the Environment (GLOBE), and Science on a Sphere (SOS), connect the project's work to the public [17]. Valley AIRNow informs the public about their lifestyle choices' effects on air quality [17]. It emphasizes small-scale, everyday actions people can take that collectively will improve the air in their communities [17]. GLOBE aims to support air quality and environmental education within the K-12 school science curriculum. The SHENAIR project supports teachers and trains faculty to teach specifically about pollution related topics in their science classes [17]. Through the SOS program SHENAIR uses emerging 3-D technology to help students visualize environmental and air quality processes. This pilot program at James Madison University (JMU) will help students of all ages understand scientific processes more easily and can also be used as a tool to study the effects of teaching in 3-D versus 2-D [17].

Because O_3 and PM are the most problematic pollutants affecting the Shenandoah Valley, the SHENAIR project is focusing on these two. In order to better understand the causes of their relatively high concentrations in the Shenandoah Valley the project aims to use VDEQ, National Weather Service (NWS), and National Oceanic and Atmospheric Association (NOAA) data and monitoring stations to observe air pollution levels and changes in the valley [17]. It will also use computer modeling of various air quality scenarios to better understand emissions and transport. Combining these models with meteorology and geographical information systems (GIS) land use

and land cover (LULC) data, SHENAIR will be able to provide decision support tools for policy makers to develop the best and most cost-effective method of improving air quality [17].

1.6 Research Objectives

There are two main parts to this study. The first part assesses the spatial and temporal allocation of emissions within the Shenandoah Valley. Using emissions inventory data from VISTAS we will break down anthropogenic emissions by county and city in the valley to determine where they are highest. The VISTAS data also include biogenic emissions from trees, bushes, grasses, and soil. Our objective in this first part will be to quantitatively describe the major sources of emissions in the Shenandoah Valley. If biogenic emissions are much higher than anthropogenic emissions it will be difficult for policy-makers to regulate industry and human activity effectively. We will also identify the largest sources within the Shenandoah Valley that might be suitable targets for emissions reductions.

The second objective of this study will be to test the sensitivity of predicted O_3 and PM concentrations under various emissions scenarios. The base scenario will be one in which emissions for the Shenandoah Valley will be our unaltered results from the first part of the study. After the base scenario has been run we will proceed to manipulate emissions within the valley to quantify their effect on ambient air pollution. In the first scenario we will set all anthropogenic emissions within the valley to zero to distinguish between air pollution generated from local emissions versus air pollution originating from regions outside the Shenandoah Valley. The results of this sensitivity study will help quantify the potential for local air pollution control measures to reduce O_3 and PM within the valley.

Additional scenarios will quantify the sensitivity of O_3 and PM to various strategies that the local governments of the Shenandoah Valley might consider to manage air quality. For example, the impacts of idle reduction rules, school bus retrofitting, and public awareness campaigns may lead to improved air quality. In collaboration with SHENAIR participants, we will develop alternative emissions inventories that account for such changes and run the air quality model with them. We will then quantify the changes in predicted O_3 and PM concentrations that result from the reductions in emissions. Based on these results, the local governments can gauge the impact of air management policies they might implement.

The final scenario will examine the effects on ambient air quality due to greenhouse gas reduction plans. Through ICLEI, an international association of local governments, many policies are being and will be implemented within the valley to reduce its carbon footprint. These policies are likely to have the added benefit of reducing USEPA criteria pollutant concentrations as well. For example, mandating higher energy efficiency for streetlights would reduce the need for

electricity in the valley. The lower demand, and thus generation, of electricity would also lower anthropogenic VOCs, NO_x, SO_2, and other pollutant emissions associated with coal-fired power plants that provide most of the valley's power. Furthermore if measures are taken to implement new renewable energy sources, such as wind and solar power, instead of using conventional fossil-fuel energy sources, the reduction in pollutant emissions would be even greater. Our goal will be to quantify these reductions based on ICLEI's plans for the Shenandoah Valley and to predict their impact on pollutant concentrations.

2. Emission Inventories and Model Validation

The first portion of this chapter focuses on seven air pollutants emitted in the Shenandoah Valley: volatile organic compounds (VOCs), nitrogen oxides (NO_x), carbon monoxide (CO), fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), and ammonia (NH_3). Both biogenic and anthropogenic emissions are considered. In 2002, biogenic sources accounted for more than half of VOC emissions. The remaining pollutants were emitted entirely by anthropogenic sources. Highway vehicles were responsible for the majority of NO_x and CO emissions, at 58% and 72%, respectively; agriculture and miscellaneous sources were mainly responsible for PM_{10} and NH_3, at 53% and 95%, respectively; and industrial fuel combustion was the source of 73% of SO_2 emissions. No single source was overwhelmingly responsible for $PM_{2.5}$. Fuel combustion, industrial processes, and miscellaneous sources all contributed to $PM_{2.5}$ emissions.

The second portion of this chapter describes a model performance evaluation of the Community Multiscale Air Quality model (CMAQ) specifically for the Shenandoah Valley. CMAQ was installed on Virginia Tech's System X supercomputer and run for January and July 2002, using inputs developed by the Visibility Improvement State and Tribal Association of the Southeast (VISTAS) regional planning organization. Excellent agreement between our output files and the VISTAS benchmark indicates that the model is running correctly on our computer system. Compared to observed concentrations, the model tended to underestimate CO and NO_2, while for O_3 the model underestimated the peaks and overestimated the troughs. Overall model performance was average for gaseous species and poorer for particulate species, for which predicted concentrations were 15-65% lower than observations depending on species, location, and time of year.

2.1 2002 Emissions in the Shenandoah Valley

An "emissions inventory" is a budget of air pollutant emissions by species, source, time period, and spatial domain. For example, the USEPA's National Emissions Inventory contains estimates of NO_x emissions in each of four major categories—point, area, mobile, and biogenic—per year for each state. The inventory may be further broken down into individual sources and for modeling purposes, finer temporal and spatial scales down to one hour and 4-km grid cells, respectively.

New measurement techniques and technology advancements have led to ever more accurate emission inventories. Nevertheless, there are always discrepancies between inventories and measured data. One problem is that inventories tend to use averages for multiplication factors in

their calculations even though these factors may vary greatly spatially and temporally. One study found that many emissions inventories used particulate organic carbon (OC) to elemental carbon (EC) ratios between 1.5 and 5.5 while in fact true OC to EC ratios in the southeastern US were between 3 and 8 [18].

Emissions inventories are often used in air quality models. For the Shenandoah Valley the emissions inventory from the Visibility Improvement State and Tribal Association of the Southeast (VISTAS) is being used to model ambient air pollution concentrations. VISTAS is a regional planning organization (RPO) that was created as a conglomeration of ten states and the Eastern Band of Cherokee Indians [19]. A map of the states falling under VISTAS' jurisdiction is shown in Figure 2.1 [20]. The group's task is to return visibility to natural levels by the year 2050. Working with two consulting firms, VISTAS developed an inventory for the year 2002 based on the 1999 National Emissions Inventory version two (NEIv.2). It incorporated new data from state and local air quality agencies, the IMPROVE and SEARCH pollutant monitoring site networks, as well as the NEIv.2 with growth factors. Apart from accounting for temporal changes in emissions, the new 2002 base inventory also improved the accuracies of speciation and seasonal variation of EC and OC, seasonal variation and spatial allocation of ammonia (NH_3) emissions, and the precision of sulfur dioxide (SO_2) emissions [20].

Figure 2.1: A map of the states falling under VISTAS' jurisdiction [20].

To temporally and spatially allocate the emissions inventory for the Shenandoah Valley we used the Sparse Matrix Operator Kernel Emissions (SMOKE) program. Our procedure for running SMOKE is outlined in Appendix E. SMOKE supports processing of area, point, biogenic, and mobile, both onroad and nonroad, sources [21]. For processing biogenic and mobile emissions SMOKE also integrates the Biogenic Emission Inventory System, version 2.3 (BEIS2), and versions 3.09 and 3.13 (collectively known as BEIS3) [21]. Taking meteorology, raw

inventory, LULC, and grid data as inputs, SMOKE outputs gridded, speciated, and hourly processed emissions ready to be used in air quality models [21]. For our research we use meteorological input produced by the MM5 model on a 12 km × 12 km grid of the southeastern US.

To model ambient air quality we used the Community Multiscale Air Quality (CMAQ) program. CMAQ has been applied to a wide range of air quality related issues, including tropospheric O_3, fine particles, toxics, acid deposition, and visibility degradation [22]. It contains many processors including the Photolysis Rate Processor (JPROC), Initial Conditions Processor (ICON), Boundary Conditions Processor (BCON), Meteorology-Chemistry Interface Processor (MCIP), and CMAQ Chemical-Transport Model (CCTM) [22].

As with all models there are discrepancies between CMAQ's predicted air pollutant concentrations and observed values. Such discrepancies arise from the lumping of species in the model to maintain computational efficiency, inadequate spatial resolution of the grid, and inaccuracies in input data, among other causes. Studies have been conducted on CMAQ's accuracy concerning various pollutants. For sulfate CMAQ tended to slightly underestimate ambient concentrations in the fall, winter, and spring seasons while it slightly overestimated concentrations in the summertime [23, 24]. For nitrate and ammonium (NH_4^+) the trend was reversed, and concentrations were overestimated in times of cold weather while they were underestimated in warmer seasons [23, 24]. The differences between measured and modeled values were also greater for nitrate than for sulfate and ammonium [23, 24]. For OC and EC, both important factors in PM modeling, CMAQ underestimated ambient concentrations year round, though the model was more accurate in the wintertime [23, 24].

Another problem with earlier versions of CMAQ had been its treatment of secondary organic aerosols, PM that is formed from the condensation of low-volatility organic compounds from the gaseous phase into the particulate phase. CMAQ uses a modal approach to model particles, meaning it treats PM as a superposition of Aitken (particle diameter (D_p) < 0.1μm), accumulation, and coarse particles [25, 26]. Initially in its treatment of secondary PM though, it assumed all particles were fine (Aitken or accumulation) and did not account for coarse secondary particles [25, 26]. This led to some of the underpredictions and overpredictions mentioned above [26]. With the release of CMAQ version 4.4 in 2004 though, a module was built into the program which accounted for coarse SOAs [24, 27]. It also introduced seven other SOA formation mechanisms not previously accounted for in CMAQ: polymerization, sesquiterpenes, isoprene reactions, biogenic organic VOC reactions, reactivity, acid catalyzation, and heterogeneous

reactions [27]. The addition of this module has greatly improved CMAQ's accuracy in predicting concentrations, especially over the eastern US [27].

We obtained the official emission inventory (version "Base G") for the southeastern U.S. from VISTAS. The inventory describes emissions in the year 2002 on a 12-km grid. It comprises the latest state and local government agencies' information, United States Forrest Service (USFS) fire projections data, updated emissions inventories from other RPOs around the country, updated Canadian and Mexican emissions, coal combustion speciation, and the EPA's NONROAD2005 model data. Appendix A lists annual emissions of volatile organic compounds (VOC), nitrous oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), coarse and fine particulate matter (PM_{10} and $PM_{2.5}$), and ammonia (NH_3) by major source category and by state, county, city, and region. Appendix B lists each county's or city's per capita emissions of the pollutants.

Figure 2.2 shows emissions of each pollutant by county or city. For most pollutants the Shenandoah region emitted roughly the same amount of pollutants per capita and per area compared to the entire states of West Virginia and Virginia except for two species: SO_2 and NH_3. SO_2 emissions were very low, less than 3% of the two states' total, and conversely ammonia emissions were very high, nearly 30% of the total. The relatively low SO_2 emissions are due to the absence of coal-burning power plants in the Shenandoah Valley, and the high ammonia emissions are likely due to the relatively high prevalence of agriculture in the Shenandoah region. Within the Shenandoah region itself, the relative contributions of the various air pollutants differed from county/city to county/city.

Three counties, Augusta, Frederick, and Rockingham, were mainly responsible for VOCs, accounting for a combined 32% of emissions. This was mainly due to their relatively large rural land areas and thus, higher biogenic VOC emissions. Rockbridge and Shenandoah Counties were also high-VOC-emitting counties, each responsible for over 8% and 9% of the Shenandoah Valley's VOC emissions, respectively. VOC emissions in the Shenandoah Valley were also unique in that they were dominated by biogenic sources. In 2002 they accounted for 55% of the VOCs emitted within the valley while the next largest source, highway vehicles, accounted for 17%. The valley's heavily forested lands are mainly responsible for the high biogenic VOC emissions. The problem is aggravated by the fact that hickory and oak trees are the most common trees in the Shenandoah Valley [28]. These species are some of the highest emitters of biogenic VOCs such as isoprene, monoterpenes, and sesquiterpenes. The emission potentials from these trees can reach as high as 40 μg carbon per gram of tree per hour ($\mu g\ C\ g^{-1}\ hr^{-1}$), of which isoprene is responsible for 38.5 $\mu g\ C\ g^{-1}\ hr^{-1}$ [29]. On average trees and plants emitted four times more isoprene than monoterpene, the second most prominent biogenic VOC [29]. During

summertime on average Virginia forests' emission rates ranged between 20-25 μg C g^{-1} h^{-1} of isoprene and 1-1.5 μg C g^{-1} h^{-1} of monoterpene [30]. Sesquiterpenes and other compounds were emitted in small amounts.

For NO_x, the highest emitters were Berkeley, Botetourt, and Frederick Counties. All three combined accounted for about 34% of the NO_x emitted in the region, while they constituted only about 23% of both the population and area of the region.

When compared to other air pollutants, CO emissions seemed to correspond better to both the populations and land area of each of the counties and cities in the Shenandoah region. For example, the main emitters were Frederick County at 15%, followed by Augusta County at 10% and Roanoke City and County at around 9% each. Together these divisions accounted for 34% of the CO emitted in the region, but they also combined for 37.5% of the people and 30.5% of the area. The lowest emitters of CO were Buena Vista, Lexington, Staunton, Waynesboro, and Winchester, which combined to be responsible for 5.3% of the CO emitted but also 10% and 1% of the population and area, respectively.

The entire Shenandoah Valley region emitted less than 3% of the SO_2 in Virginia and West Virginia. The small contribution is due to the lack of energy generating units (EGU) in the Shenandoah Valley. Only one EGU, a small 18 megawatt gas turbine facility in Harrisonburg, exists in the region. Within the region, though, Botetourt and Rockingham Counties were the main contributors, emitting about 12.5% and 10.5% of all the SO_2. Industrial fuel combustion and other industrial processes were mainly responsible for the SO_2 emissions. Together these two counties accounted for a little over 12% of the population and 25.3% of the area.

Berkeley, Jefferson, and Rockingham Counties were mainly responsible for PM_{10} emissions in the Shenandoah region. They each emitted at least 10% and together emitted 35.5% of the PM_{10}. These three counties comprised just over 25% of both the people and area of the region.

$PM_{2.5}$ emissions were more dispersed than those for PM_{10}. They also corresponded better to population and area than other pollutants, much like CO did. The main regions responsible for $PM_{2.5}$ were Berkeley, Roanoke, and Rockingham Counties. Together they made up 30.5% of the population and 26% of the area, but 30.4% of the $PM_{2.5}$. The lowest emitters of $PM_{2.5}$ were the cities of Buena Vista, Lexington, and Staunton. These cities emitted close to 2% of the $PM_{2.5}$ but made up 4.6% of the population and 0.5% of the area.

Ammonia emissions were relatively high in the Shenandoah Valley. Within the region, ammonia was predominantly emitted in Rockingham County, which accounted for a whopping 45.7% of the region-wide total. Augusta County and Page County were also important emitters of ammonia at 18.5% and 13.5%, respectively. These three counties encompassed under 20% of the

population and just under 40% of the land area but were responsible for almost 78% of the ammonia emitted.

Figure 2.3 shows emissions by major source type within the Shenandoah Valley. A unique characteristic of the valley is Interstate 81 (I-81) that runs through it. According to the US Federal Highway Administration (FHWA) the average annual daily traffic (AADT) on the Shenandoah Valley portion of this highway were 41,500 vehicles in 2002, with AADT being higher in urban areas than rural areas. Out of these 41,500 vehicles slightly over 30% are heavy-duty trucks, though urban areas have a lower percentage of heavy-duty truck traffic. Highway vehicles on this busy highway were chiefly responsible for NO_x and CO emissions, and were significant emitters of VOCs. They accounted for 58% of NO_x and 72% of CO emissions. For VOCs, they accounted for 17% of emissions though primarily isoprene-emitting biogenic sources were responsible for 52% of emissions.

For SO_2, industrial fuel combustion was chiefly responsible with 72% of the emissions. PM_{10} and NH_3 were mainly emitted from miscellaneous sources, primarily agriculture, which accounted for 52% and 95% of them, respectively. The $PM_{2.5}$ category was not dominated by any single emissions source to the extent that other air pollutant categories were. Miscellaneous sources, probably mostly windblown dust, led with 25% of the emissions but were followed by other fuel combustion and industrial fuel combustion sources at 21% and 14.4%, respectively. Both PM categories were unique in that almost all the various types of sources contributed in their emissions. Only electrical utilities fuel combustion was not significant in the emissions of PM, probably because electrical utilities fuel combustion was not an important source of emissions in the Shenandoah region overall. Appendix A contains detailed emissions charts.

Point sources are large facilities that emit sufficient amounts of pollutants that they must monitor and report their emissions to the DEQ. The Shenandoah Valley has 121 point sources that emitted at least 10 tons of pollutants per year. Individually these sources did not emit large amounts of pollutants, but collectively they emitted over 3000 tons of CO, 4100 tons of NO_x, 1350 tons of PM_{10}, 5700 tons of SO_2, and 5000 tons of VOCs in 2002. Except for SO_2, these numbers account for 7% or less of total emissions in the Shenandoah Valley. For SO_2 point sources accounted for about 20% of emissions. Appendix C lists all the non energy generating unit (NEGU) point sources in the Shenandoah Valley.

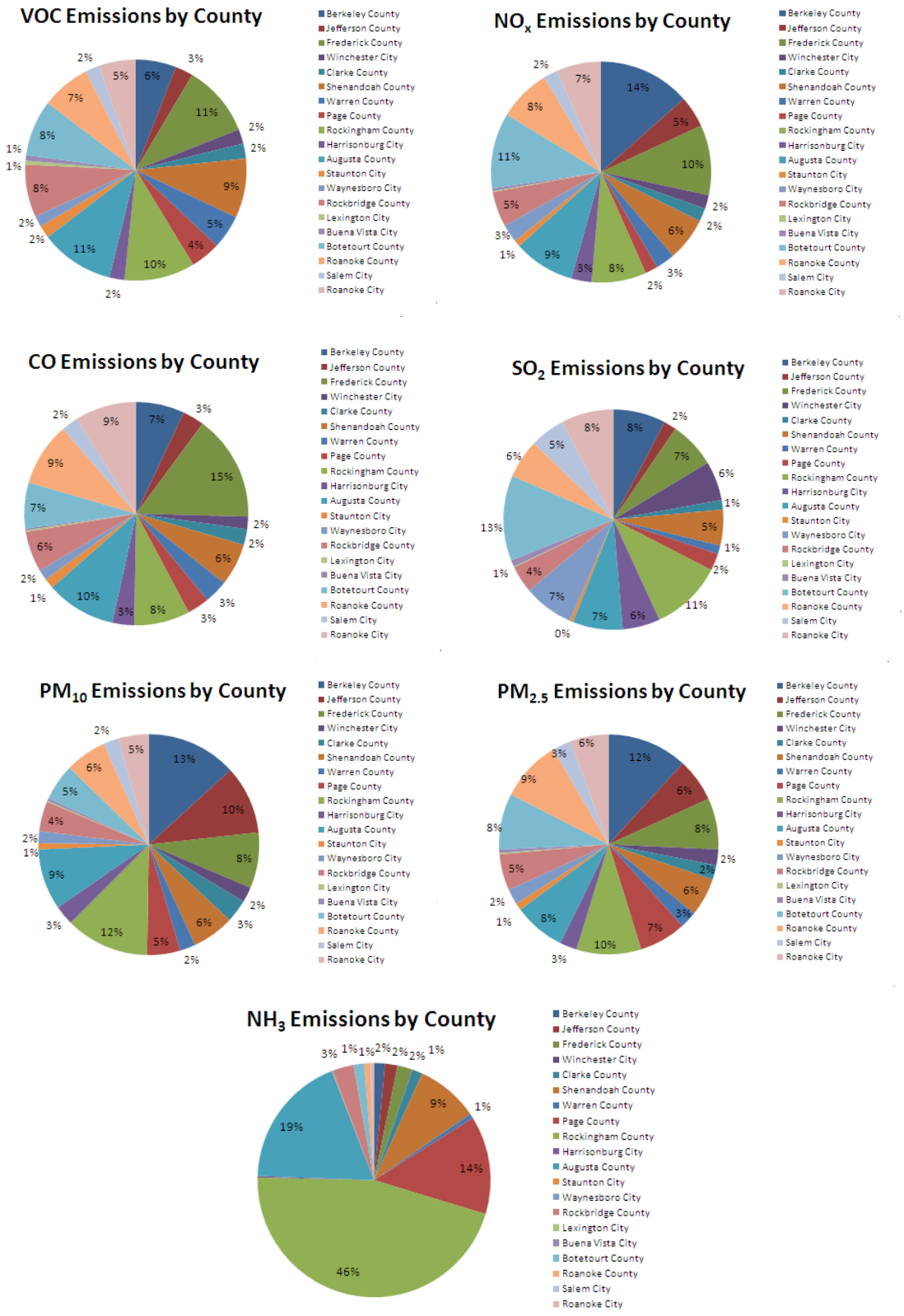


Figure 2.2: Percentages of the air pollutants emitted in the Shenandoah Valley by county or city.

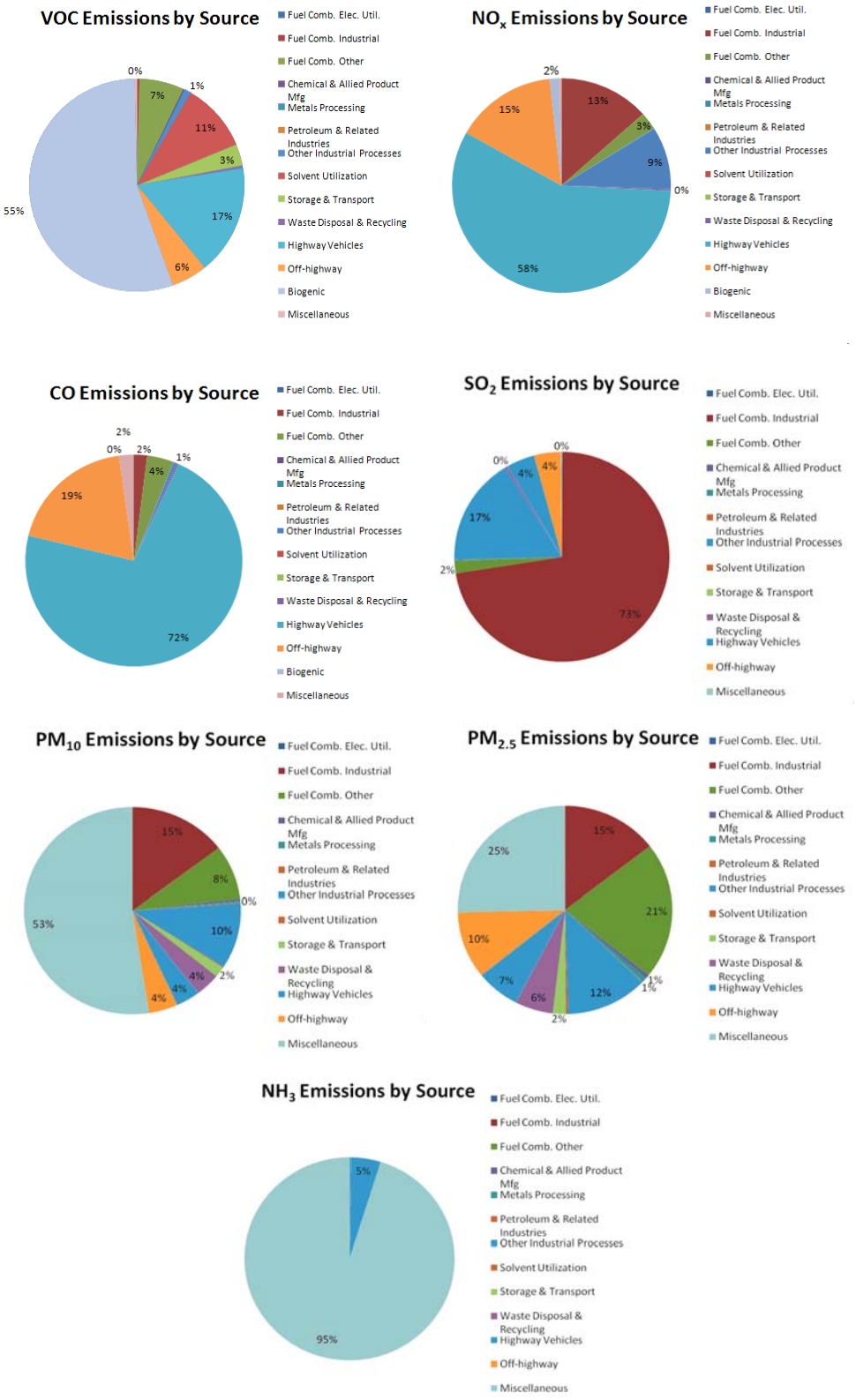


Figure 2.3: Percentages of the air pollutants emitted in the Shenandoah Valley by source type. VOC and NO_x emissions have a biogenic source category while other pollutants do not.

2.2 Air Quality Monitoring Sites

Table 2.1 lists all the air quality monitoring sites within the Shenandoah region, and Figure 2.4 shows the location of all the sites in the Shenandoah Valley. For each site, the species measured and the site's latitudinal and longitudinal coordinates, as well as their geographic location, are listed. We compared our model results against pollutant concentrations observed at these sites.

The limited types of measurements at each site preclude comparison of the emission inventory to ambient pollutant ratios. Traditionally, emission inventories are validated by comparing the ratio of total emissions of, e.g. NO_x/CO and VOC/NO_x, to ambient measurements of these pollutants. In the case of the Shenandoah Valley, however, the only sites measuring multiple primary pollutants are Harrisonburg with PM_{10} and SO_2 and Vinton with NO_x and SO_2. As noted earlier, SO_2 emissions in the Shenandoah Valley are negligible, so the usefulness of any possible comparisons is limited. And unfortunately, no sites in the valley measure VOCs.

Figure 2.4: Locations of the monitoring sites used for comparison to model output.

Table 2.1: Air quality monitoring sites in the Shenandoah Valley.

Station Name	Pollutant	Site Type	Location	City/County	Lat/Long	State Code	County Code	Site ID	Land Use	Location Setting
Natural Bridge	O_3	SLAMS IMPROVE	Natural Bridge, Ranger Station	Rockbridge Co.	37° 37' 34" 79° 30' 47"	51	163	0003	Forest	Rural
Harrisonburg	PM_{10}, SO_2	SLAMS	Valley DEQ Office, 4411 Earl Road	Harrisonburg, Rockingham Co.	38° 23' 22" 78° 54' 51"	51	165	0002	Agricultural	Rural
Rest	O_3	SLAMS	Woodbine Road, Lester Building Systems	Rest, Frederick Co.	39° 16' 58" 78° 04' 53"	51	069	0010	Agricultural	Rural
Luray	O_3, $PM_{2.5}$	SLAMS	Luray Caverns Airport	Luray Page Co.	38° 39' 48" 78° 30' 17"	51	139	0004	Agricultural	Rural
Front Royal	PM_{10}	SLAMS	Warren Co. Memorial Hospital, 1000 Shenandoah Avenue	Front Royal Warren Co.	38° 55' 58" 78° 11' 54"	51	187	0004	Residential	Suburban
Winchester	PM_{10}	SLAMS	Winchester Courts Building	Winchester	39° 11' 08" 78° 09' 47"	51	840	0002	Commercial	Urban
Vinton	SO_2, NO_2, O_3	NAMS/ SLAMS	East Vinton Elementary School, Ruddell Road	Vinton Roanoke Co.	37° 17' 08" 79° 53' 03"	51	161	1004	Residential	Suburban
Cherry	PM_{10}	SLAMS	101 Cherry Hill Circle	Roanoke City	37° 16' 33" 79° 59' 58"	51	770	0011	Residential	Suburban
Carver	CO	SLAMS	Carver Road & Courtland Drive	Roanoke City	37° 17' 05" 79° 56' 01"	51	770	0013	Commercial	Urban
Roanoke	$PM_{2.5}$, Speciation	SLAMS SPM	Raleigh Court Library	Roanoke City	37° 15' 22" 79° 59' 06"	51	770	0014	Residential	Suburban
Salem	$PM_{2.5}$	SLAMS	Market St. Fire Station	Salem	37° 21' 24" 79° 10' 31"	51	775	0010	Commercial	Urban
James River	AOC, AEC, $ASO_4^=$	SLAMS IMPROVE	James River Face Wilderness	Rockbridge Co.	34° 34' 38" 79° 30' 15"	51	163	9000	Forest	Rural

2.3 Model Performance Evaluation

We ran the Community Multiscale Air Quality model (CMAQ) version 4.6 to predict air pollutant concentrations over the VISTAS domain using emissions, meteorological, and boundary condition input files. We then compared our modeled output against the VISTAS CMAQ version 4.5 benchmark files. Figure 2.5 compares isoprene, NO_x, O_3, paraffins, accumulation mode aerosol sulfate, and Aitken/ultrafine mode aerosol sulfate concentrations on 1 July 2002 from our model run against the VISTAS benchmark case. For each pollutant, the hours at which its concentration was greatest is displayed. Overall there was good correspondence between our model and the benchmark files. Only with paraffins and ultrafine sulfate were there recognizable discrepancies. In both cases our model showed slightly higher concentrations of both pollutants in areas where their concentrations were already high. The model showed that NO_x, O_3, and accumulation mode sulfate were relatively lower in the Shenandoah Valley compared to nearby urban areas such as Washington, Baltimore, and Pittsburg. Isoprene, paraffins, and ultrafine sulfate, though, were highest at different areas in and around the Shenandoah Valley. Small differences between the two versions of the model are expected because of updates and corrections to the inorganic aerosol module.

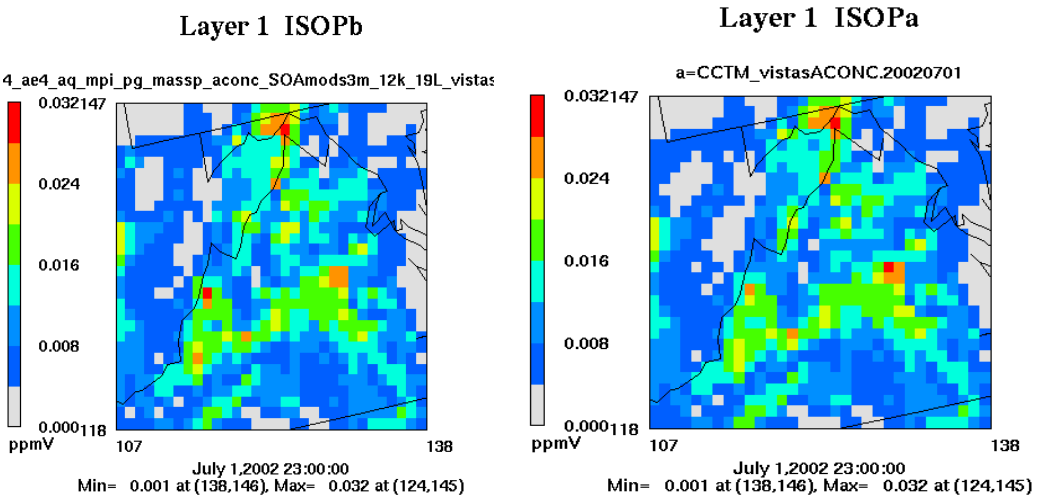
Model performance is evaluated by comparing predicted versus observed, i.e. actual measured, concentrations. Agreement is never perfect due the limitations of modeling. While a great deal of effort goes into developing model inputs, such as the meteorological fields and emission inventory, uncertainties and inaccuracies remain. Additional uncertainty stems from the representation of chemical reactions used in the model and the need to average spatially varying parameters over 12 km × 12 km grid cells, among others. Nevertheless, models remain a valuable tool for studying the response of the system to changes in inputs, or in the case to be investigated as part of this research, to determine the change in predicted ozone and $PM_{2.5}$ concentrations that result from different air quality management strategies.

Figure 2.6 shows times series plots over the first 14 days in January and July 2002 for our modeled concentrations versus observed data for all monitoring data available in the Shenandoah Valley. The observed data are hourly for all pollutants except $PM_{2.5}$, which is an integrated measurement over 24 hours. For CO our modeled concentrations were lower than the observed concentrations. This was especially true when observed concentrations peaked. For NO_2 our modeled values closely matched the observed concentrations in January but were lower in July. We were unable to compare O_3 concentrations in January since this pollutant is not routinely measured during the winter. But for O_3 in July, we found that model predictions did not fluctuate

as much as the observed values. The crests and troughs of our modeled concentrations were lower and higher than the observed concentrations, respectively. For $PM_{2.5}$ there were few observations to compare with the model. For SO_2 model results were slightly higher than observed values at times while they were slightly lower at other times.

Table 2.2 shows the mean bias (MB), mean normal bias (MNB), mean absolute gross error, mean normalized gross error, and root mean square error for the comparisons. These are metrics of the agreement between the model and observations. In general, a mean normalized bias (absolute value) of less than 15% and mean normalized gross error (absolute value) of less than 35% are considered excellent; bias less than 30% and error less than 50% are considered good; and bias less than 60% and error less than 75% are considered average. In the Shenandoah Valley, model performance is average to good for CO, good for NO_2, average for O_3 at Luray and Vinton and poor at Rest and Natural Bridge, poor to average for SO_2, and mostly good for $PM_{2.5}$. Performance for particle speciation, i.e. organic carbon (AOC), elemental carbon (AEC), nitrate (ANO_3), and sulfate (ASO_4) is average, for the most part. Biases are always negative, indicating that the model always underpredicts the observed concentrations. Overall, model performance is average and should be good enough to be used for sensitivity studies, where we are investigating the differences in model predictions between case studies and not the absolute values.

a)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0.024
0.016
0.008
0.000118
ppmV
107
138
July 1,2002 23:00:00
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0.024
0.016
0.008
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ppmV
107
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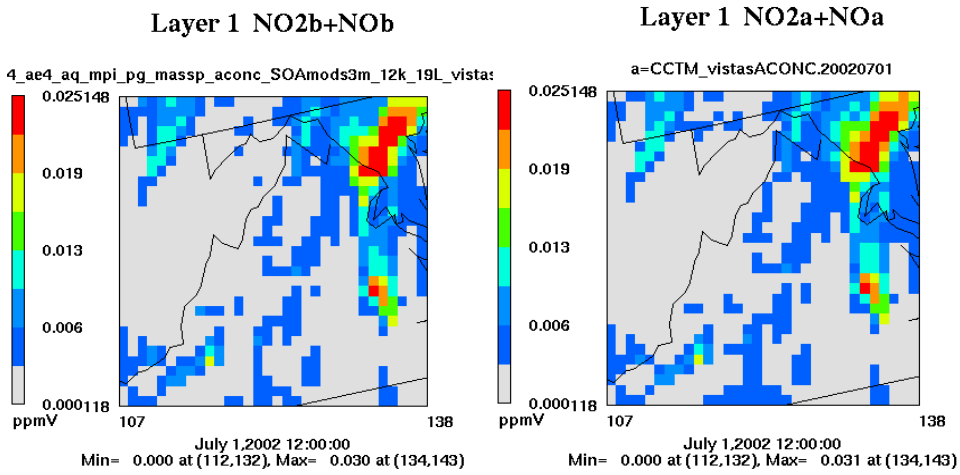
Min= 0.001 at (138,146), Max= 0.032 at (124,145)

b)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0.013
0.006
0.000118
ppmV
107
138
July 1,2002 12:00:00
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0.013
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ppmV
107
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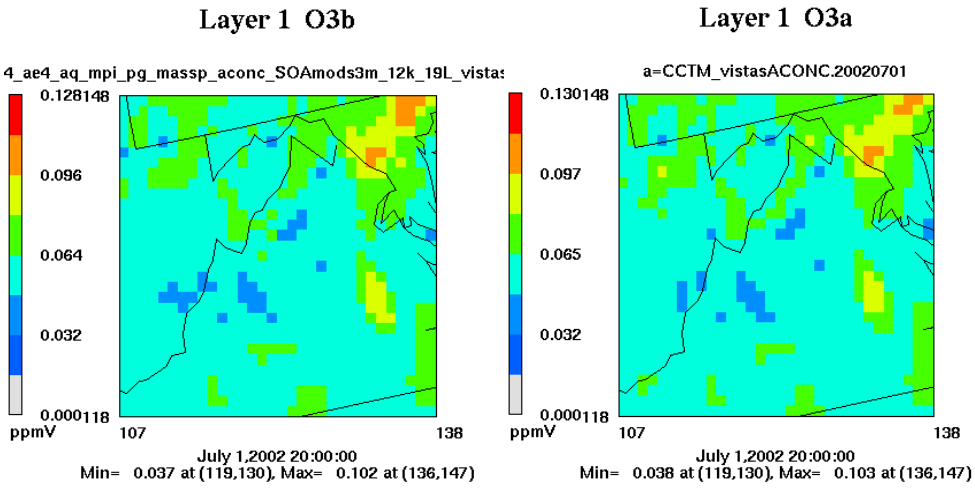
c)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0.032
0.000118
ppmV
107
138
July 1,2002 20:00:00
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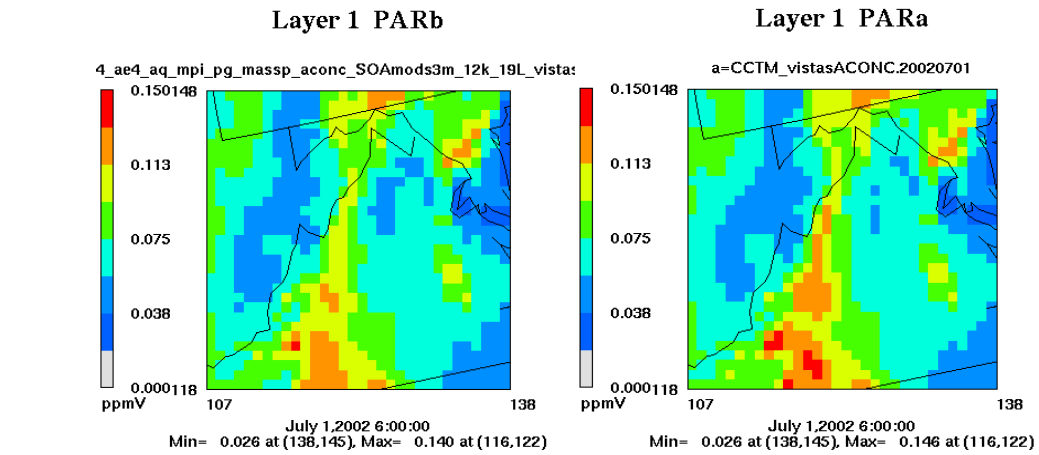
d)



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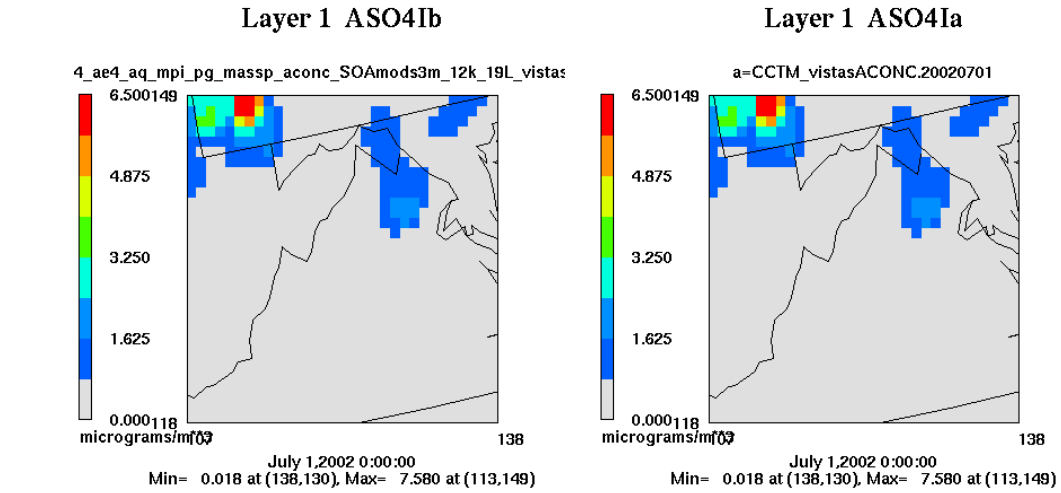

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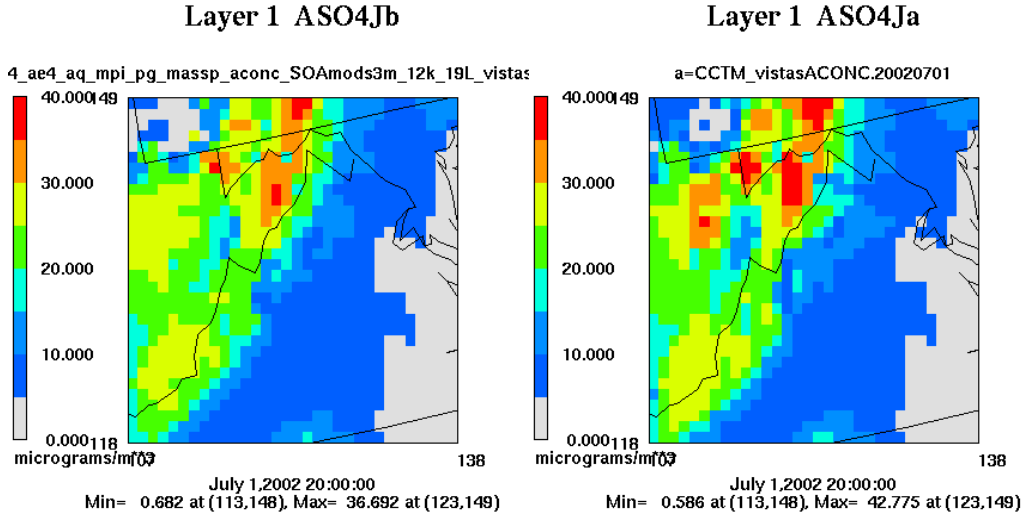
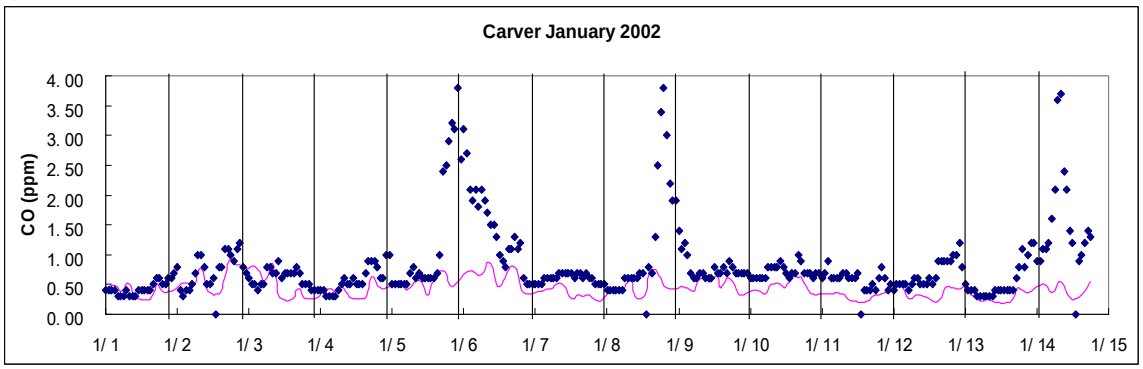


Figure 2.5: Comparison maps of CMAQ output in the benchmark case (left) and our model runs on System X (right). Comparisons are for a) isoprene, b) NO_x c) ozone, d) paraffins, e) accumulation mode aerosol sulfate, and f) Aitken/ultrafine mode aerosol sulfate.

a)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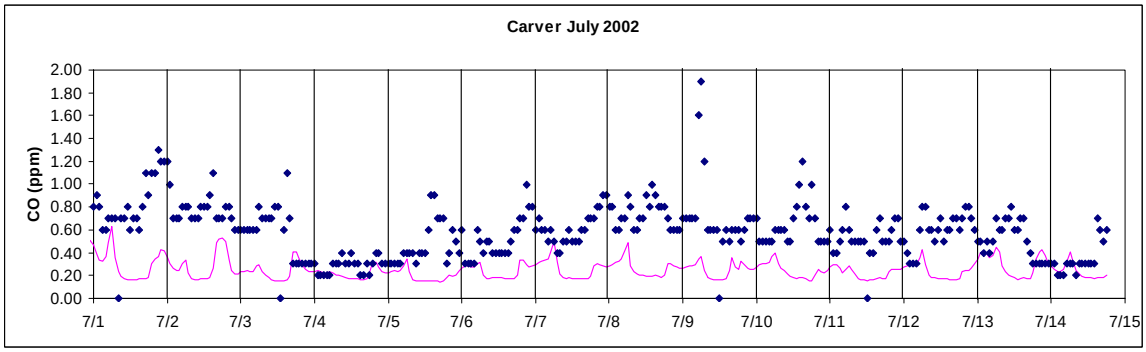
3. 50
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13
1/ 14
1/ 15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1.20
1.00
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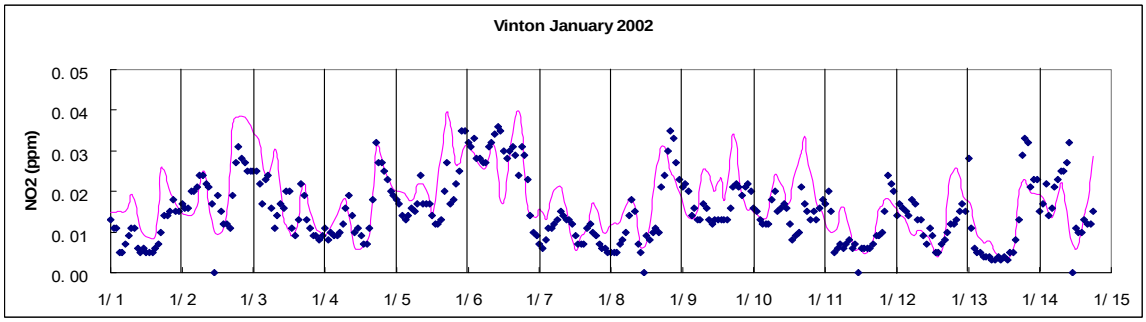
0.60
0.40
0.20
0.00
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13
7/14
7/15

b)


Vinton January 2002
NO2 (ppm)
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0. 04
0. 03
0. 02
0. 01
0. 00
1/ 1
1/ 2
1/ 3
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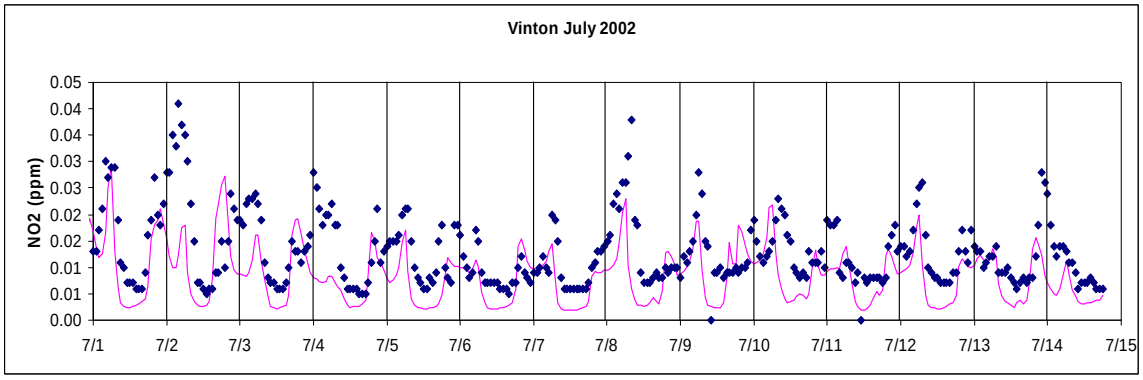
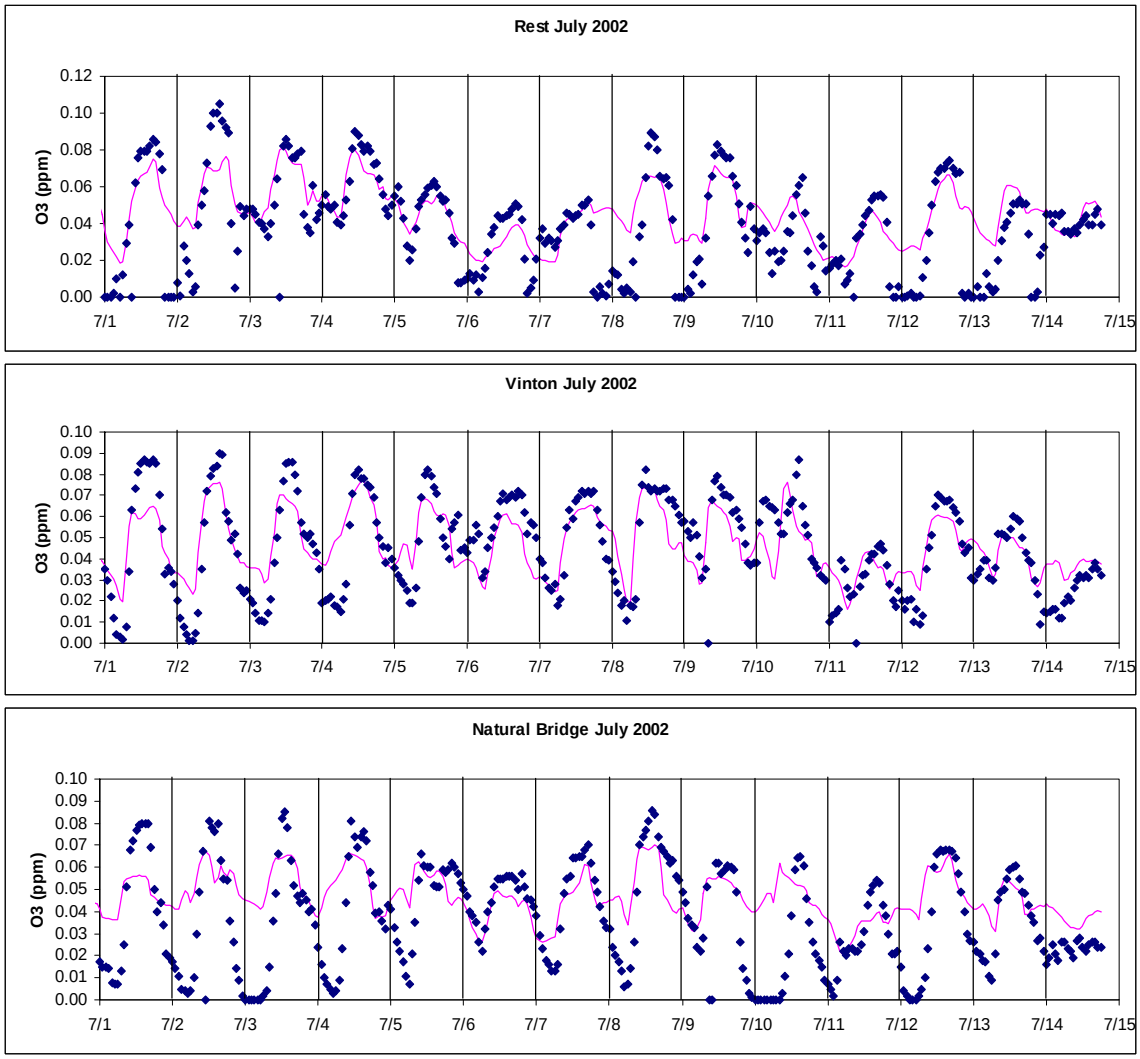
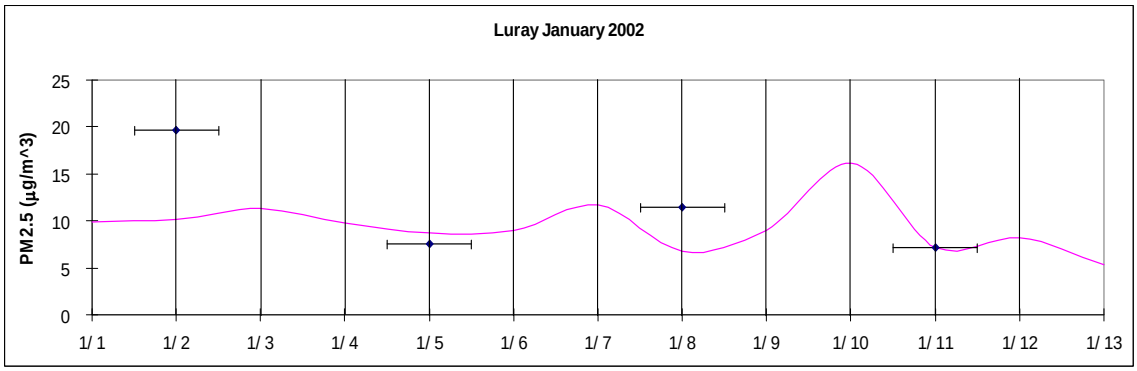
1/ 12
1/ 13
1/ 14
1/ 15

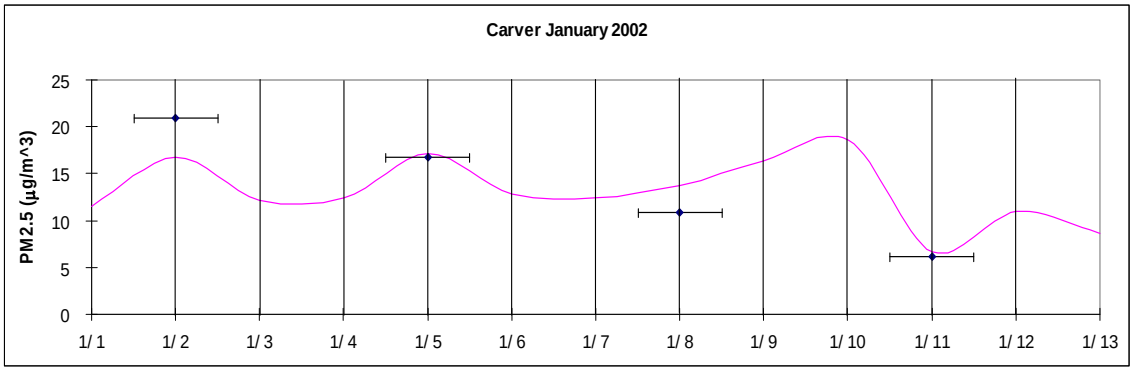

Vinton July 2002
NO2 (ppm)
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13
7/14
7/15

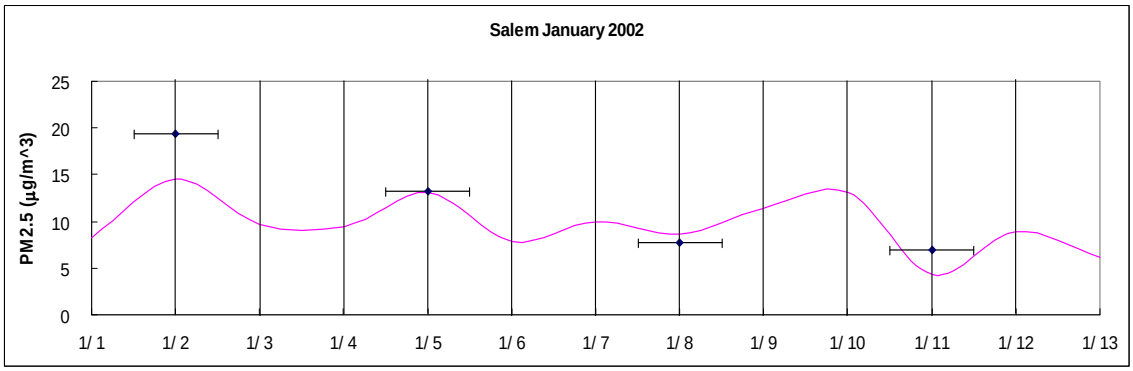
c)

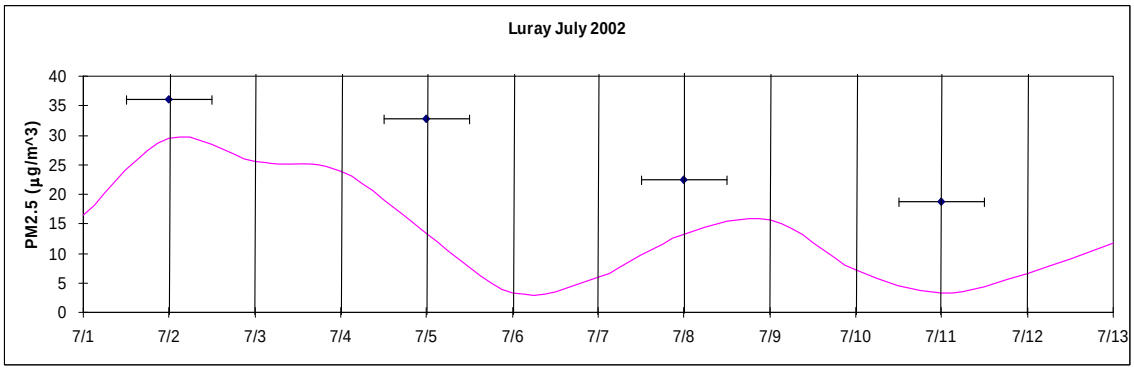

Rest July 2002
O3 (ppm)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
7/1 7/2 7/3 7/4 7/5 7/6 7/7 7/8 7/9 7/10 7/11 7/12 7/13 7/14 7/15
Vinton July 2002
O3 (ppm)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
7/1 7/2 7/3 7/4 7/5 7/6 7/7 7/8 7/9 7/10 7/11 7/12 7/13 7/14 7/15
Natural Bridge July 2002
O3 (ppm)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
7/1 7/2 7/3 7/4 7/5 7/6 7/7 7/8 7/9 7/10 7/11 7/12 7/13 7/14 7/15

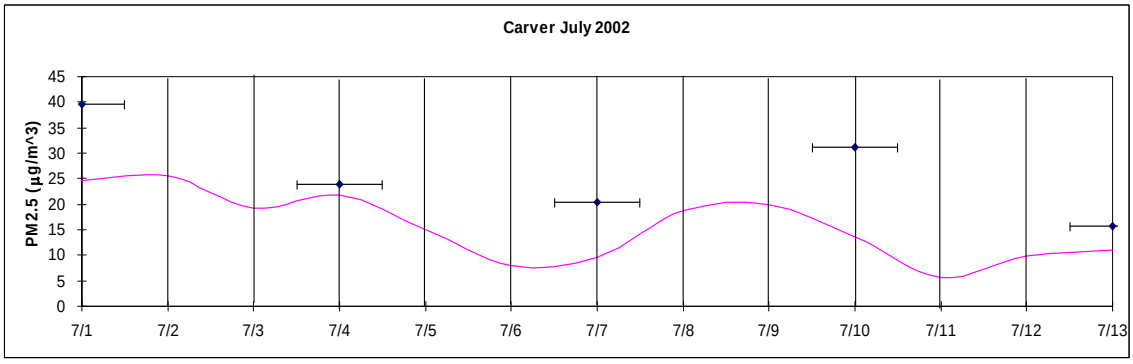
d)

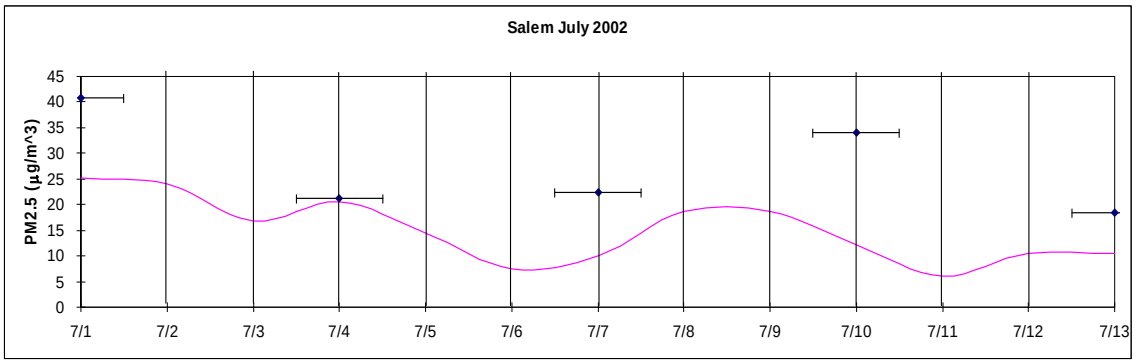

Luray January 2002
PM2.5 (µg/m^3)
25
20
15
10
5
0
1/ 1 1/ 2 1/ 3 1/ 4 1/ 5 1/ 6 1/ 7 1/ 8 1/ 9 1/ 10 1/ 11 1/ 12 1/ 13


Carver January 2002
PM2.5 (µg/m^3)
25
20
15
10
5
0
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13

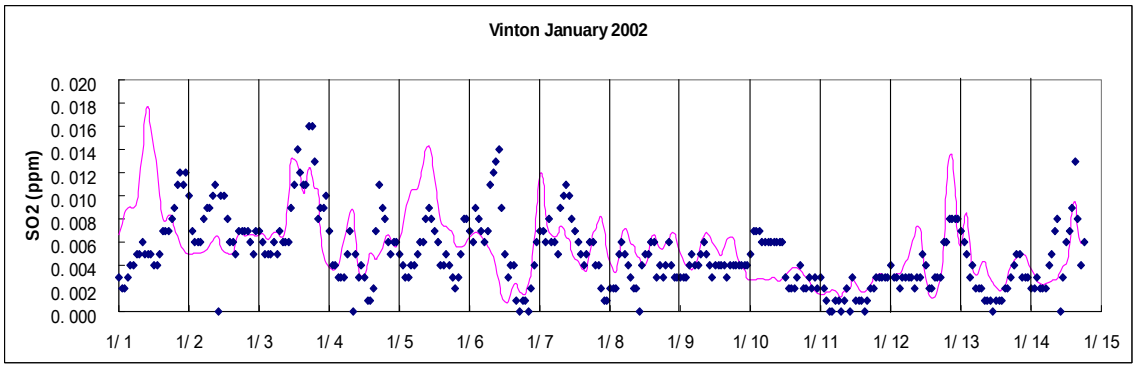

Salem January 2002
PM2.5 (µg/m^3)
25
20
15
10
5
0
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13

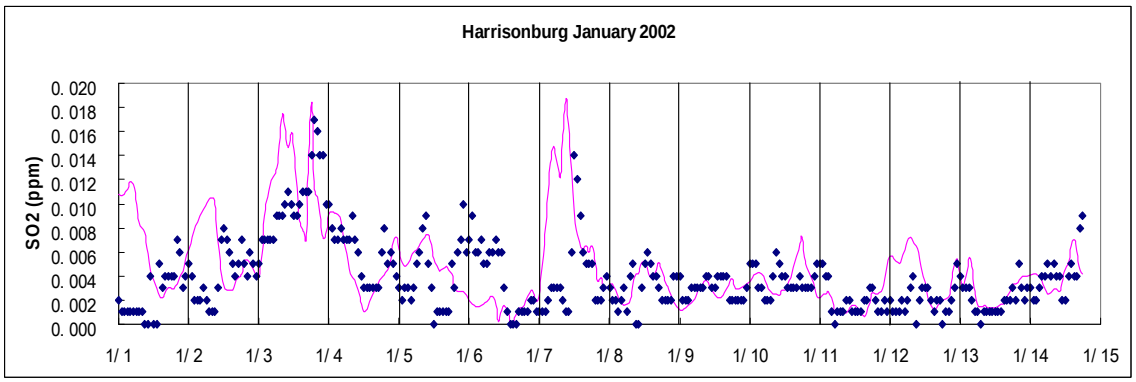

Luray July 2002
PM2.5 (µg/m^3)
40
35
30
25
20
15
10
5
0
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13

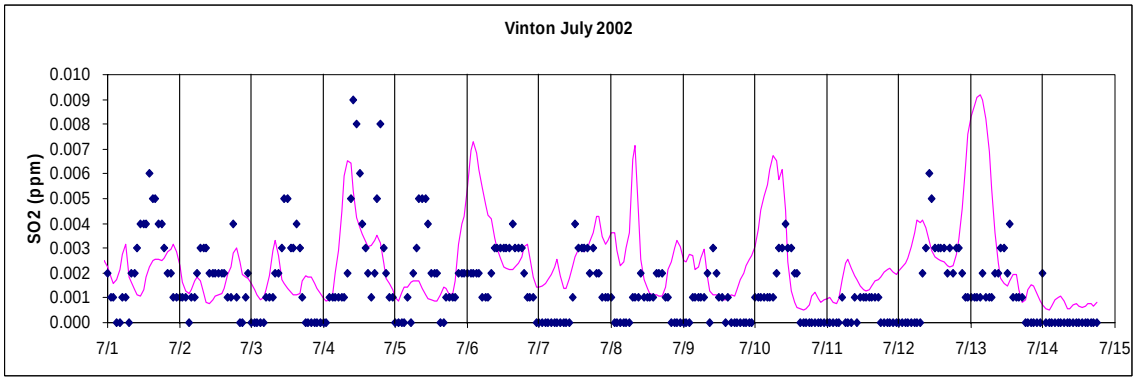

Carver July 2002
PM2.5 (µg/m^3)
45
40
35
30
25
20
15
10
5
0
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13

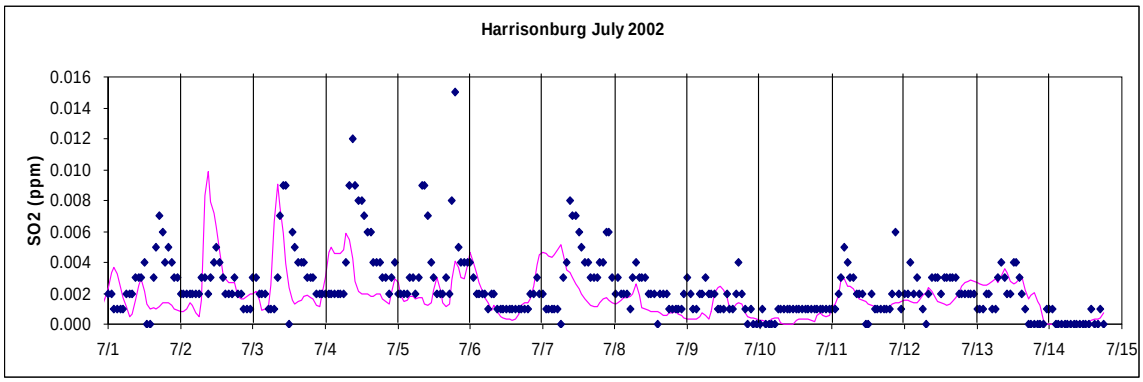

Salem July 2002
PM2.5 (µg/m^3)
45
40
35
30
25
20
15
10
5
0
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13

e)

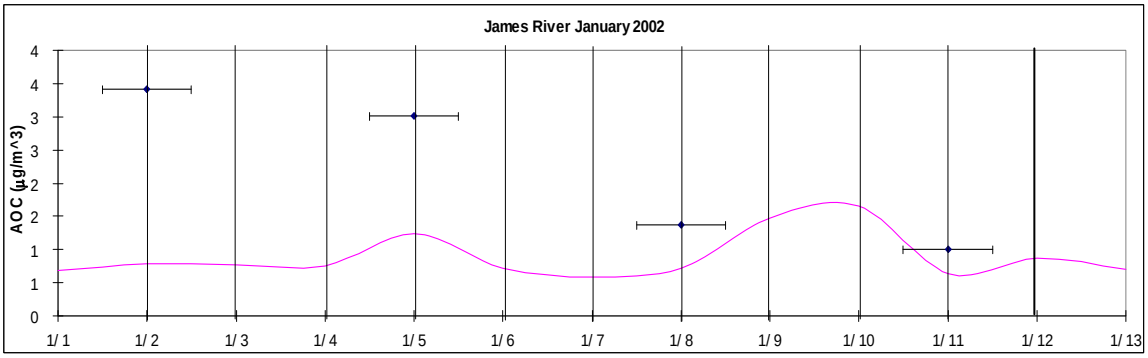

Vinton January 2002
SO2 (ppm)
0. 020
0. 018
0. 016
0. 014
0. 012
0. 010
0. 008
0. 006
0. 004
0. 002
0. 000
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13
1/ 14
1/ 15

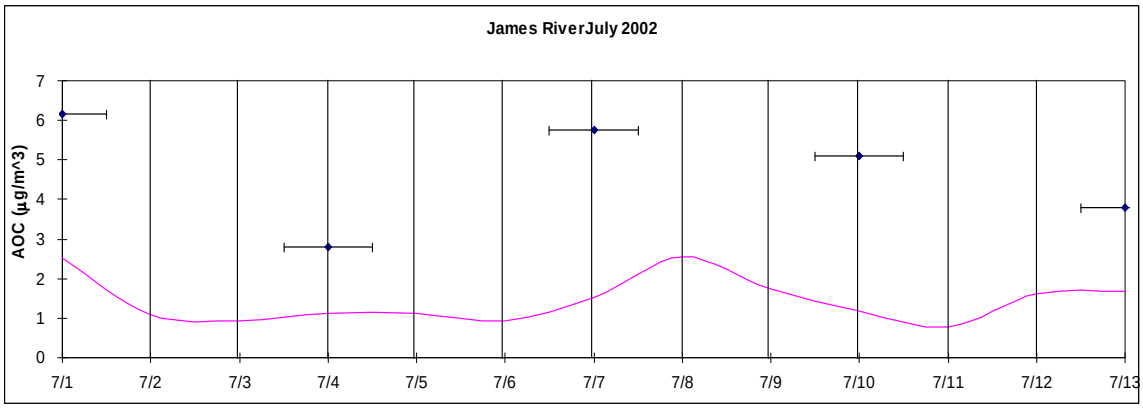

Harrisonburg January 2002
SO2 (ppm)
0. 020
0. 018
0. 016
0. 014
0. 012
0. 010
0. 008
0. 006
0. 004
0. 002
0. 000
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13
1/ 14
1/ 15


Vinton July 2002
SO2 (ppm)
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13
7/14
7/15

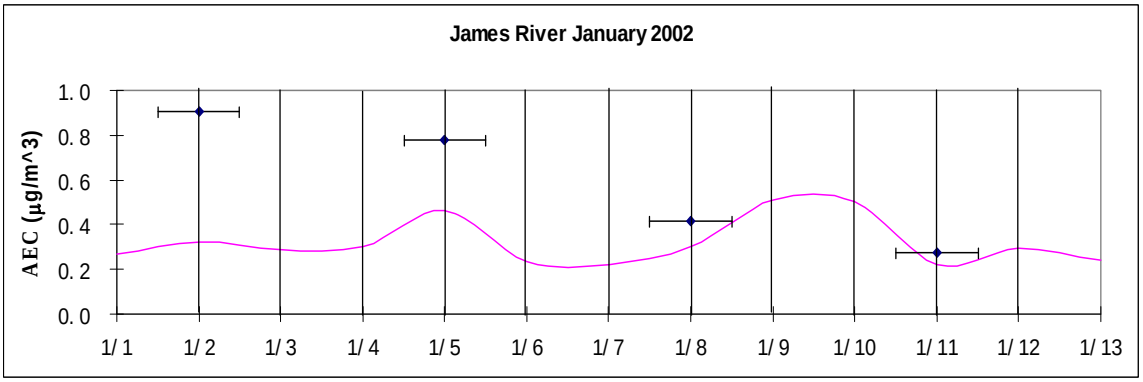

Harrisonburg July 2002
SO2 (ppm)
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13
7/14
7/15

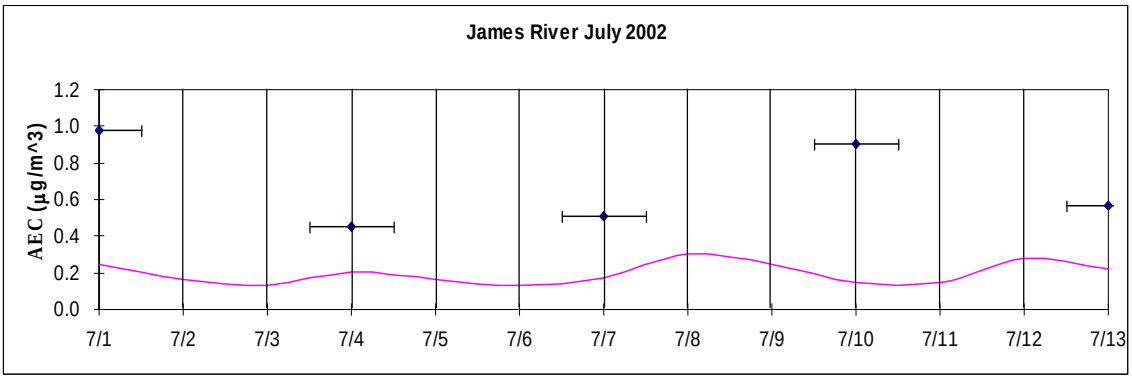
f)


James River January 2002
AOC (µg/m^3)
4
4
3
3
2
2
1
1
0
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13

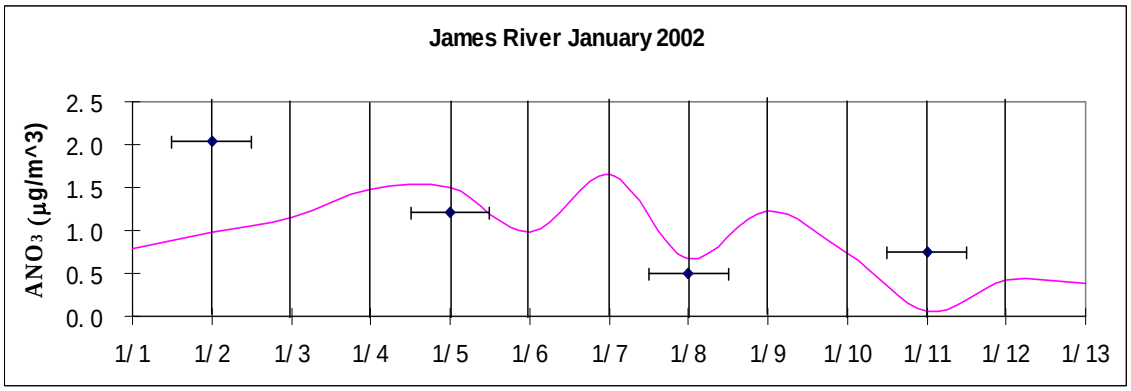

James RiverJuly 2002
AOC (µg/m^3)
7
6
5
4
3
2
1
0
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13

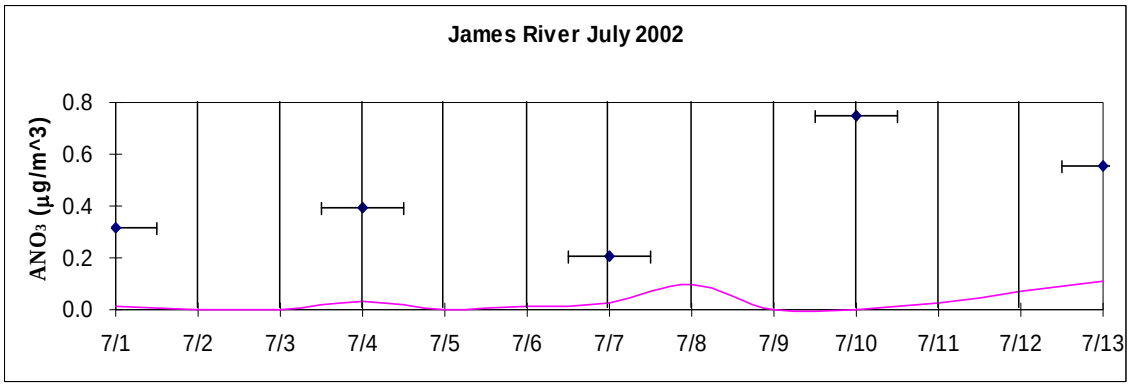
g)


James River January 2002
AEC (µg/m^3)
1. 0
0. 8
0. 6
0. 4
0. 2
0. 0
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13

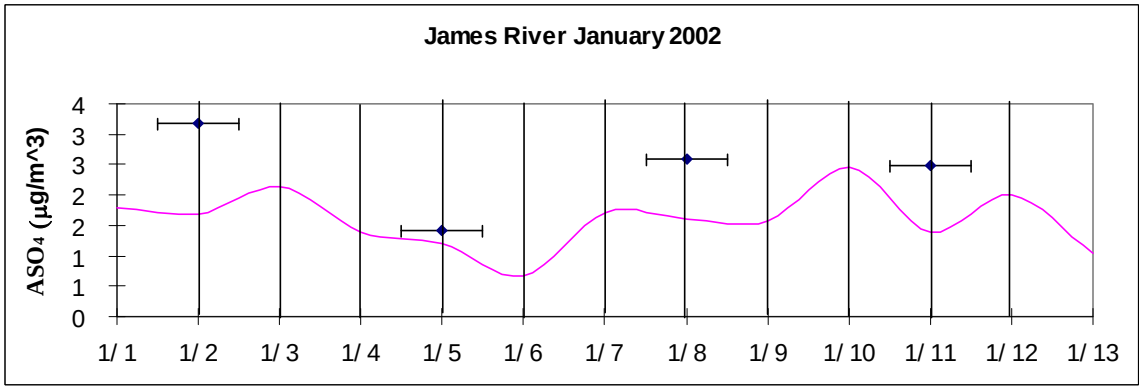

James River July 2002
AEC (µg/m^3)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13

h)


James River January 2002
ANO3 (µg/m^3)
2. 5
2. 0
1. 5
1. 0
0. 5
0. 0
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13


James River July 2002
ANO3 (µg/m^3)
0.8
0.6
0.4
0.2
0.0
7/1
7/2
7/3
7/4
7/5
7/6
7/7
7/8
7/9
7/10
7/11
7/12
7/13

i)


James River January 2002
ASO4 (µg/m^3)
4
3
3
2
2
1
1
0
1/ 1
1/ 2
1/ 3
1/ 4
1/ 5
1/ 6
1/ 7
1/ 8
1/ 9
1/ 10
1/ 11
1/ 12
1/ 13

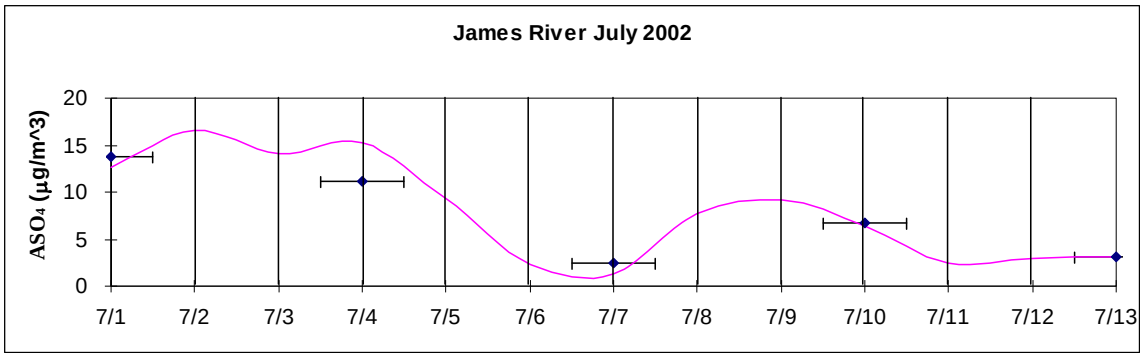


Figure 2.6: Modeled concentrations (pink lines) versus observed concentrations (blue dots) at various sites. Comparisons for a) CO, b) NO_2, c) O_3, d) $PM_{2.5}$, e) SO_2, f) AOC, g) AEC, h) ANO_3, and i) ASO_4. In January 2002 there was no observed O_3. Particle measurements are shown as bars spanning the 24-hour sampling period.

Table 2.2: Number of samples (N), mean bias (MB), mean normal bias (MNB), mean absolute gross error (MAGE), mean normal gross error (MNGE), and root mean square error (RMSE) for each pollutant at each site.

Pollutant	Site Name	Month	N	MB (ppm or mg m^{-3})[a]	MNB (%)	MAGE (ppm or mg m^{-3})[a]	MNGE (%)	RMSE (ppm or mg m^{-3})[a]
CO	Carver	Jan	327	-0.39	-34	0.02	40	0.70
CO	Carver	Jul	332	-0.34	-49	0.34	52	0.41
NO_2	Vinton	Jan	327	0.00	28	0.01	43	0.01
NO_2	Vinton	Jul	344	0.00	-31	0.01	44	0.01
O_3	Rest	Jul	323	0.00	151	0.12	164	0.02
O_3	Luray	Jul	332	0.01	48	0.01	63	0.02
O_3	Vinton	Jul	334	0.00	45	0.01	62	0.01
O_3	Natural Bridge	Jul	315	0.01	140	0.02	153	0.02
SO_2	Vinton	Jan	320	0.00	36	0.00	59	0.00
SO_2	Harrisonburg	Jan	317	0.00	87	0.00	118	0.00
SO_2	Vinton	Jul	219	0.00	88	0.00	120	0.00
SO_2	Harrisonburg	Jul	299	0.00	-7	0.00	64	0.00
$PM_{2.5}$	Luray	Jan	4	-3.22	-18	3.80	26	5.26
$PM_{2.5}$	Carver	Jan	4	-0.11	4	2.00	14	2.55
$PM_{2.5}$	Salem	Jan	4	-1.65	-13	2.14	19	2.81
$PM_{2.5}$	Luray	Jul	4	-14.10	-54	14.10	54	14.70
$PM_{2.5}$	Carver	Jul	5	-10.00	-37	10.00	37	11.59
$PM_{2.5}$	Salem	Jul	5	-11.74	-41	11.74	41	13.76
AOC[b]	James River	Jan	4	-1.36	-55	1.36	55	1.63
AOC[b]	James River	Jul	5	-3.12	-65	3.12	65	3.29
AEC[c]	James River	Jan	4	-0.27	-38	-0.27	38	0.34
AEC[c]	James River	Jul	5	-0.49	-68	0.49	68	0.53
ANO_3[d]	James River	Jan	4	-0.32	-21	0.56	51	0.66
ANO_3[d]	James River	Jul	5	-0.41	-91	0.41	91	0.45
ASO_4[e]	James River	Jan	4	-0.95	-36	0.95	36	1.05
ASO_4[e]	James River	Jul	4	0.39	-6	1.68	24	2.22

[a] Units are ppm for gases (CO, NO_2, O_3, SO_2) and μg m^{-3} for particles ($PM_{2.5}$, AOC, AEC, ANO_3, ASO_4).
[b]Aerosol organic carbon.
[c]Aerosol elemental carbon.
[d]Aerosol nitrate.
[e]Aerosol sulfate.

3. Air Quality Scenario Modeling Results and Discussion

This chapter, presented in manuscript style, describes sensitivity studies of air pollution in the Shenandoah Valley. The introductory portions of the chapter summarize the information presented in previous chapters. Though air quality in the Shenandoah Valley had improved in the 1990s it started to worsen again after the turn of the century. The Shenandoah Valley Air Quality Project (SHENAIR) united various local governments and institutions in 2005 to tackle the growing problem of air pollution, particularly O_3 and $PM_{2.5}$. SHENAIR's objective is to identify the most economically and politically feasible ways to increase air quality in the valley. We modeled multiple air pollution scenarios based on differing local emissions to predict what impact they would have on ambient air pollution concentrations in the valley. Firstly, to investigate the potential for local governmental actions to impact the valley's air quality, we considered a scenario in which all anthropogenic emissions in the valley were zero. Secondly, we developed a scenario which amalgamated emission reduction strategies being considered by local governments and predicted changes in O_3 and $PM_{2.5}$ concentrations. Thirdly, we developed a scenario which considered greenhouse gas reductions and their impact on air quality. We found that even if anthropogenic emissions in the valley were reduced to zero, O_3 concentrations would remain unchanged or might even increase slightly, though $PM_{2.5}$ concentrations would fall significantly. As a result of policy initiatives being considered to reduce air pollution, $PM_{2.5}$ could be reduced by controlling local emissions but O_3 would be difficult to control at the local level. Controlling O_3 would most likely require a larger geographical collaboration.

3.1 Introduction

Air quality in the Shenandoah Valley has deteriorated in recent years. The valley exceeds the USEPA's NAAQS standards for O_3 a few days each year, and with stricter $PM_{2.5}$ standards coming into effect, the valley risks exceeding those as well. Visibility is poor in the valley region, and the haze obscures the spectacular vistas from the Shenandoah National Park.

The Shenandoah Valley consists of a strip of 20 counties and independent cities in the states of Virginia and West Virginia. The region starts at the southern end in Roanoke County and it continues northeastward in Virginia close to the West Virginia border. At its northeastern end the Shenandoah Valley region spills out of Virginia and into the two counties that make up the West Virginia panhandle. It is bordered by mountains on both its sides. The region consists of ten small cities, making it less dense than the urbanized regions of northern and eastern Virginia but denser than sparsely populated West Virginia. Agriculture, especially dairy and poultry production, is an important industry in the region. Running through the middle of the valley, Interstate 81 is a

major transit route connecting many cities in the southern US to those in the north. Additionally, the Shenandoah Valley's dense vegetation leads to large amounts of biogenic emissions that contribute to local air pollution. Figure 3.1 shows a map of the counties and cities that make up the Shenandoah Valley within the states of Virginia and West Virginia. Locations of O_3 and $PM_{2.5}$ monitoring sites are also shown on the map.

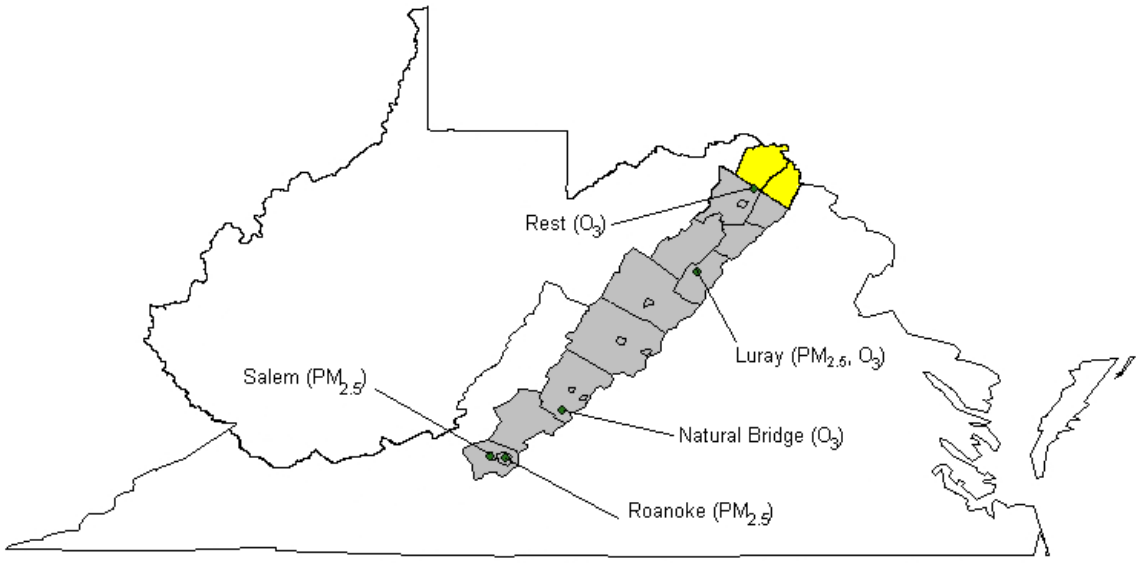


Figure 3.1: A map of the Shenandoah Valley within the states of Virginia (gray) and West Virginia (yellow). The green dots show the locations of O_3 and $PM_{2.5}$ monitoring sites.

The Virginia Department of Environmental Quality (VDEQ) currently maintains four O_3 and PM_{10} sites and three $PM_{2.5}$ sites in the Shenandoah Valley. Summary measurements of these three pollutants in the valley are shown in Figures 3.2-3.4. Figure 3.2 shows maximum 8-hour average O_3 concentrations between 1980 and 2007 while Figure 3.3 shows the number of days that violated the USEPA NAAQS standard. Violations of the NAAQS standard are known as "exceedances". Figure 3.4 shows maximum 24-hour averages, and Figure 3.5 shows annual average PM_{10} concentrations between 1985 and 2007, while Table 3.1 displays $PM_{2.5}$ 24-hour maximum and annual average concentrations between 2005 and 2007.

Since the 1980s a few ozone exceedances have been common each year in the Shenandoah Valley, though there has not been a consistent trend over time. There was however, good correlation between the number of exceedances and the reported maximum 8-hour concentration. In the early 1980s three to five exceedances were normal for Roanoke. They dipped temporarily in the mid-1980s but rose sharply in 1987 and 1988. From 1989 to 1997 exceedances per year remained low in all counties. In 1998 another sharp increase in O_3 exceedances was recorded in all counties. In 2003 the number of exceedances started dropping in all counties and by 2005 no

exceedances were reported. The year 2002 is important because it is the base year we used in our research. The varying number of exceedances over the last 25 years reflects year-to-year meteorological differences that impact O_3 formation and long-term changes in emissions of O_3 precursors.

PM_{10} concentrations in the Shenandoah Valley never exceeded NAAQS standards over the last 20 years and were fairly constant from year to year. There was also a slight overall reduction in PM_{10} concentrations between 1985 and 2007. The annual arithmetic mean (AAM) and the maximum 24-hour PM_{10} concentration were not strongly correlated. Throughout this time the AAM PM_{10} concentrations measured in Roanoke were in the 40-60 μg m^{-3} range in the mid to late 1980s and over the next 20 years fell to 15-30 μg m^{-3}, where they currently stand. As new monitoring sites came online over the years they always reported AAM concentrations below 31 μg m^{-3}. Maximum 24-hour PM_{10} concentrations varied more than AAM concentrations from year to year. These measurements also showed unusually high concentrations in 1987 and 1997, the same years O_3 concentrations were high. Aside from these years, in which maximum 24-hour concentrations exceeded 110 μg m^{-3} in Roanoke, levels did not exceed 100 μg m^{-3} in Roanoke or 75 μg m^{-3} in other places. When the national $PM_{2.5}$ standards were introduced, Salem and Roanoke exceeded the annual standard in 2005. A new $PM_{2.5}$ measuring station was installed in 2006 in Page County, and this station reported no exceedances for that year.

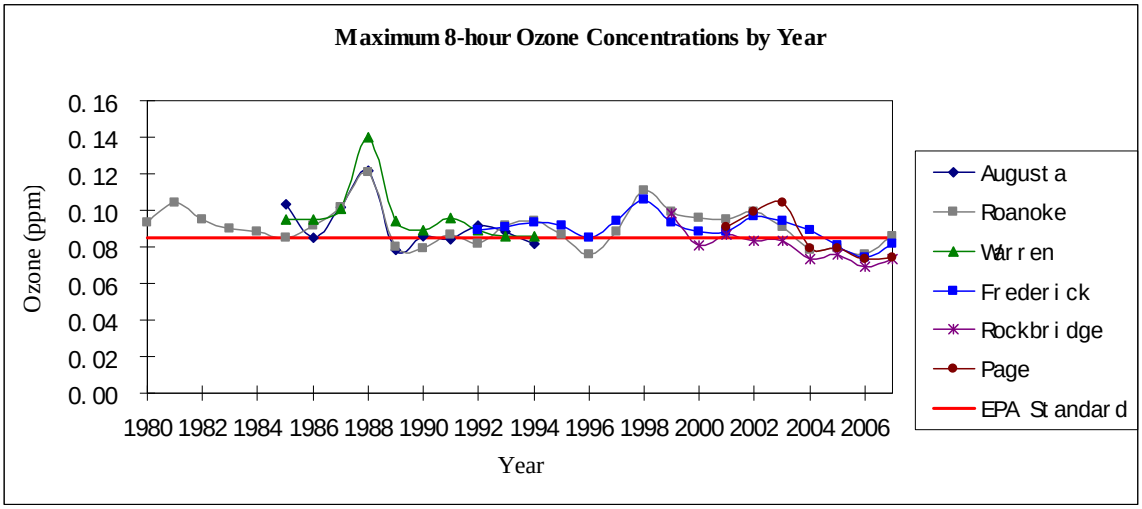


Figure 3.2: Maximum 8-hour average O_3 concentrations from 1980 to 2007.

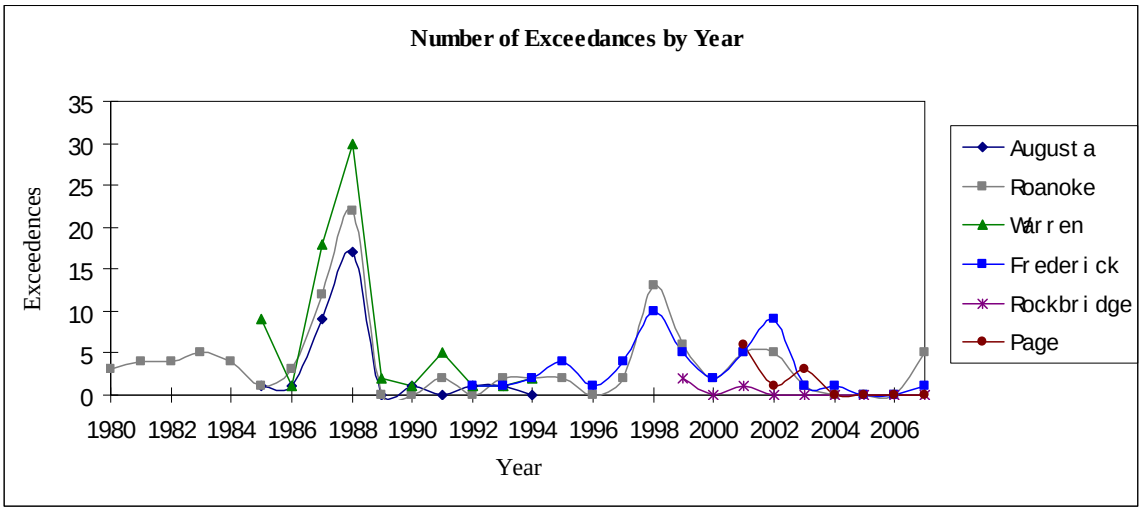


Figure 3.3: O_3 exceedances for the years 1980 through 2007.

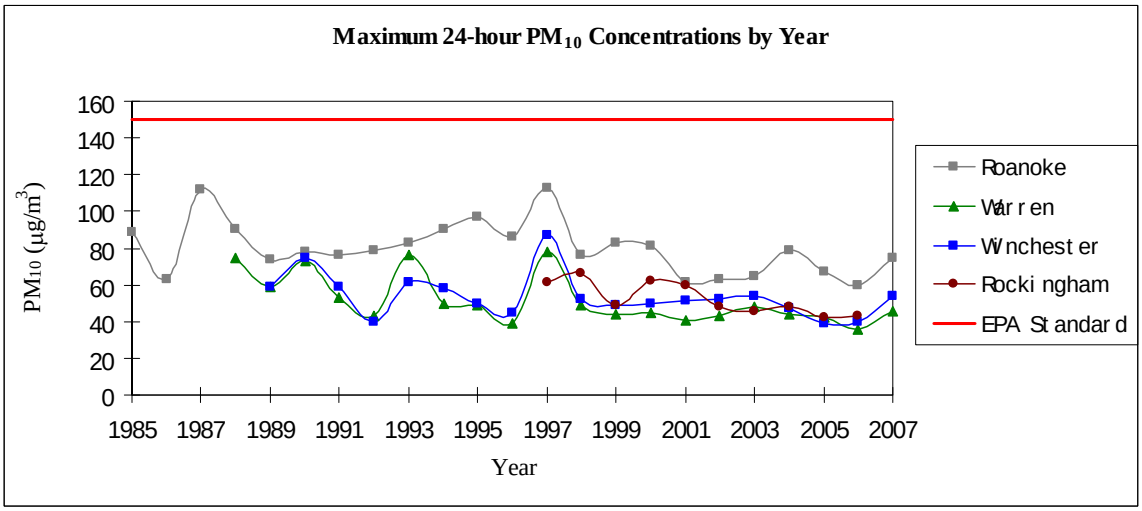


Figure 3.4: Maximum 24-hour average PM_{10} concentrations from 1985 to 2007.

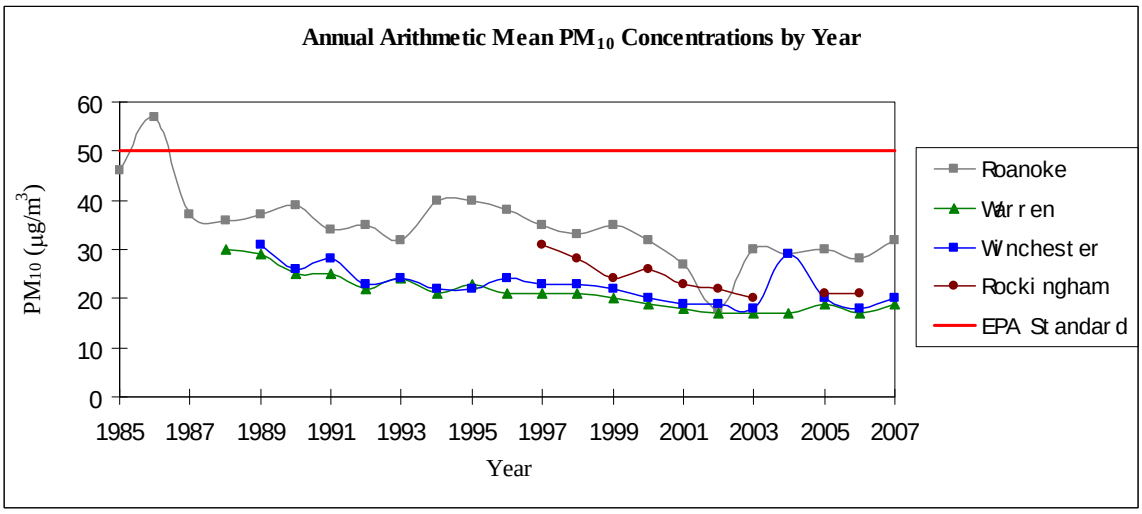


Figure 3.5: Maximum annual average PM_{10} concentrations from 1985 to 2007.

Table 3.1: Maximum 24-hour and annual arithmetic mean $PM_{2.5}$ concentrations between 2005 and 2007. Exceedances of the NAAQS are in bold.

Year	Roanoke		Salem		Page	
	24-Hour ($\mu g/m^3$)	AAM[a] ($\mu g/m^3$)	24-Hour ($\mu g/m^3$)	AAM ($\mu g/m^3$)	24-Hour ($\mu g/m^3$)	AAM ($\mu g/m^3$)
2005	35.4	**15.1**	37	**16**	**41.2**	14
2006	29.9	14.2	21.9	12	28.3	12.1
2007	**45.2**	14.2	NA	NA	33.2	12.5

[a]Annual arithmetic mean.

To tackle the problem of high ambient O_3 and $PM_{2.5}$ concentrations the Shenandoah Air Quality Project (SHENAIR) began in 2005 [17]. Local governmental officials realized that air pollution was a regional and multi-pollutant issue and that the problem needed to be solved through a larger effort than what individual counties or cities alone could provide [17]. The objective of the SHENAIR project is to improve overall air quality in the Shenandoah Valley by providing a strong scientific basis for environmental policy decisions [17]. The SHENAIR Institute is a conglomeration of local governments, universities, and various agencies. In order to work towards its goals, the project is gathering, maintaining, and modeling data on meteorology, air pollution emissions, and concentrations; researching the effects of local and regionally transported air pollution; and studying the relationships between air quality, public health, ecological health, and economic growth [17].

The objective of this study is to determine the potential for actions at the local governmental level in the Shenandoah Valley to improve its air quality. We use a three-dimensional chemical transport model over the southeastern US to determine the sensitivity of predicted pollutant concentrations to changes in emissions. First, we must distinguish between air pollution generated from local emissions versus air pollution coming from regions outside the Shenandoah Valley. In the first scenario we will set all anthropogenic emissions within the valley to zero and will model predicted concentrations stemming from regionally transported pollution. Then, we will quantify the sensitivity of O_3 and PM to locally implemented air quality management strategies, such as idle reduction rules, school bus retrofitting, and public awareness campaigns. In collaboration with SHENAIR participants, we will develop alternative emissions inventories that account for such changes and test the air quality model with them. We also consider policies whose main goal is to reduce emissions of greenhouse gases and whose secondary effects may include improvements in air quality. Based on these results, the local governments can gauge the impact of air management policies they might implement.

3.2 Methods

3.2.1 Model

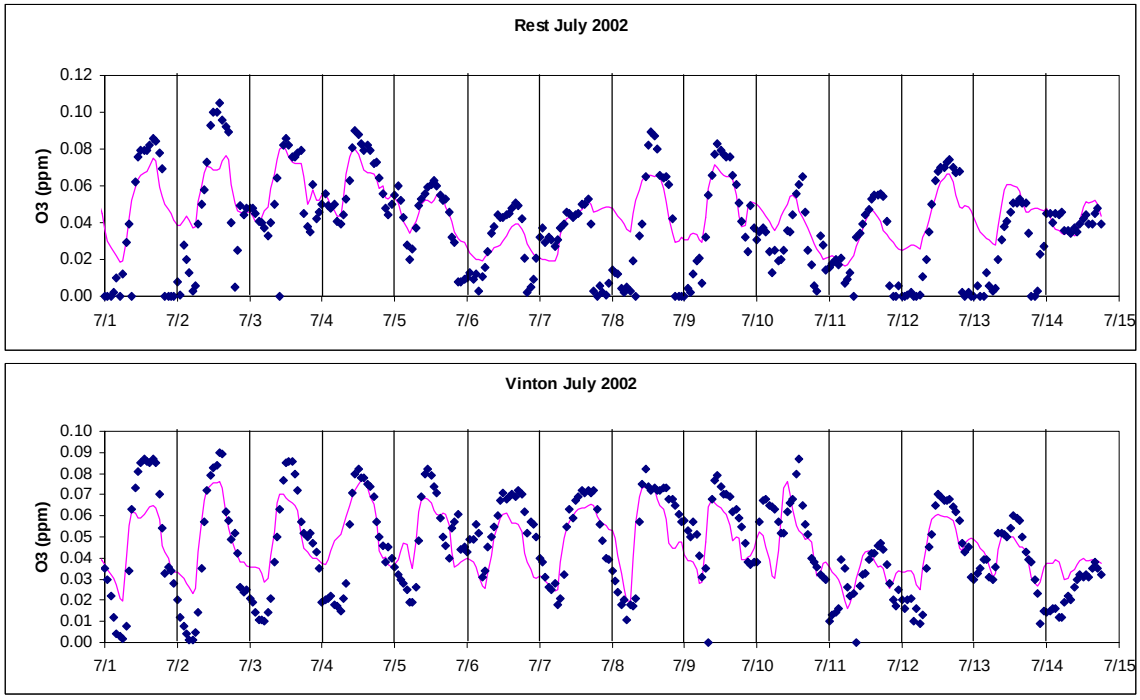
We ran the Community Multiscale Air Quality model (CMAQ) version 4.6 to predict air pollutant concentrations using emissions, meteorological, and boundary condition input files obtained from the VISTAS regional planning organization for the year 2002. We then verified our modeled output against the VISTAS CMAQ version 4.5 benchmark files in January and July. Overall there was good agreement between our model and the benchmark files. Only with paraffins and ultrafine SO_4 were there recognizable discrepancies. In both cases our model showed slightly higher concentrations of both pollutants in areas where their concentrations were already high. Differences between the two versions of the model are expected because of updates and corrections to the inorganic aerosol module.

Model performance is evaluated by comparing predicted versus observed, i.e. actual measured, concentrations. Figure 3.6 shows times series plots of modeled versus observed O_3 and $PM_{2.5}$ concentrations at a northern site (Rest or Luray) and a southern site (Vinton or Salem) in the Shenandoah Valley. The magnitude of the modeled concentrations is generally correct, but for O_3 in July, we found that our model did not fluctuate as much as the observed values. The crests and troughs of our modeled concentrations were lower and higher than the observed concentrations, respectively. We were unable to compare O_3 concentrations for January since this pollutant is not routinely measured during the winter. For CO, not shown, our modeled concentrations were lower than the observed concentrations. This was especially true when observed concentrations peaked. For NO_2 our modeled values closely matched the observed concentrations for January but they were lower for July. For SO_2 our model results were slightly higher than observed values at times while they were slightly lower at other times.

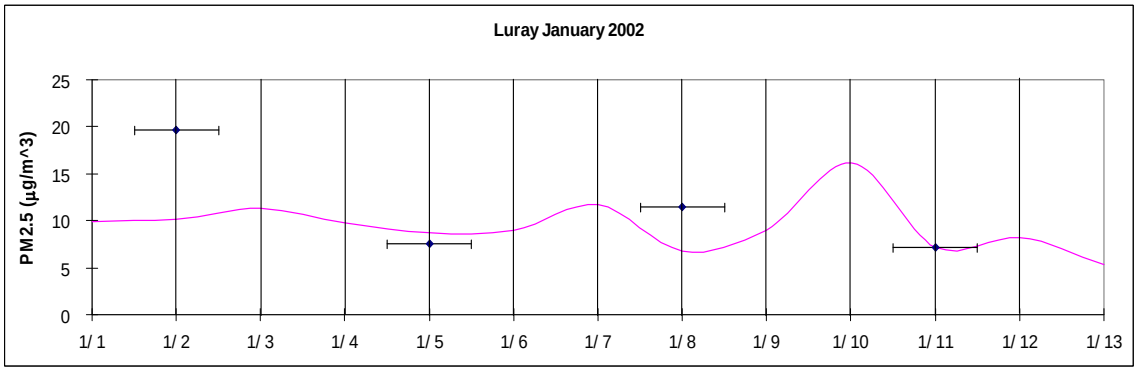
Table 3.2 shows the mean bias (MB), mean normal bias (MNB), mean absolute gross error, mean normalized gross error, and root mean square error for the comparisons. In general, a mean normalized bias (absolute value) of less than 15% and mean normalized gross error (absolute value) of less than 35% are considered excellent; bias less than 30% and error less than 50% are considered good; and bias less than 60% and error less than 75% are considered average. In the Shenandoah Valley, model performance is average to good for CO, good for NO_2, average for O_3 at Luray and Vinton and poor at Rest and Natural Bridge, poor to average for SO_2, and mostly good for $PM_{2.5}$. Performance for particle speciation, i.e. organic carbon (AOC), elemental carbon (AEC), nitrate (ANO_3), and sulfate (ASO_4) is average, for the most part. Biases are always negative, indicating that the model always underpredicts the observed concentrations. Overall, model performance is average and should be good enough to be used for sensitivity studies,

where we are investigating the differences in model predictions between case studies and not the absolute values.

a)



b)



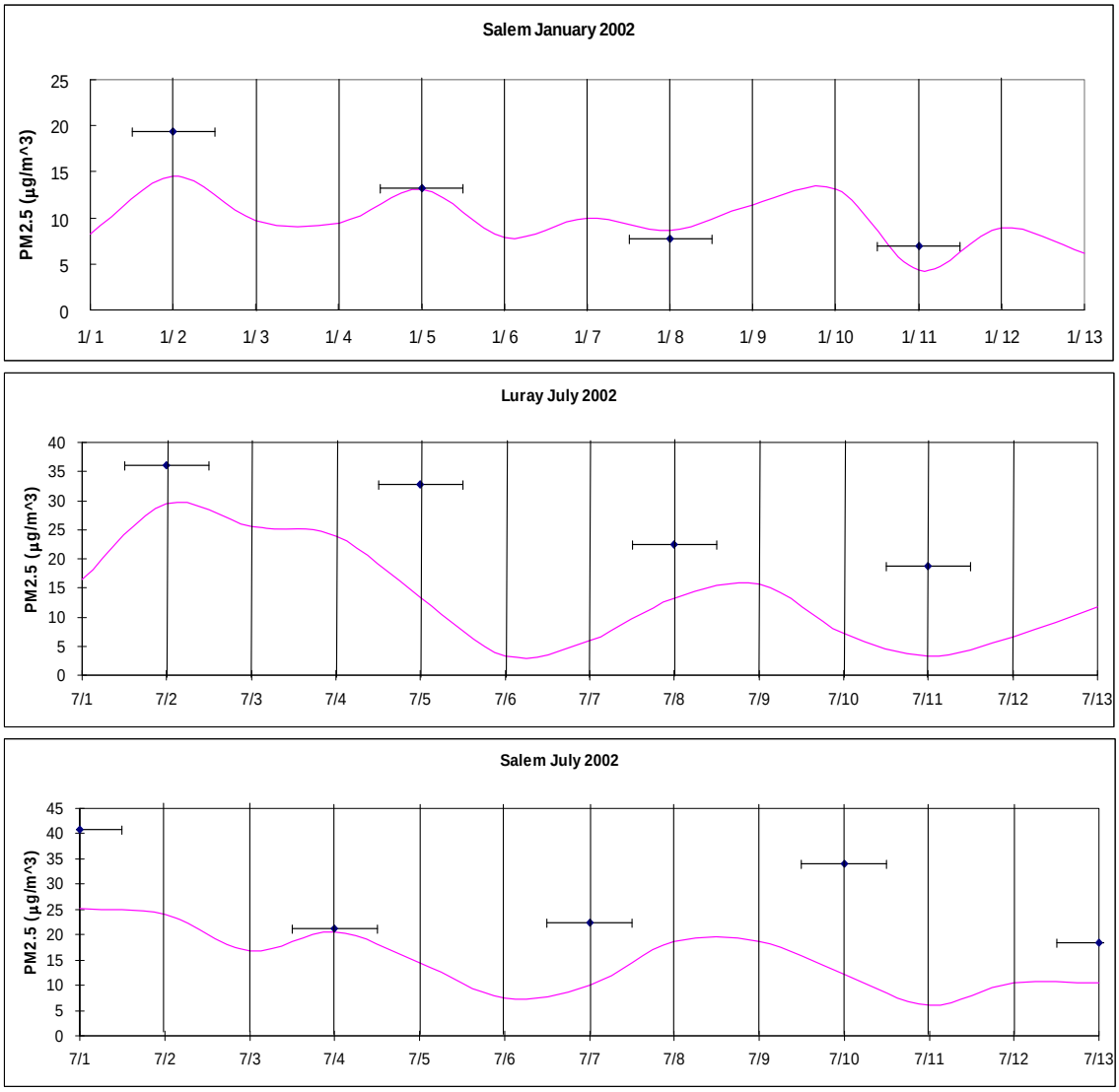


Figure 3.6: Modeled concentrations (pink lines) versus observed concentrations (blue dots) at sites in the northern and southern end of the valley. Comparisons for a) O_3 in July and b) $PM_{2.5}$ in January and July. Particle measurements are shown as bars spanning the 24-hour sampling period.

Table 3.2: Number of samples (N), mean bias (MB), mean normal bias (MNB), mean absolute gross error (MAGE), mean normal gross error (MNGE), and root mean square error (RMSE) for each pollutant at each site.

Pollutant	Site Name	Month	N	MB (ppm or mg m^{-3})[a]	MNB (%)	MAGE (ppm or mg m^{-3})[a]	MNGE (%)	RMSE (ppm or mg m^{-3})[a]
CO	Carver	Jan	327	-0.39	-34	0.02	40	0.70
CO	Carver	Jul	332	-0.34	-49	0.34	52	0.41
NO_2	Vinton	Jan	327	0.00	28	0.01	43	0.01
NO_2	Vinton	Jul	344	0.00	-31	0.01	44	0.01
O_3	Rest	Jul	323	0.00	151	0.12	164	0.02
O_3	Luray	Jul	332	0.01	48	0.01	63	0.02
O_3	Vinton	Jul	334	0.00	45	0.01	62	0.01
O_3	Natural Bridge	Jul	315	0.01	140	0.02	153	0.02
SO_2	Vinton	Jan	320	0.00	36	0.00	59	0.00
SO_2	Harrisonburg	Jan	317	0.00	87	0.00	118	0.00
SO_2	Vinton	Jul	219	0.00	88	0.00	120	0.00
SO_2	Harrisonburg	Jul	299	0.00	-7	0.00	64	0.00
$PM_{2.5}$	Luray	Jan	4	-3.22	-18	3.80	26	5.26
$PM_{2.5}$	Carver	Jan	4	-0.11	4	2.00	14	2.55
$PM_{2.5}$	Salem	Jan	4	-1.65	-13	2.14	19	2.81
$PM_{2.5}$	Luray	Jul	4	-14.10	-54	14.10	54	14.70
$PM_{2.5}$	Carver	Jul	5	-10.00	-37	10.00	37	11.59
$PM_{2.5}$	Salem	Jul	5	-11.74	-41	11.74	41	13.76
AOC[b]	James River	Jan	4	-1.36	-55	1.36	55	1.63
AOC[b]	James River	Jul	5	-3.12	-65	3.12	65	3.29
AEC[c]	James River	Jan	4	-0.27	-38	-0.27	38	0.34
AEC[c]	James River	Jul	5	-0.49	-68	0.49	68	0.53
ANO_3[d]	James River	Jan	4	-0.32	-21	0.56	51	0.66
ANO_3[d]	James River	Jul	5	-0.41	-91	0.41	91	0.45
ASO_4[e]	James River	Jan	4	-0.95	-36	0.95	36	1.05
ASO_4[e]	James River	Jul	4	0.39	-6	1.68	24	2.22

[a] Units are ppm for gases (CO, NO_2, O_3, SO_2) and μg m^{-3} for particles ($PM_{2.5}$, AOC, AEC, ANO_3, ASO_4).
[b]Aerosol organic carbon.
[c]Aerosol elemental carbon.
[d]Aerosol nitrate.
[e]Aerosol sulfate.

3.2.2 Episodes

We reviewed meteorological classifications of each day in 2002 to select representative modeling episodes during the year. A spatial synoptic classification (SSC) was assigned to each day of the year at multiple airports in Virginia and West Virginia. There are seven SSC categories, which are primarily based on two meteorological factors: humidity and temperature [31]. A day is classified as either dry or moist in terms of humidity and either polar, moderate, or tropical depending on temperature. The seventh category represents days in which the weather was undergoing a transition, and an eighth category is assigned to days for which data was unavailable. Table 3.3 shows the SSC classification system.

Table 3.3: The SSC meteorology classification system.

SSC Number	Meteorology
1	Dry Moderate
2	Dry Polar
3	Dry Tropical
4	Moist Moderate
5	Moist Polar
6	Moist Tropical
7	Transition
8	No Data

To represent the Shenandoah Valley, we considered SSCs for Roanoke, Virginia, at the southern end of the valley, and for Martinsburg, West Virginia, at the northern end. We selected the weeks of January 16-22, April 2-8, June 24-30, August 8-14, and October 18-24 because they encompassed all four seasons as well as all the different SSC categories. We also tried to select weeks with minimal rainfall since CMAQ is more accurate under dry conditions [32]. Table 3.4 shows SSCs for Roanoke and Martinsburg for the five selected weeks. For example, during the week of January 16-22 in Roanoke, the first three days and the last two days had an SSC of 1 (dry moderate), and the fourth and fifth days had an SSC of 5 (moist polar).

Table 3.4: SSC classifications for Roanoke and Martinsburg for the selected weeks. The first digit is the SSC on the first day of the week, the second digit is the SSC on the second day of the week, etc.

Week	Roanoke	Martinsburg
January 16-22	1115511	5118541
April 2-8	3722221	7722223
June 24-30	3364411	1664411
August 8-14	1113333	2211363
October 18-24	2145415	2452215

3.2.3 Sensitivity studies

We developed alternative emissions scenarios using the SMOKEv2.4 model. The Base Case uses the Base G version of the VISTAS emissions inventory. To quantify the impact of locally emitted versus regionally transported pollutants on the valley's air quality, we developed a Zero Case. We set anthropogenic emissions—area, point, and onroad and nonroad mobile sources—to zero in all counties and cities in the Shenandoah Valley. To quantify the impact of locally directed air management strategies, we developed a Local Reductions scenario which amalgamated emission reduction strategies being considered by local governments. Because the impact of any single strategy by itself was very small, we did not consider individual policies but instead focused on their collective impact. To quantify the impact of greenhouse gas reductions, we developed a Greenhouse Gas (GHG) Case which considered policies recommended as part of the ICLEI Local Governments for Sustainability organization.

3.4 Results

3.4.1 Zero Case

The results focus on O_3 and $PM_{2.5}$ since these two pollutants were the main problems facing the valley. In the Zero Case, we found significant reductions in predicted concentrations of $PM_{2.5}$ compared to the Base Case. The top half of Table 3.7 shows the percent change in $PM_{2.5}$ at selected monitoring sites in the Shenandoah Valley over each of the five weeks. The large reductions imply that local $PM_{2.5}$ emissions and precursor pollutant emissions are significant contributors to local $PM_{2.5}$ concentrations. $PM_{2.5}$ reductions varied according to the time of year though. They were greatest in the winter and lowest in the summer. In Roanoke and Salem in the southern end of the Shenandoah Valley, the places with routine measurements of $PM_{2.5}$ in 2002, the Zero Case predicted a 57% reduction in $PM_{2.5}$ in Roanoke and a 46% reduction in Salem for January 16-22 compared to the Base Case, but only a 31% and 27% reduction for these two sites, respectively, for August 8-14. In the northern end of the valley at Luray the model predicted a 44% reduction for the week in January but a lesser 26% reduction for the week in August. Base Case $PM_{2.5}$ concentrations did not differ significantly by season though, so the differences in percent reduction between colder seasons and warmer seasons suggest that temperature plays an important role in $PM_{2.5}$ creation. A possible explanation may be that biogenic VOCs, which are predominant in warmer months but insignificant in cooler months, are responsible for much of the summer $PM_{2.5}$. Isoprene and other biogenic VOCs can nucleate to form particles. It is also possible that a larger fraction of the $PM_{2.5}$ originates from transported particles and aerosol precursors during the summer. Maps of Zero Case $PM_{2.5}$ concentrations in the Shenandoah Valley

compared to Base Case concentrations on one day in each of the five modeling episode weeks can be seen in Figure 3.7a. Figure 3.9 shows the Zero Case $PM_{2.5}$ time series along with results from the Base Case and other scenarios at specific monitoring sites.

Differences in the response of individual PM species—aerosol elemental carbon (AEC), aerosol ammonium (ANH_4), aerosol nitrate (ANO_3), aerosol organic carbon (AOC), and aerosol sulfate (ASO_4)—in the Zero Case indicate that some are more locally influenced while others are mainly transported into the valley. In terms of absolute concentrations, ASO_4 dominated PM in the valley followed by relatively similar amounts of ANH_4, ANO_3, and AOC. AEC had the lowest concentrations relative to the other PM constituents. Comparing the Zero Case to the Base Case for these constituents we found that reductions were greatest for AEC, AOC, and ANO_3; these three species are more strongly influenced by local emissions compared to the others. Percent reductions were lowest for ASO_4, which was expected since SO_4 emissions were low in the valley. Figure 3.9c-g shows the Zero Case PM species' time series along with results from the Base Case and other scenarios.

By meteorological conditions, i.e. SSC, we found that concentrations tended to be highest on dry moderate and dry tropical days and lowest on moist moderate and moist tropical days. Percent reductions in $PM_{2.5}$ were also greatest during moist days. Comparing the weeks in June and August, both of which had a temperature average of 24 °C and similar emissions but different rainfall and moisture characteristics, we found that reductions in predicted concentrations were slightly higher in June. The lower $PM_{2.5}$ concentrations and increased reductions on moist days are most likely because wet deposition removes particles from the air on moist days, and warm weather with ample sunlight promotes secondary aerosol formation.

The Zero Case produces almost no change in time-averaged O_3 concentrations in the Shenandoah Valley, and in fact, at times O_3 concentrations increased even with much lower emissions of O_3 precursors. O_3 formation is very complex, depending on both NO_x and VOCs, as well as meteorological conditions. The non-linear chemistry of O_3 formation allows for situations when reductions in NO_x can actually lead to an increase in O_3 concentrations because less NO_x is available to scavenge the radicals that promote O_3-forming reactions.

The lack of sensitivity of O_3 to zeroed anthropogenic emissions suggests that nearly all of the O_3 is transported into the valley from upwind areas and/or sufficient O_3 precursors are transported into the valley, where they may react with each other and with the valley's biogenic VOC emissions to form O_3. Shenandoah Valley biogenic VOCs, which were unchanged in the Zero Case, accounted for 56% of all VOC emissions, and these pollutants may be playing a large role in O_3 formation. Our model predicted that an increase in O_3 would be highest in the fall if

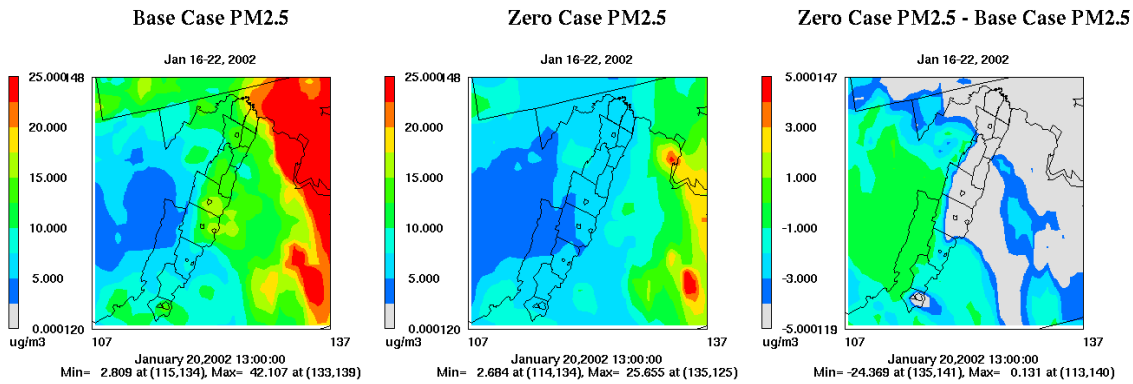
anthropogenic emissions were zeroed. At specific sites we found that O_3 concentrations increased by 35%, 122%, and 11% in October at Rest, Vinton, and Natural Bridge, respectively, in the Zero Case. In the spring and summer increases were not as drastic, and even nonexistent at times, but a decrease in O_3 concentrations is unlikely to be achieved by simply reducing anthropogenic emissions in the valley. Maps of Zero Case O_3 concentrations in the Shenandoah Valley compared to Base Case concentrations can be seen in Figure 3.7b. Figure 3.9 shows plots of O_3 concentrations at specific locations for the five modeled weeks for the Zero Case.

One positive result concerning O_3 in the Zero Case was that the peak O_3 concentrations were not as high. While most of the O_3 in the valley is present due to transport from other places, emissions in the valley elevate peak concentrations. This means that maximum 8-hour O_3 concentrations may fall and may comply with USEPA regulations even if annual average O_3 concentrations are higher. The bottom half of Table 3.7 shows modeled percent changes for O_3 for various times and locations.

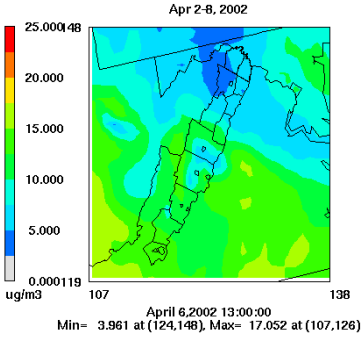
As a function of SSC, O_3 concentrations were highest on dry tropical days in both the Base and Zero Cases. As days became cooler and more humid, O_3 concentrations decreased. The same is true for differences in O_3 concentrations between the Base Case and the Zero Case. On moist days differences were lower but on dry tropical days increases in O_3 concentrations were more pronounced.

To better understand O_3 formation in the valley we modeled two different scenarios: one with NO_x emissions reduced and a separate one with VOC emissions reduced. These sensitivity runs allowed us to determine whether O_3 in the Shenandoah Valley is NO_x-limited or VOC-limited. We found that both these cases resulted in nearly indistinguishable concentrations of O_3 relative to each other and were similar to the Zero Case as well. This result confirmed that transported O_3 and O_3 precursors were more responsible for O_3 pollution than locally emitted pollutants.

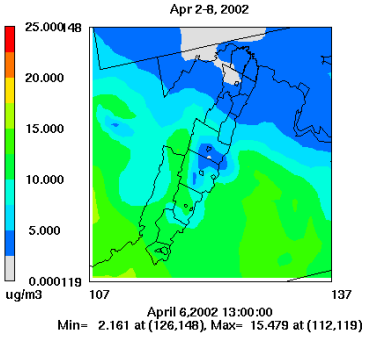
a)



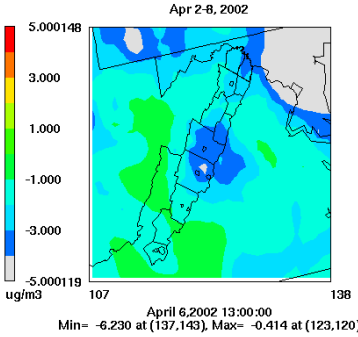
Base Case PM2.5



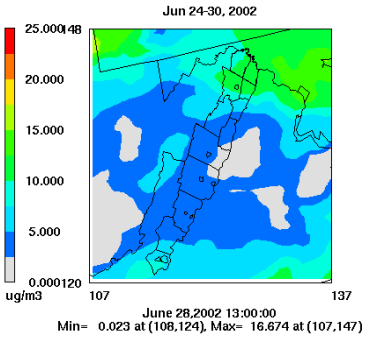
Zero Case PM2.5



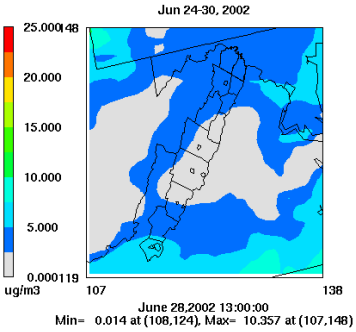
Zero Case PM2.5 - Base Case PM2.5



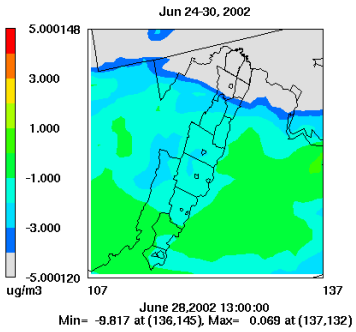
Base Case PM2.5



Zero Case PM2.5



Zero Case PM2.5 - Base Case PM2.5



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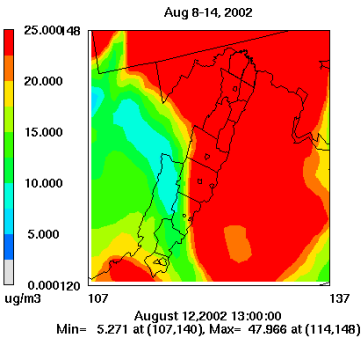
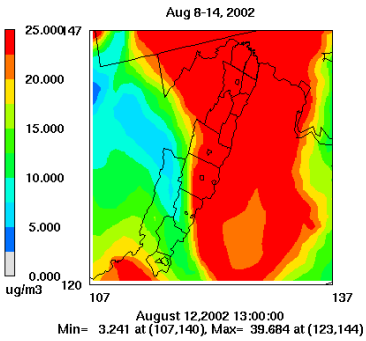
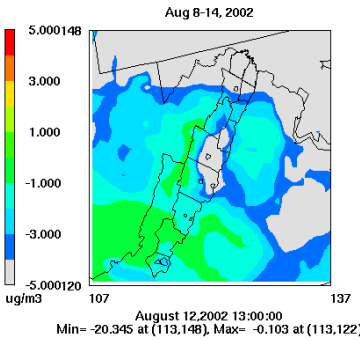


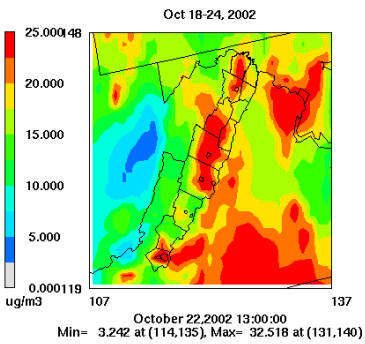
Zero Case PM2.5



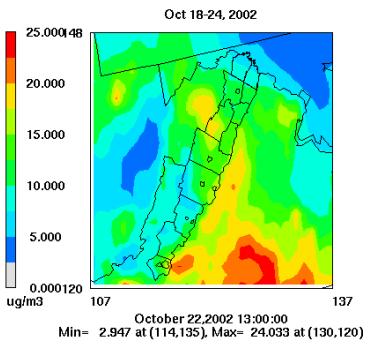
Zero Case PM2.5 - Base Case PM2.5



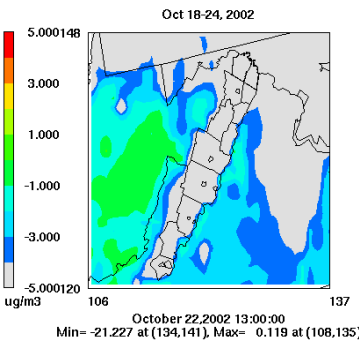
Base Case PM2.5



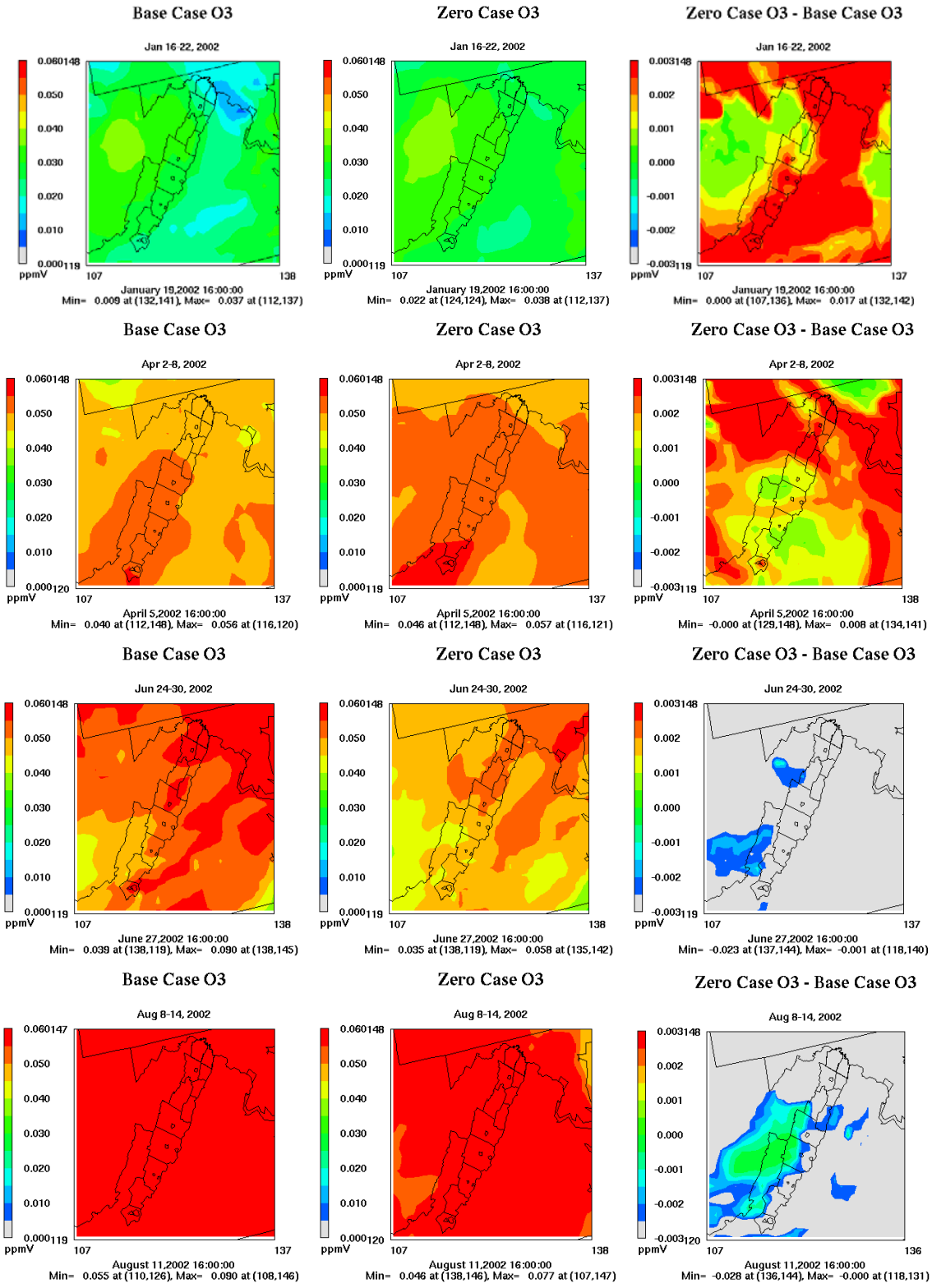
Zero Case PM2.5



Zero Case PM2.5 - Base Case PM2.5



b)


Base Case O3
Zero Case O3
Zero Case O3 - Base Case O3
Jan 16-22, 2002
January 19,2002 16:00:00
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Min= 0.022 at (124,124), Max= 0.038 at (112,137)
Min= 0.000 at (107,136), Max= 0.017 at (132,142)
Apr 2-8, 2002
April 5,2002 16:00:00
Min= 0.040 at (112,148), Max= 0.056 at (116,120)
Min= 0.046 at (112,148), Max= 0.057 at (116,121)
Min= -0.000 at (129,148), Max= 0.008 at (134,141)
Jun 24-30, 2002
June 27,2002 16:00:00
Min= 0.039 at (138,119), Max= 0.090 at (138,145)
Min= 0.035 at (138,119), Max= 0.058 at (135,142)
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Aug 8-14, 2002
August 11,2002 16:00:00
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Min= 0.046 at (138,146), Max= 0.077 at (107,147)
Min= -0.028 at (136,144), Max= -0.000 at (118,131)
ppmV

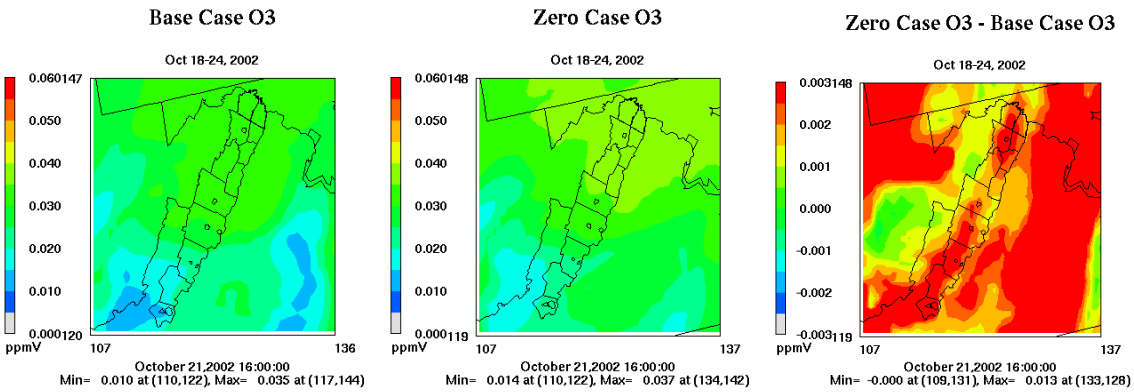


Figure 3.7: Maps of concentrations in the Shenandoah Valley region for the Base Case (left column), Zero Case (middle column), and the difference between the two (right column) for a) $PM_{2.5}$ and b) O_3.

3.4.2 Local Air Management Strategies

In conjunction with governmental and academic participants in SHENAIR, we developed a package of local air management strategies and then tested the sensitivity of predicted O_3 and $PM_{2.5}$ to the changes in emissions. We attempted to select strategies that would have the biggest impact on reducing pollutant emissions and the resulting air pollution. The nine strategies were idling reduction for heavy-duty diesel trucks, mandating the use of low-VOC or zero-VOC paint, converting all lighting to fluorescent bulbs, retrofitting school buses and city buses to run on compressed natural gas (CNG), increasing the energy efficiency of buildings, lowering storage emissions, increasing the use of electric or push lawnmowers, reformulating vehicle gasoline, and enhancing public transport, biking and walking options as alternatives to driving. These strategies are summarized in Table 3.5 and Appendix D shows policy initiatives that governments can implement to achieve them.

Interstate 81 is a major highway that runs all the way through the Shenandoah Valley. It accommodates a great deal of tractor-trailer traffic, and many of these trucks park at truck stops throughout the valley to rest, refuel, and sleep. While parked, the trucks' engines are often idled rather than turned off because electricity generated by the engine is needed to power air conditioning in the summer or heating in the winter, as well as televisions, radios and other accessories in the cab. NO_x, VOC and PM emissions from idling can be significant and degrade air quality in the truck stop area. A study found that if a truck operated for eleven hours a day and idled for six, idling would account for 13% of the total NO_x, 6% of the total CO, 21% of the total VOC, and 3% of the total PM emissions from the truck [33]. These emissions can be greatly reduced if idling alternatives are adopted. Alternatives can range from auxiliary power units attached to trucks to electrifying truck stops [34]. For our model we assumed the local governments would be successful in cutting idling emissions in half. This would result in a 6%

drop in NO_x, 10% drop in VOC, and 1.5% drop in PM emissions from heavy duty diesel trucks in the valley.

Paint is a key emitter of emissions, chiefly VOC. Especially as paint dries, VOCs are released into the air. Newer paints are being manufactured with low or close to zero VOC content [35]. If these paints are implemented and replace regular paint, VOC emissions from surface coating can be reduced by 98%.

Using fluorescent lighting can also significantly reduce pollutant emissions. Converting conventional incandescent lighting to fluorescent lighting can reduce energy demand by 15% [36]. For our model we assumed that all incandescent lighting in the Shenandoah Valley would be switched to fluorescent lighting. This would not reduce emissions in the valley but it could produce a 15% reduction in emissions in the electricity generation required for the valley. To replicate this reduction in our model we assumed that most of the power supplied to Virginia and West Virginia was generated in these two states. We then assumed that since the Shenandoah Valley consisted of 10% of the population of these states, they most likely used about 10% of the electricity. Multiplying the 15% reduction in emissions by the population percentage, we estimated that Virginia and West Virginia power plant emissions would be reduced by 1.5%.

Using CNG instead of diesel in buses has been an effective pollution reduction technique in many places. A study found that doing so reduced NO_x and PM emissions by 40% [37]. The effect of these lower emissions can be even more effective if public transport usage is increased and buses replace vehicular traffic. For our model we assumed all buses would be converted to CNG and thus a 40% reduction in emissions from buses would follow.

Increasing the energy efficiency of buildings would have a similar effect as using fluorescent lighting would. Measures such as using double-pane windows, closing heat-escaping cracks in buildings, and constructing buildings so they use the least amount of electricity led to a decline of up to 30% in electricity usage in New York [38]. In our model we assumed that the Shenandoah Valley would require 15% less electricity if new buildings would be designed to be efficient and if old buildings were retrofitted to be more efficient. Using the same analysis we used for fluorescent lighting, we predicted that emissions from Virginia and West Virginia power plants would be reduced by 1.5%.

Emissions from storage facilities, such as gas stations and fuel storage tanks, account for 3% of VOC emissions in the Shenandoah Valley. Tightening up these tanks, sealing cracks, and implementing new technologies that capture vapors can reduce VOC emissions from storage facilities by 60% [39, 40].

Off-road vehicles, especially lawnmowers, are significant emitters of NO_x, VOCs, CO, and PM. Replacing traditional gasoline powered lawnmowers with electric or manual push mowers would eliminate lawnmower emissions and can play an important role in reducing emissions of all these pollutants [41]. For our model we assumed half of the lawnmowers in the valley could be replaced by electric or push mowers through policies implemented by local governments.

Reformulating gasoline to have a lower Reid Vapor Pressure (RVP) can reduce vehicle NO_x emissions by 26% and VOCs by 31% [42]. Local governments could require gas stations in the valley to carry low RVP gasoline. This would affect almost all vehicles in the valley and reduce NO_x and VOC emissions.

Lastly, enhancing vehicle transport alternatives would be critical to reducing all pollutant emissions in the Shenandoah Valley. On-road vehicles accounted for 58% of the NO_x, 17% of the VOCs, and 7% of the PM emitted in the valley. A study found that improving vehicle transport alternatives led to a 15% decline in vehicular traffic in a London suburb [43]. For our model we predicted that local governments can see a 10% decline in vehicular traffic if good public transport, biking, and walking options are developed. This would correspond to a 10% decline in on-road vehicle pollutant emissions.

Table 3.5: Emissions reductions strategies proposed for the Local Reductions Case.

Proposed Measure	Emissions Reduction Estimate	Fraction of Anthropogenic Emissions in the Valley or Fraction of Power Plant Emissions
Idling reduction for heavy-duty diesel trucks	NO_x = 6% VOC = 10% PM = 1.5% if half of all trucks use idling alternatives	NO_x = 7.5% VOC = 3.6% PM = 0.2%
Low- or zero-VOC paint	VOC = 97-99% of paint and solvent emissions	VOC = 11%
Fluorescent lighting	NO_x = 15% PM = 15% SO2 = 15% of the valley's share of power plant emissions, assuming all lightbulbs are replaced	1.5% of all VISTAS powerplant emissions are due to Shenandoah Valley usage
Retrofitting school buses and city buses	NO_x = 40% PM = 40%	NO_x = 5.8% PM = 0.7%
Green buildings	NO_x = 15% PM = 15% SO2 = 15% of the valley's share of power plant emissions	1.5% of all VISTAS powerplant emissions are due to Shenandoah Valley usage
Lower storage emissions	VOC = 60%	VOC = 9%
Clean lawnmowers	CO = 50% NO_x = 50% VOC = 50% PM = 50% of lawnmower emissions if half of all mowers are replaced	NO_x = 15% VOC = 6% PM = 10%
Reformulated gasoline	NO_x = 26% VOC = 31% of gasoline-powered vehicle emissions	NO_x = 58% VOC = 17%
More public transport, biking, walking options	CO = 10% NO_x = 10% VOC = 10% PM = 10% of gasoline-powered vehicle emissions	NO_x = 58% VOC = 17% PM = 7%

The Local Reductions Case resulted in significant reductions in $PM_{2.5}$ in Roanoke, Salem and Luray. The model predicted greater reductions in Roanoke than Salem, most likely due to Roanoke being a larger and more industrialized metropolitan area than Salem. Roanoke would likely see $PM_{2.5}$ concentrations fall between 16-24% while Salem would likely see reductions between 10-19%. In both cases the reductions were higher in the winter months than the summer months, consistent with results from the Zero Case. For Luray in the northern end of the valley

there was a slight reversal in the trend; the summer months saw a larger reduction than winter months though seasonal differences were less. $PM_{2.5}$ reductions for the Local Reductions Case hovered between 10-13% for all the modeled weeks. These results show that the policies in the Local Reductions Case will affect $PM_{2.5}$ in the northern end of the valley differently than the southern end, though reductions in $PM_{2.5}$ concentrations can be expected in both places. Figure 3.8a shows maps of $PM_{2.5}$ concentrations for the Local Reductions Case in the Shenandoah Valley region while Figure 3.9 shows concentrations at specific monitoring sites The top half of Table 3.7 shows percent changes in $PM_{2.5}$ concentrations between the Local Reductions Case and Base Case.

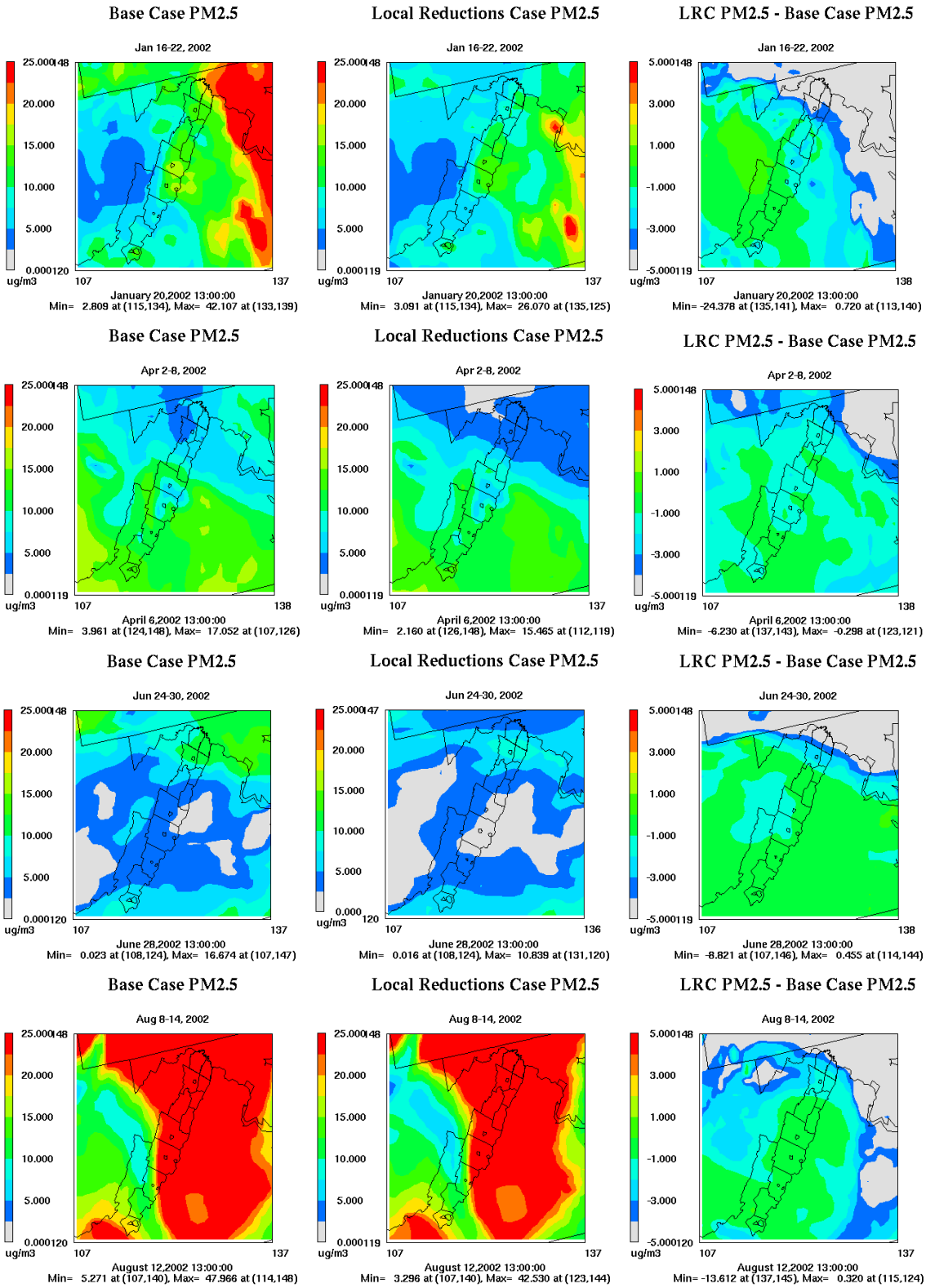
Results for individual PM species were similar to the Zero Case. Concentrations of all PM species were lower, though the reductions were not as great as in the Zero Case. The percent reductions were highest for the AEC, AOC, and ANO_3 species while they were lowest for ASO_4. Figure 3.9 shows Local Reductions Case PM species' time series for the five modeled weeks.

By SSC, $PM_{2.5}$ concentrations were highest on dry moderate and dry tropical days and lowest on moist moderate and moist tropical days. Percent reductions in $PM_{2.5}$ were also greatest during moist days. Between June and August, which had similar temperatures and emissions but different rainfall and moisture characteristics, percent reductions were slightly higher in June than in August.

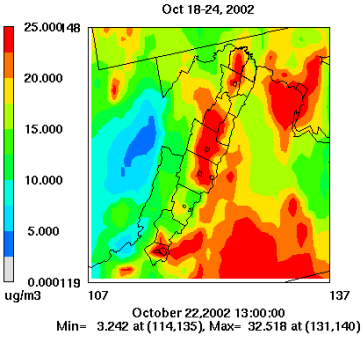
For ozone though, the Local Reductions Case did not produce significant reductions in ambient concentrations; results were consistent with the Zero Case as well. Ozone concentration changes ranged from -1% to 87%, depending on the location and time of year. The model predicted the greatest increases for the month of October and the least differences in the summer months. The bottom half of Table 3.7 shows percent differences between the Local Reductions Case and Base Case O_3 concentrations, and Figure 3.8b shows maps of O_3 concentrations for the Local Reductions Case in the Shenandoah Valley region. Figure 3.9 shows O_3 time series in the Local Reductions Case at specific monitoring sites.

As with the Zero Case we saw similar correlations between O_3 concentrations and meteorology for the Local Reductions Case. Increases in O_3 concentrations were more pronounced on dry tropical days and less on other SSC types, particularly moist days.

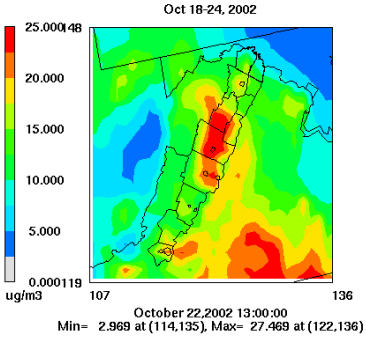
a)


Base Case PM2.5
Local Reductions Case PM2.5
LRC PM2.5 - Base Case PM2.5
Jan 16-22, 2002
January 20,2002 13:00:00
Min= 2.809 at (115,134), Max= 42.107 at (133,139)
Min= 3.091 at (115,134), Max= 26.070 at (135,125)
Min= -24.378 at (135,141), Max= 0.720 at (113,140)
Apr 2-8, 2002
April 6,2002 13:00:00
Min= 3.961 at (124,148), Max= 17.052 at (107,126)
Min= 2.160 at (126,148), Max= 15.465 at (112,119)
Min= -6.230 at (137,143), Max= -0.298 at (123,121)
Jun 24-30, 2002
June 28,2002 13:00:00
Min= 0.023 at (108,124), Max= 16.674 at (107,147)
Min= 0.016 at (108,124), Max= 10.839 at (131,120)
Min= -8.821 at (107,146), Max= 0.455 at (114,144)
Aug 8-14, 2002
August 12,2002 13:00:00
Min= 5.271 at (107,140), Max= 47.966 at (114,148)
Min= 3.296 at (107,140), Max= 42.530 at (123,144)
Min= -13.612 at (137,145), Max= 0.320 at (115,124)
ug/m3

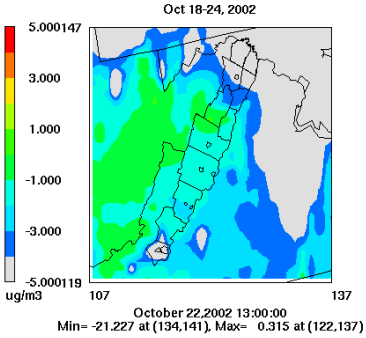
Base Case PM2.5



Local Reductions Case PM2.5

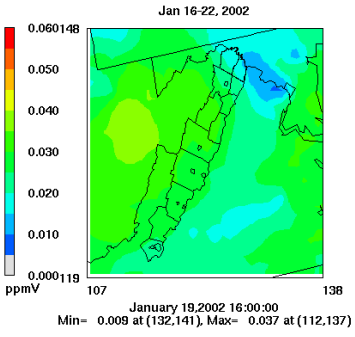


LRC PM2.5 - Base Case PM2.5

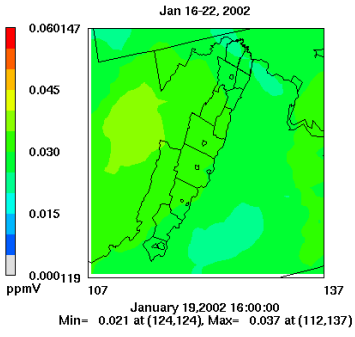


b)

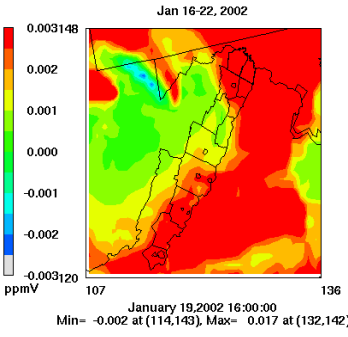
Base Case O3



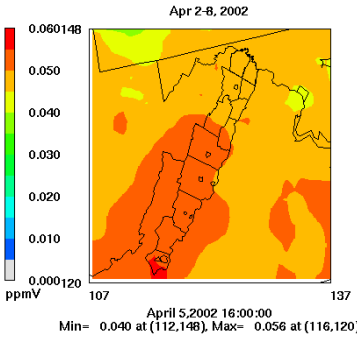
Local Reductions Case O3



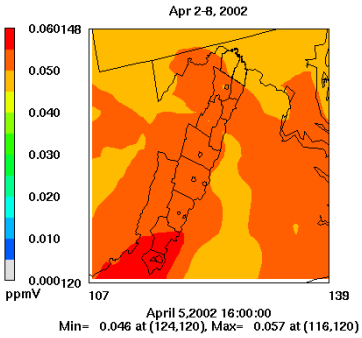
LRC O3 - Base Case O3



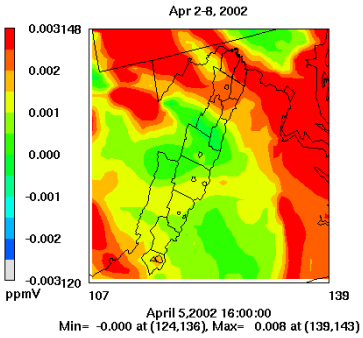
Base Case O3



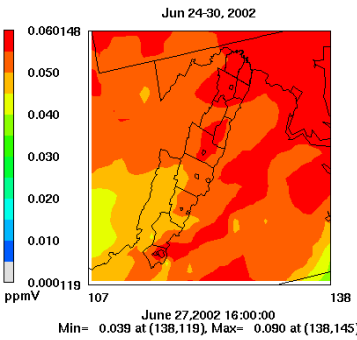
Local Reductions Case O3



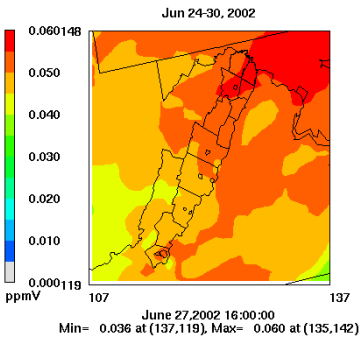
LRC O3 - Base Case O3



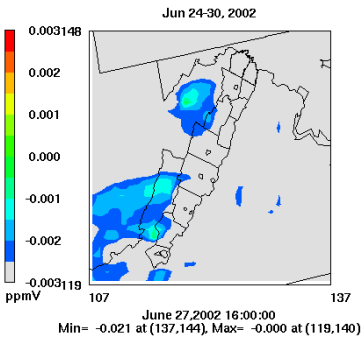
Base Case O3



Local Reductions Case O3



LRC O3 - Base Case O3



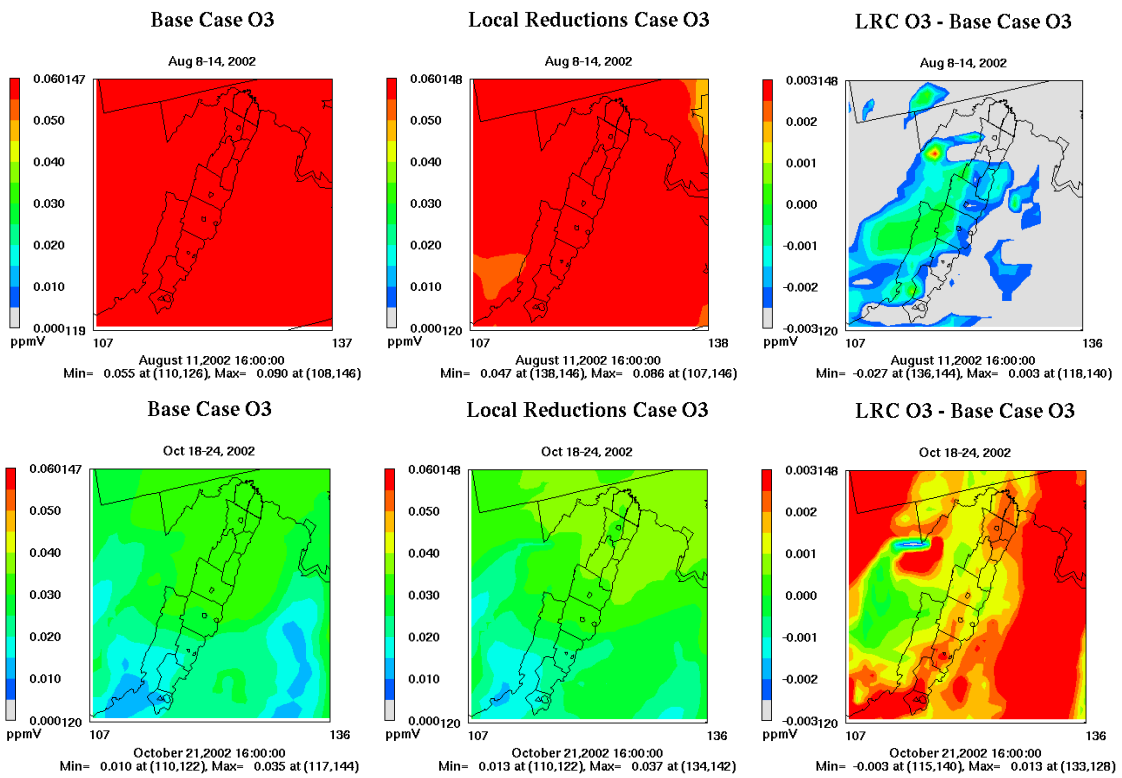


Figure 3.8: Maps of concentrations in the Shenandoah Valley region for the Base Case (left column), Local Reductions Case (middle column), and the difference between the two (right column) for a) $PM_{2.5}$ and b) O_3.

3.4.3 Greenhouse Gas Reductions

The GHG Reductions Case combines ten strategies being considered by local governments to reduce GHG emissions in the valley. Five of these were also included in the Local Reductions Case since they would have major impacts on both GHG and criteria pollutant emissions. These included switching to fluorescent lighting, constructing energy-efficient buildings, retrofitting buses to run on CNG, using electric or push lawnmowers, and enhancing public transport, biking, and walking transportation options. Five different strategies were included in this scenario: placing caps on industrial emissions, increasing the energy efficiency of all appliances used in the valley, mandating the use of energy-efficient traffic lights and street lights, mandating all gasoline sold in the valley to contain 10% ethanol, and mandating all diesel sold in the valley to contain 20% biodiesel. These strategies are summarized in Table 3.6 and Appendix D shows policy initiatives that governments can implement to achieve them.

Placing caps on industrial emissions would be a bold move but could be implemented by local governments to reduce GHG emissions in the valley. A 10% decrease in industrial emissions would be in line with the Kyoto Protocol, which many cities and counties in the US

have adopted through the Cool Cities program. This would reduce emissions by 10% for point sources.

Using energy-efficient appliances would reduce greenhouse gas emissions by lowering energy demand and thus emissions from power plants. Currently the Energy Star label is placed on all appliances that meet predetermined energy efficiency requirements. Adopting Energy Star appliances can reduce energy demand for appliances by 25% [44], which would correspond to a similar reduction in power plant emissions. Since appliances account for about 65% of electricity use in the US [45], this would be a significant reduction.

Using high pressure sodium lamps in place of conventional lamps for street lights and traffic lights will also reduce electricity demand. This policy is different from adopting fluorescent lighting because street lights require high intensity lamps which fluorescent lighting can not provide. Adopting high pressure sodium lamps would reduce the electricity demand of street and traffic lighting by 30% [46].

Mandating that all gas stations in the valley carry gasoline that contains 10% ethanol and diesel that contains 20% biodiesel would help reduce CO_2 emissions from vehicles. In terms of criteria pollutant emissions VOCs would be reduced by 20% though NO_x emissions would be largely unchanged [47-49] PM emissions would also decrease for diesel operated vehicles but would be unchanged for gasoline operated vehicles [47-49].

Table 3.6: Strategies proposed for the GHG Reductions Case.

Proposed Measure	**Emissions Reduction Estimate**	**Fraction of Anthropogenic Emissions in the Valley or Fraction of Power Plant Emissions**
B20 in all diesel	NO_x = -2% VOC = 20% PM = 12%	NO_x = 58% VOC = 17% $PM_{2.5}$ = 7% for all mobile sources
E10 in all gasoline	NO_x = 0% VOC = 20% PM = 0%	NO_x = 58% VOC = 17% $PM_{2.5}$ = 7% for all mobile sources
Energy efficient traffic and street lights	NO_x = 10% VOC = 10% PM = 10% of powerplant emissions	1.5% of all VISTAS power plant emissions are due to Shenandoah Valley usage.
All energy star appliances	NO_x = 25% VOC = 25% PM = 25% of all appliances	1.5% of all VISTAS power plant emissions are due to Shenandoah Valley usage. Appliances account for about 65% of electricity consumption.
Industrial emissions caps	NO_x = 10% VOC = 10% PM = 10% of point source emissions	NO_x = 16% VOC = 8% $PM_{2.5}$ = 41% for all point sources
Fluorescent lighting	NO_x = 15% PM = 15% SO2 = 15% of the valley's share of power plant emissions, assuming all lightbulbs are replaced	1.5% of all VISTAS power plant emissions are due to Shenandoah Valley usage.
Retrofitting school buses and city buses	NO_x = 40% PM = 40%	NO_x = 5.8% PM = 0.7%
Green buildings	NO_x = 15% PM = 15% SO2 = 15% of the valley's share of power plant emissions	1.5% of all VISTAS power plant emissions are due to Shenandoah Valley usage.
Clean lawnmowers	CO = 50% NO_x = 50% VOC = 50% PM = 50% of lawnmower emissions if half of all mowers are replaced	NO_x = 15% VOC = 6% PM = 10%
More public transport, biking, walking options	CO = 10% NO_x = 10% VOC = 10% PM = 10% of gasoline-powered vehicle emissions	NO_x = 58% VOC = 17% PM = 7%

Overall results from the GHG Reductions Case were similar to the Local Reductions Case. The model predicted lower $PM_{2.5}$ concentrations compared to the Base Case. On the north end of the valley in Luray $PM_{2.5}$ concentrations dropped between 11-13%. On the south end, Roanoke saw reductions between 19-27%, and Salem saw reductions between 14-21%. As with the Local Reductions Case Luray had slightly higher reductions in the summer months while Roanoke and Salem had much higher reductions in the winter months. Roanoke and Salem also saw slightly increased reductions for the GHG Reductions Case than Luray when compared to the Local Reductions Case. This is most likely because GHG reduction policies have stronger impacts on emissions in larger urban centers such as the Roanoke-Salem area than in sparsely populated Luray. The top half of Table 3.7 shows percent changes in $PM_{2.5}$ concentrations between the Local Reductions Case and Base Case. Because results were similar to the Local Reductions Case, maps of the GHG Reductions Case are not shown.

The results for individual PM species were quite similar to the Local Reductions Case as well. For all species the model predicted similar concentrations for the GHG Reductions Case and the Local Reductions Case. The greatest percent reductions were for AEC, AOC, and ANO_3 while the lowest reductions were for ASO_4. Changes by SSC were consistent with the Local Reductions Case.

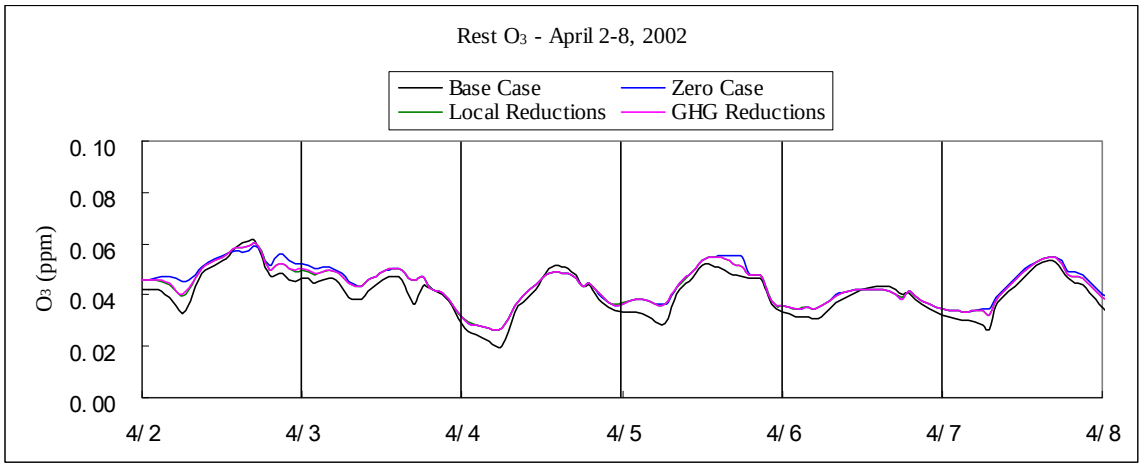
As with all the other scenarios, predictions for O_3 concentrations were not as optimistic as the $PM_{2.5}$ ones. The GHG Reductions Case predicted a slight increase in O_3 concentrations most of the time, and the numbers were very similar to the Local Reductions Case. According to the model only Rest would see a slight drop of 3% in O_3 concentrations for the week in June. Conversely all the other weeks saw a slight increase with the most extreme being a 89% increase in Vinton in October. The bottom half of Table 3.7 shows percent differences between the GHG Reductions Case and Base Case O_3 concentrations, and Figure 3.9 shows O_3 time series in the GHG Reductions Case. Changes by SSC showed similar trends as with the other scenarios.

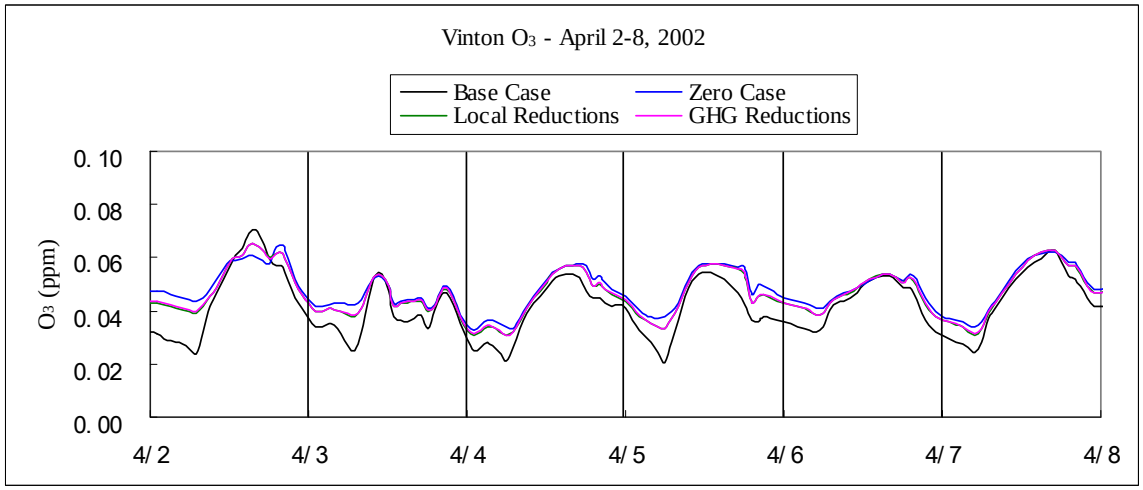
Table 3.7: Percent changes for the Zero Case, Local Reductions Case, and GHG Reductions Case from the Base Case for $PM_{2.5}$ and O_3 at selected locations and times in the Shenandoah Valley

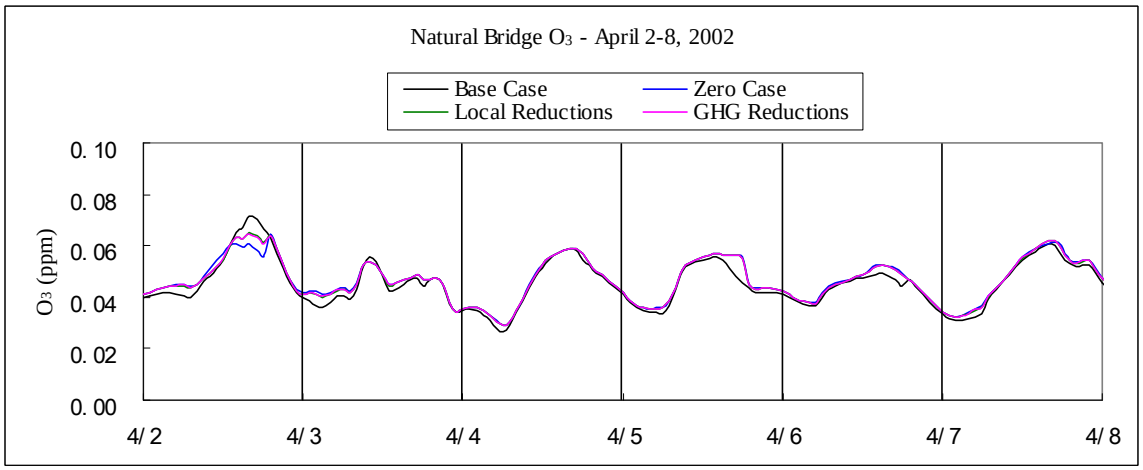
Pollutant	Site	Month	Percent Change from Base Case[a]		
			Zero Case	Local Reductions Case	GHG Reductions Case
$PM_{2.5}$	Luray	January	-44	-11	-11
		April	-35	-11	-11
		June	-33	-13	-13
		August	-26	-12	-13
		October	-40	-10	-10
	Salem	January	-46	-19	-21
		April	-26	-10	-13
		June	-26	-12	-14
		August	-27	-13	-16
		October	-34	-15	-17
O_3	Rest	April	9	8	8
		June	-3	-2	-3
		August	1	1	1
		October	35	28	30
	Vinton	April	19	14	15
		June	12	9	9
		August	18	14	14
		October	122	87	89

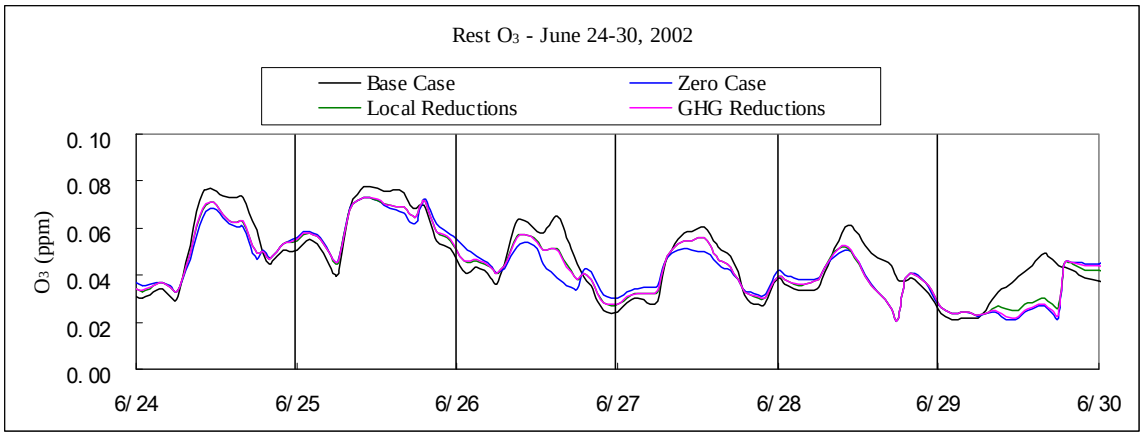
[a]Normalized bias for each case from the modeled Base Case scenario.

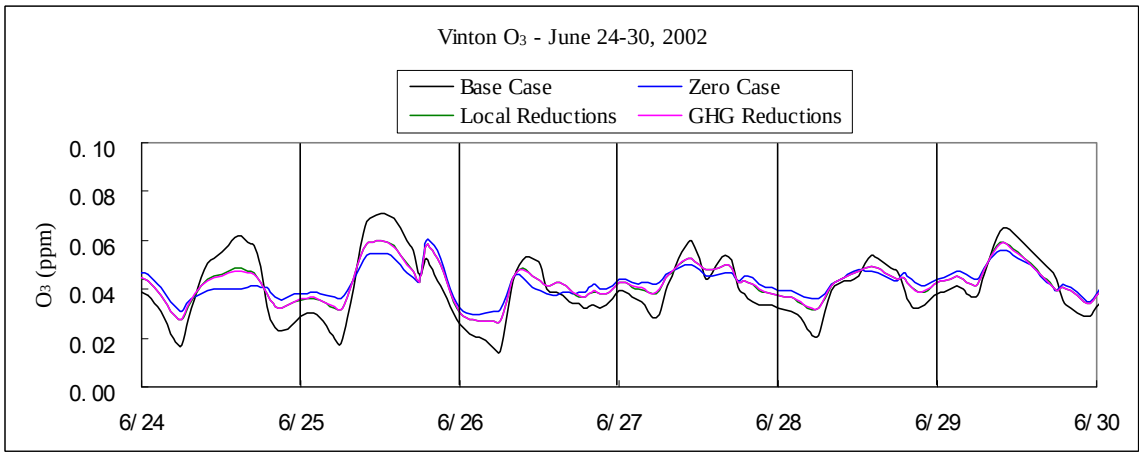
a)

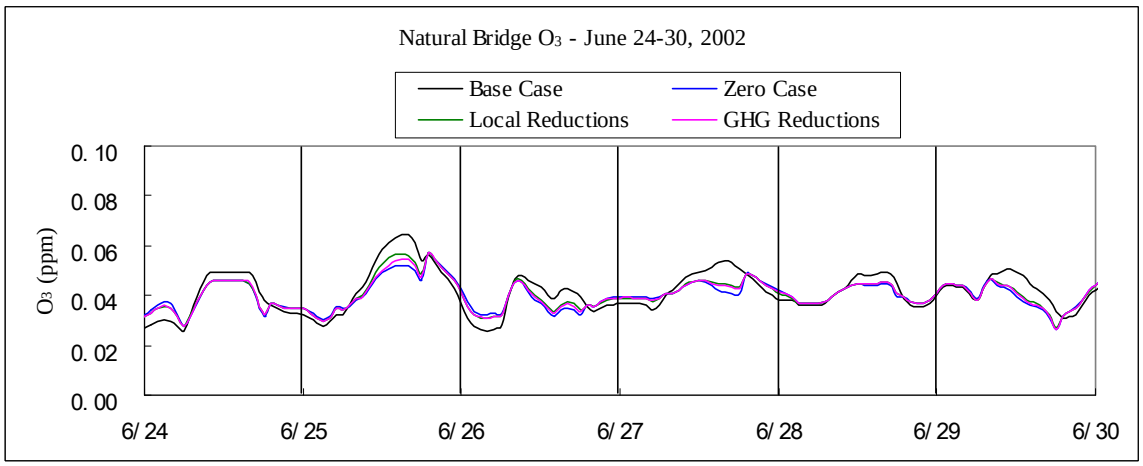

Rest O3 - April 2-8, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
4/ 2
4/ 3
4/ 4
4/ 5
4/ 6
4/ 7
4/ 8

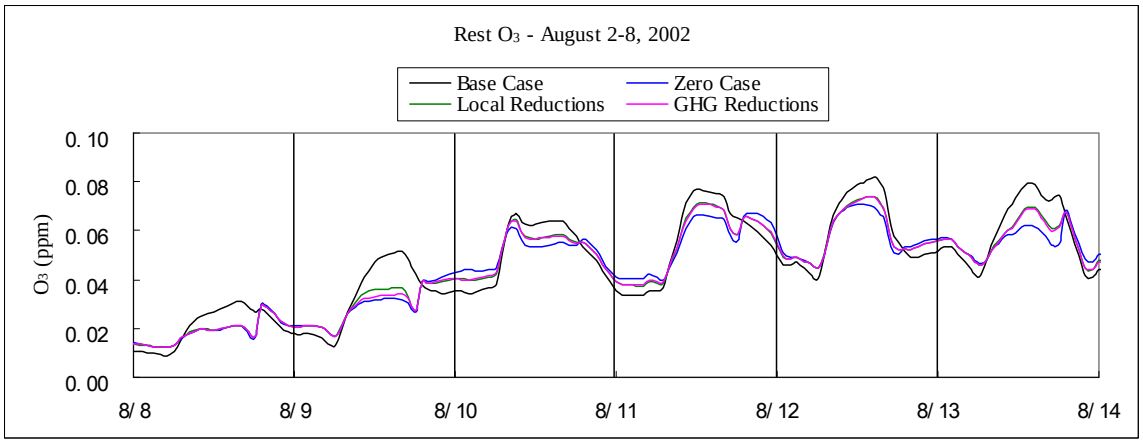

Vinton O3 - April 2-8, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
4/ 2
4/ 3
4/ 4
4/ 5
4/ 6
4/ 7
4/ 8

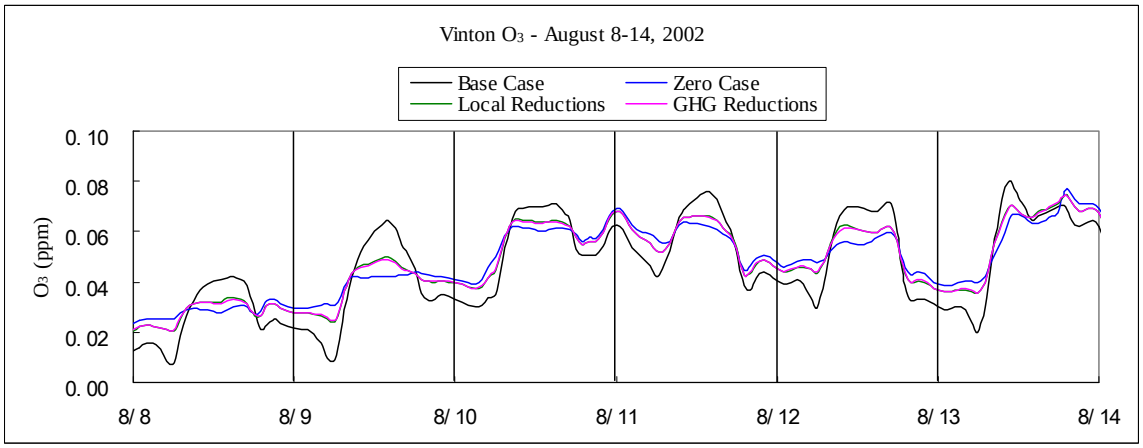

Natural Bridge O3 - April 2-8, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
4/ 2
4/ 3
4/ 4
4/ 5
4/ 6
4/ 7
4/ 8

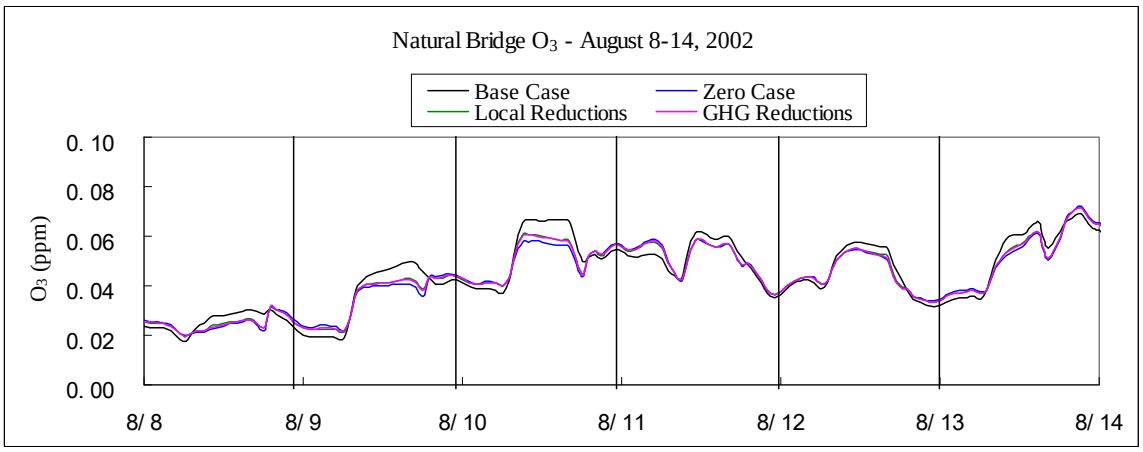

Rest O3 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
6/ 24
6/ 25
6/ 26
6/ 27
6/ 28
6/ 29
6/ 30

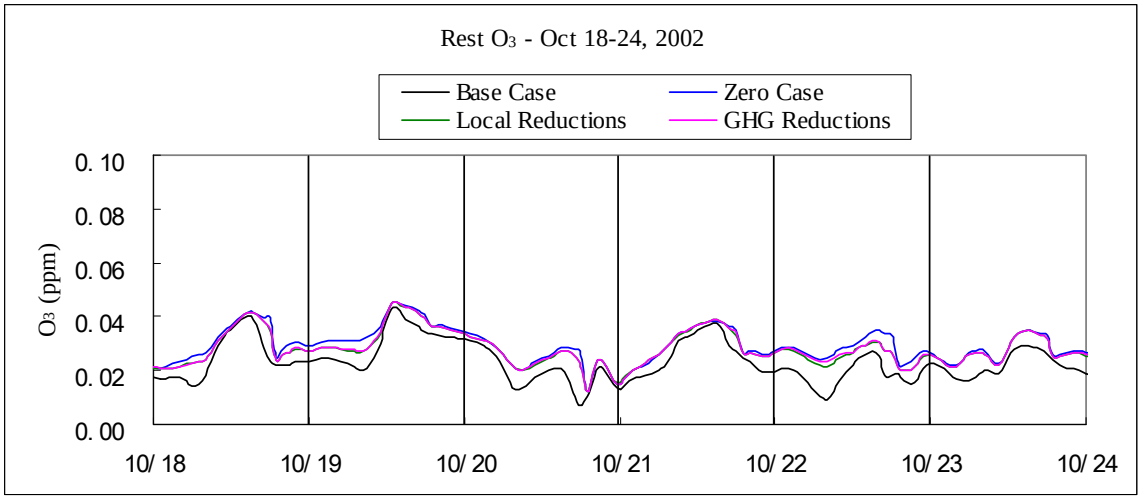

Vinton O3 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
6/ 24
6/ 25
6/ 26
6/ 27
6/ 28
6/ 29
6/ 30

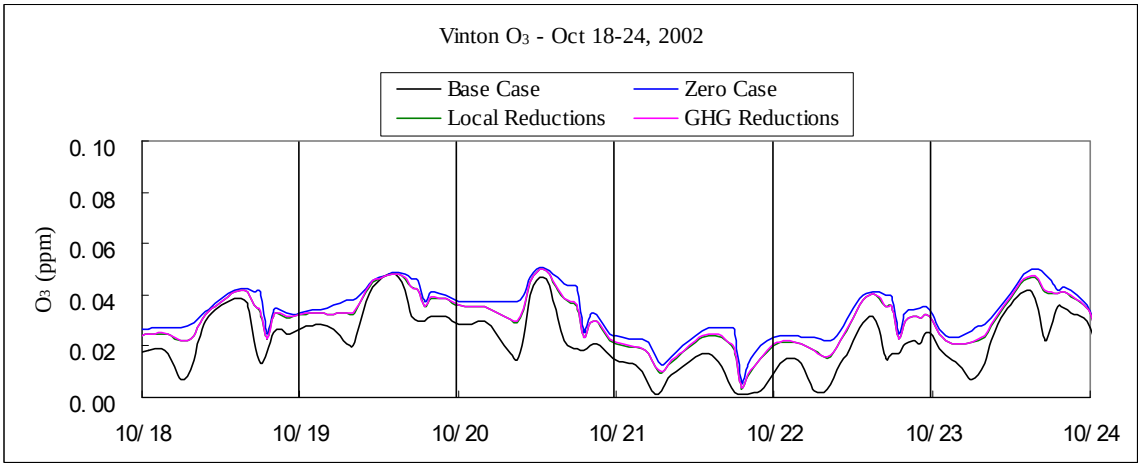

Natural Bridge O3 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
6/ 24
6/ 25
6/ 26
6/ 27
6/ 28
6/ 29
6/ 30

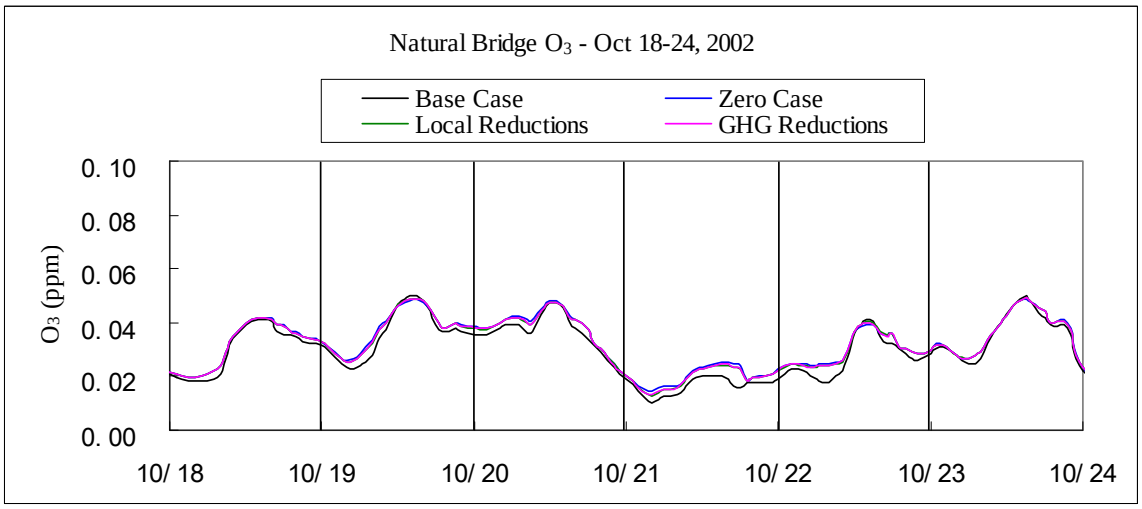

Rest O3 - August 2-8, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
8/ 8
8/ 9
8/ 10
8/ 11
8/ 12
8/ 13
8/ 14


Vinton O3 - August 8-14, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
8/ 8
8/ 9
8/ 10
8/ 11
8/ 12
8/ 13
8/ 14

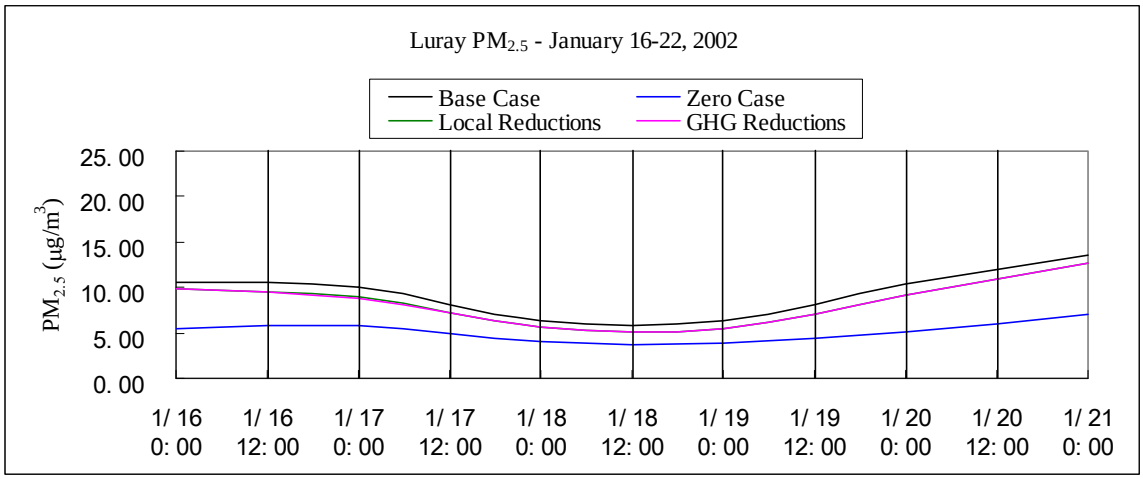

Natural Bridge O3 - August 8-14, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
8/ 8
8/ 9
8/ 10
8/ 11
8/ 12
8/ 13
8/ 14

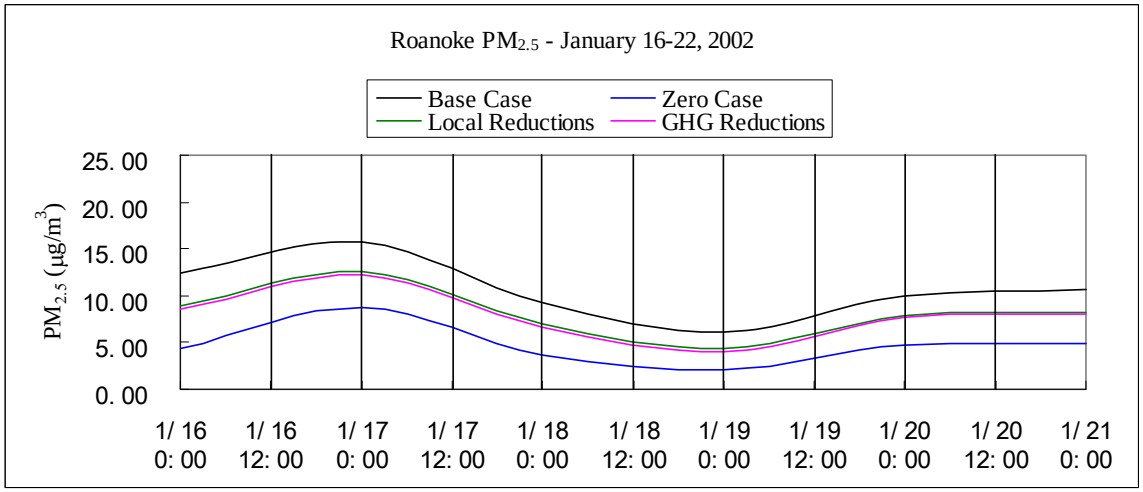

Rest O3 - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
10/ 18
10/ 19
10/ 20
10/ 21
10/ 22
10/ 23
10/ 24

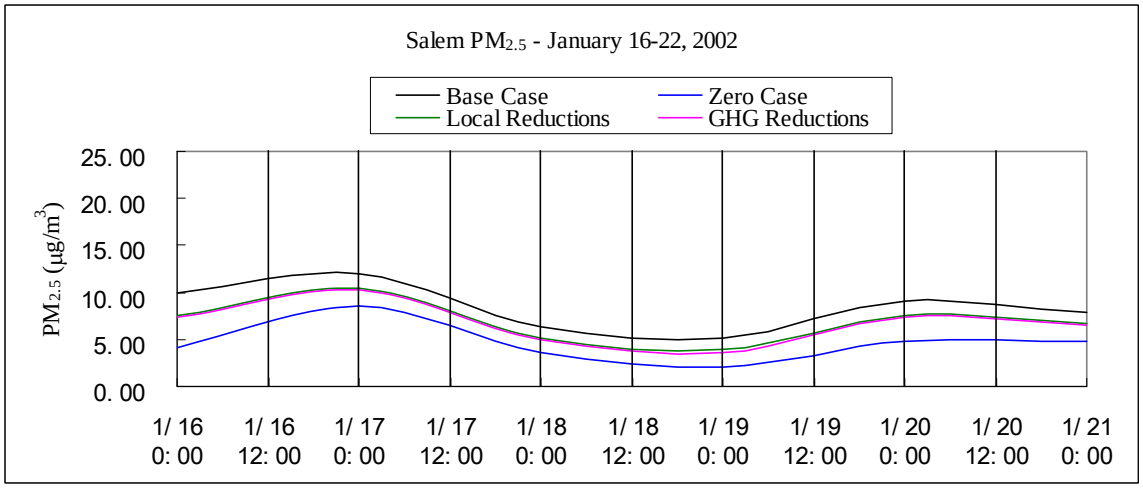

Vinton O3 - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
10/ 18
10/ 19
10/ 20
10/ 21
10/ 22
10/ 23
10/ 24

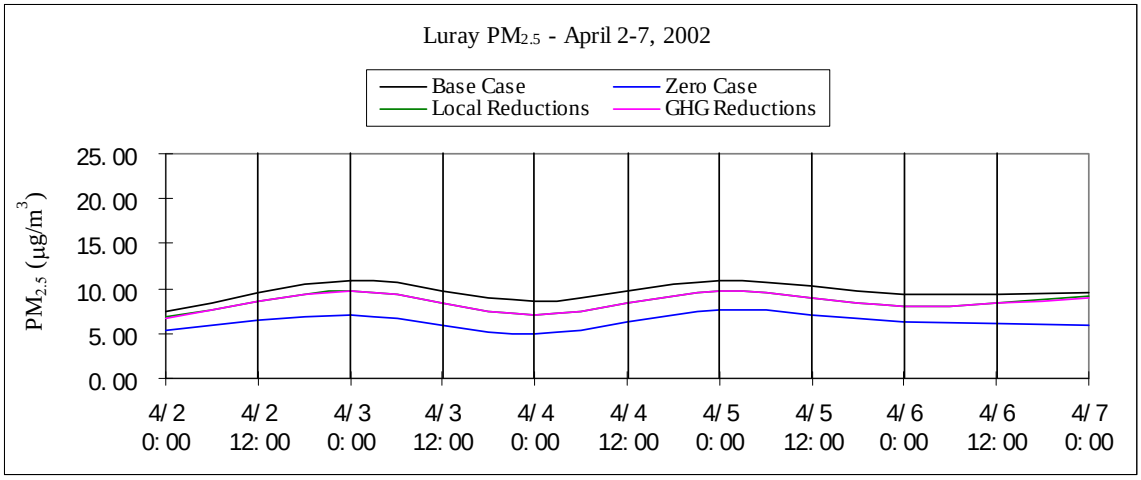

Natural Bridge O3 - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
O3 (ppm)
0. 10
0. 08
0. 06
0. 04
0. 02
0. 00
10/ 18
10/ 19
10/ 20
10/ 21
10/ 22
10/ 23
10/ 24

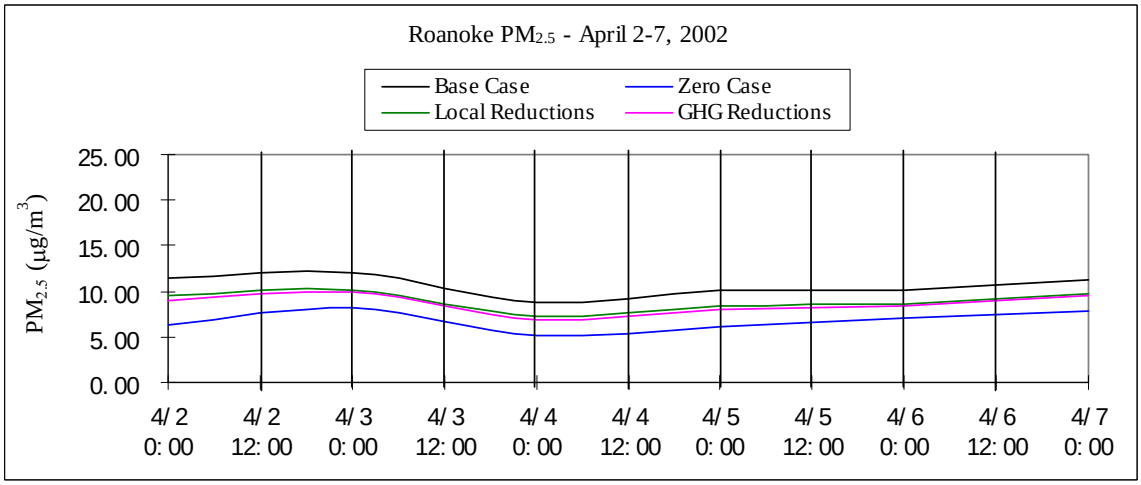
b)

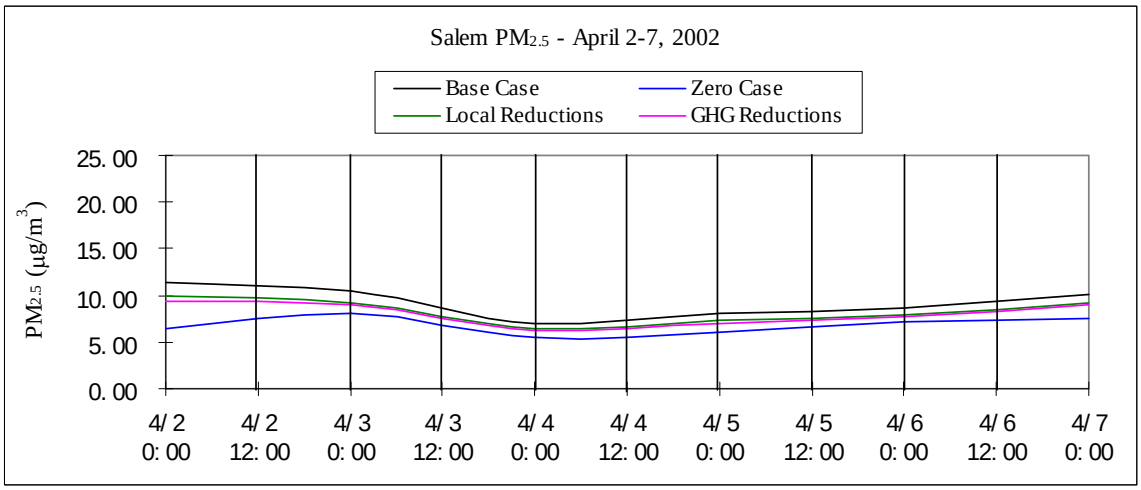

Luray PM2.5 - January 16-22, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
1/ 16 0: 00
1/ 16 12: 00
1/ 17 0: 00
1/ 17 12: 00
1/ 18 0: 00
1/ 18 12: 00
1/ 19 0: 00
1/ 19 12: 00
1/ 20 0: 00
1/ 20 12: 00
1/ 21 0: 00

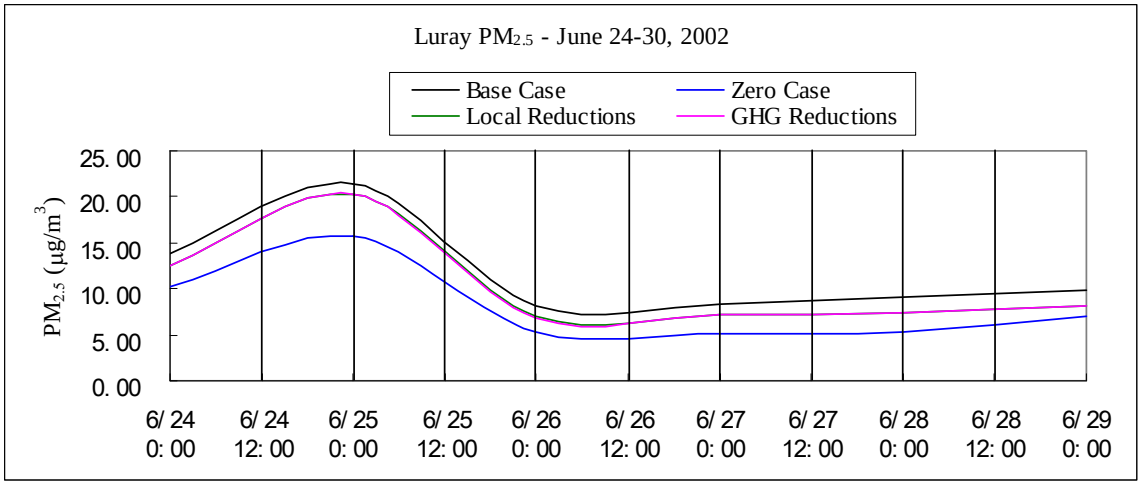

Roanoke PM2.5 - January 16-22, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
1/ 16 0: 00
1/ 16 12: 00
1/ 17 0: 00
1/ 17 12: 00
1/ 18 0: 00
1/ 18 12: 00
1/ 19 0: 00
1/ 19 12: 00
1/ 20 0: 00
1/ 20 12: 00
1/ 21 0: 00

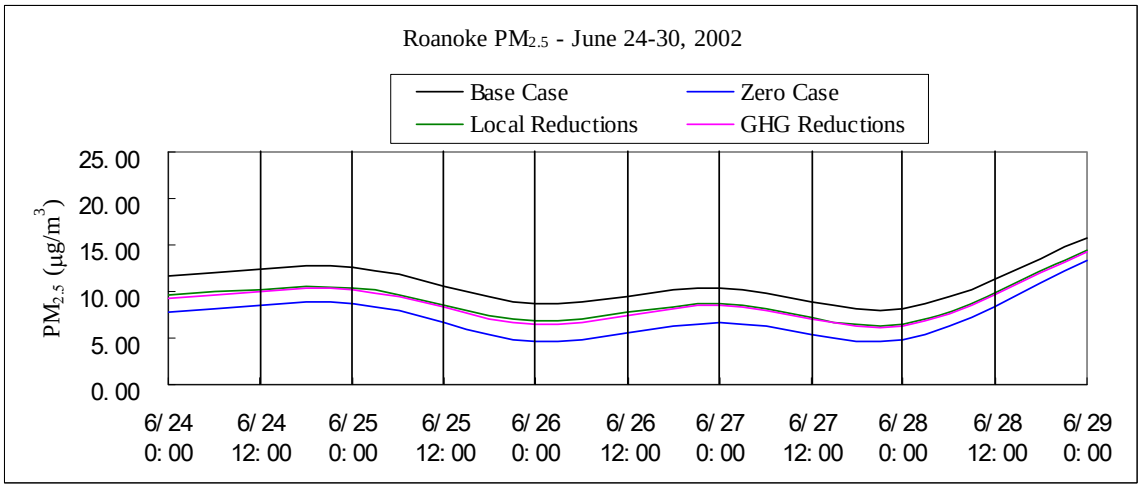

Salem PM2.5 - January 16-22, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
1/ 16 0: 00
1/ 16 12: 00
1/ 17 0: 00
1/ 17 12: 00
1/ 18 0: 00
1/ 18 12: 00
1/ 19 0: 00
1/ 19 12: 00
1/ 20 0: 00
1/ 20 12: 00
1/ 21 0: 00

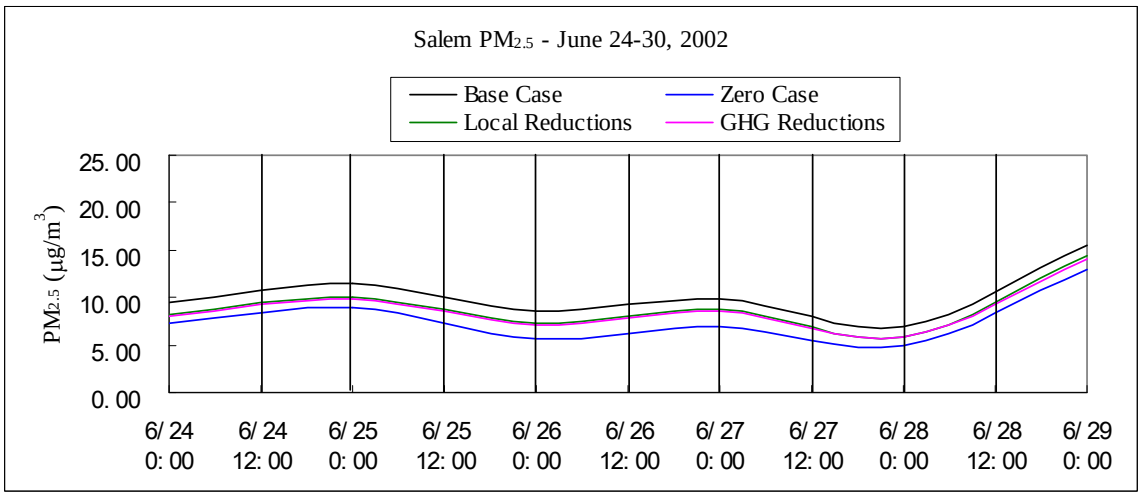

Luray PM2.5 - April 2-7, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
4/ 2 0: 00
4/ 2 12: 00
4/ 3 0: 00
4/ 3 12: 00
4/ 4 0: 00
4/ 4 12: 00
4/ 5 0: 00
4/ 5 12: 00
4/ 6 0: 00
4/ 6 12: 00
4/ 7 0: 00

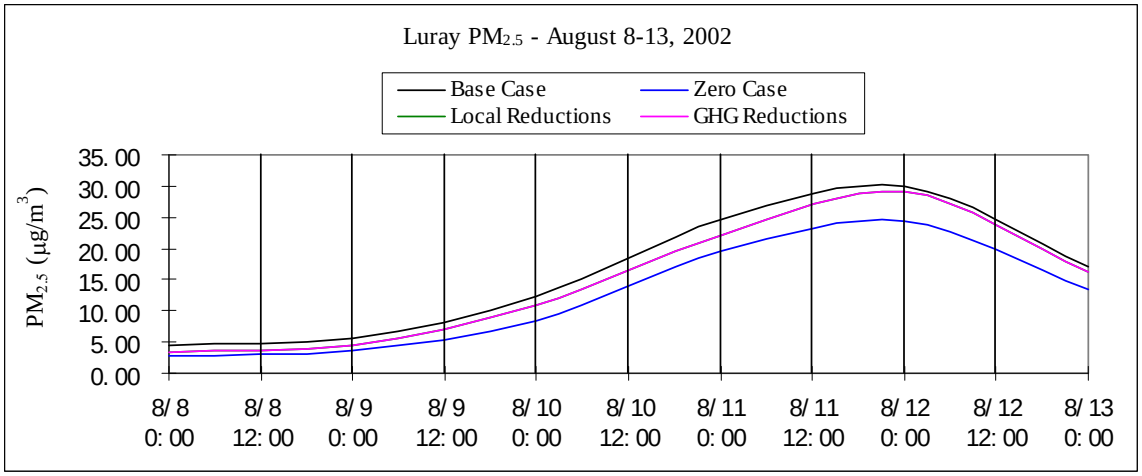

Roanoke PM2.5 - April 2-7, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
4/ 2 0: 00
4/ 2 12: 00
4/ 3 0: 00
4/ 3 12: 00
4/ 4 0: 00
4/ 4 12: 00
4/ 5 0: 00
4/ 5 12: 00
4/ 6 0: 00
4/ 6 12: 00
4/ 7 0: 00

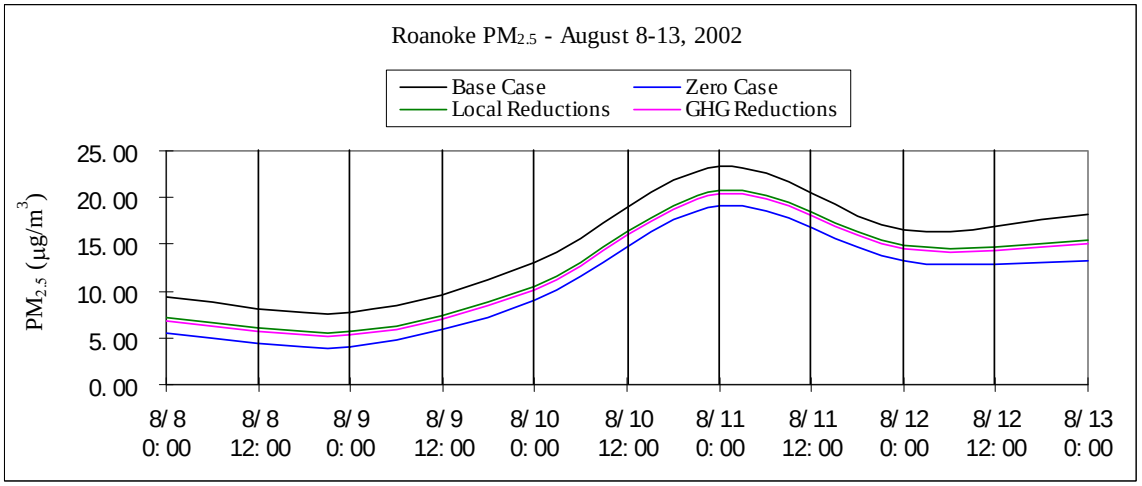

Salem PM2.5 - April 2-7, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
4/ 2 0: 00
4/ 2 12: 00
4/ 3 0: 00
4/ 3 12: 00
4/ 4 0: 00
4/ 4 12: 00
4/ 5 0: 00
4/ 5 12: 00
4/ 6 0: 00
4/ 6 12: 00
4/ 7 0: 00

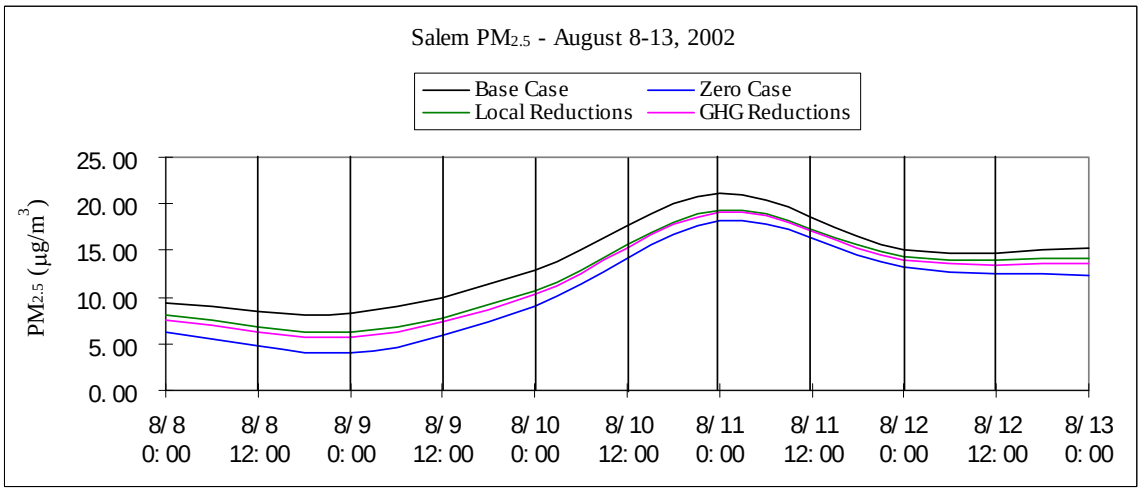

Luray PM2.5 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
6/ 24 0: 00
6/ 24 12: 00
6/ 25 0: 00
6/ 25 12: 00
6/ 26 0: 00
6/ 26 12: 00
6/ 27 0: 00
6/ 27 12: 00
6/ 28 0: 00
6/ 28 12: 00
6/ 29 0: 00

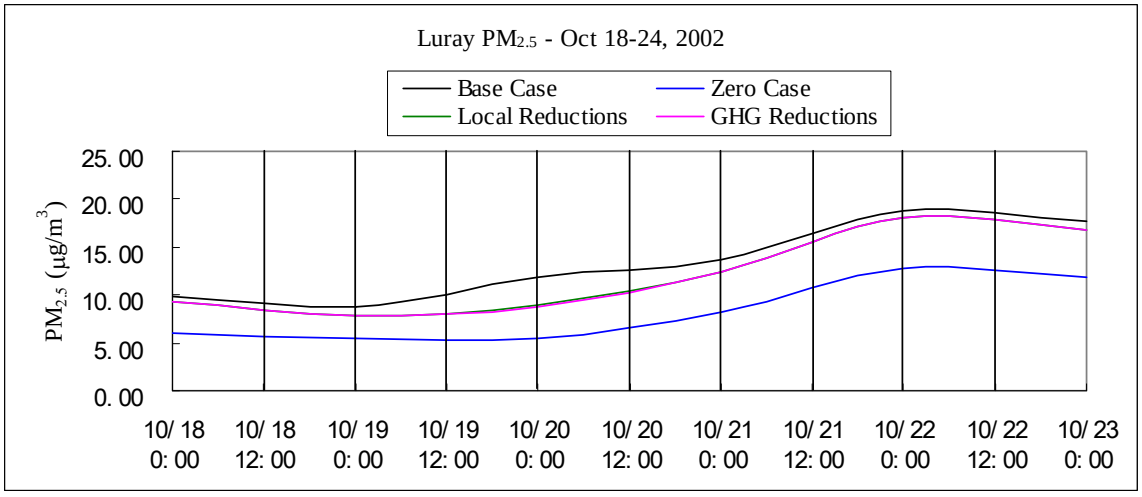

Roanoke PM2.5 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
6/ 24 0: 00
6/ 24 12: 00
6/ 25 0: 00
6/ 25 12: 00
6/ 26 0: 00
6/ 26 12: 00
6/ 27 0: 00
6/ 27 12: 00
6/ 28 0: 00
6/ 28 12: 00
6/ 29 0: 00

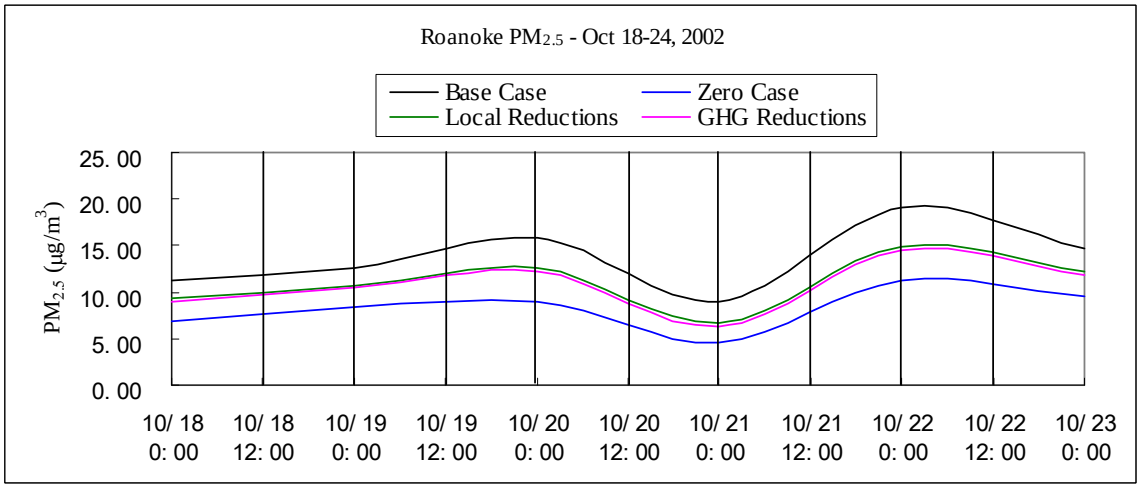

Salem PM2.5 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
6/ 24 0: 00
6/ 24 12: 00
6/ 25 0: 00
6/ 25 12: 00
6/ 26 0: 00
6/ 26 12: 00
6/ 27 0: 00
6/ 27 12: 00
6/ 28 0: 00
6/ 28 12: 00
6/ 29 0: 00

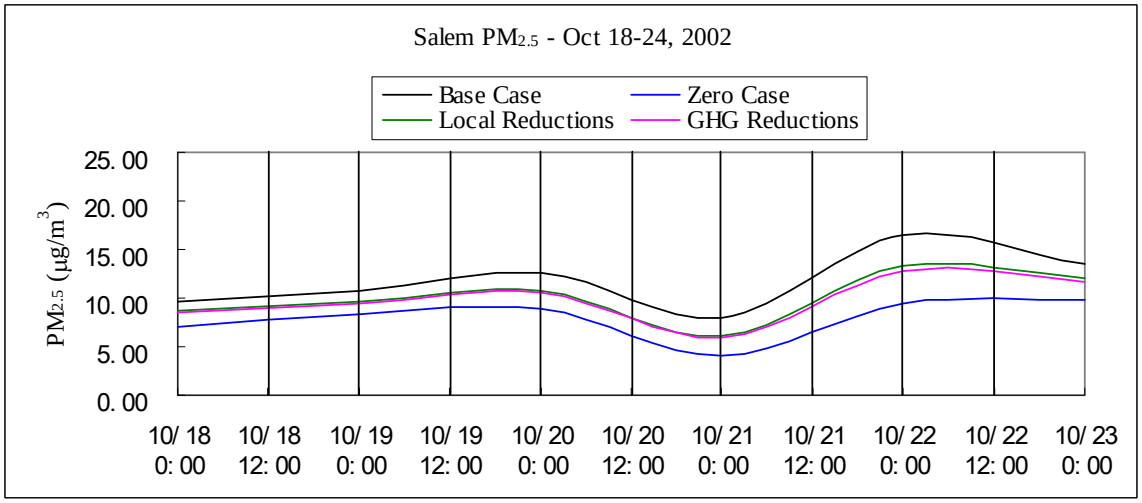

Luray PM2.5 - August 8-13, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
35. 00
30. 00
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
8/ 8 0: 00
8/ 8 12: 00
8/ 9 0: 00
8/ 9 12: 00
8/ 10 0: 00
8/ 10 12: 00
8/ 11 0: 00
8/ 11 12: 00
8/ 12 0: 00
8/ 12 12: 00
8/ 13 0: 00


Roanoke PM2.5 - August 8-13, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
8/ 8 0: 00
8/ 8 12: 00
8/ 9 0: 00
8/ 9 12: 00
8/ 10 0: 00
8/ 10 12: 00
8/ 11 0: 00
8/ 11 12: 00
8/ 12 0: 00
8/ 12 12: 00
8/ 13 0: 00

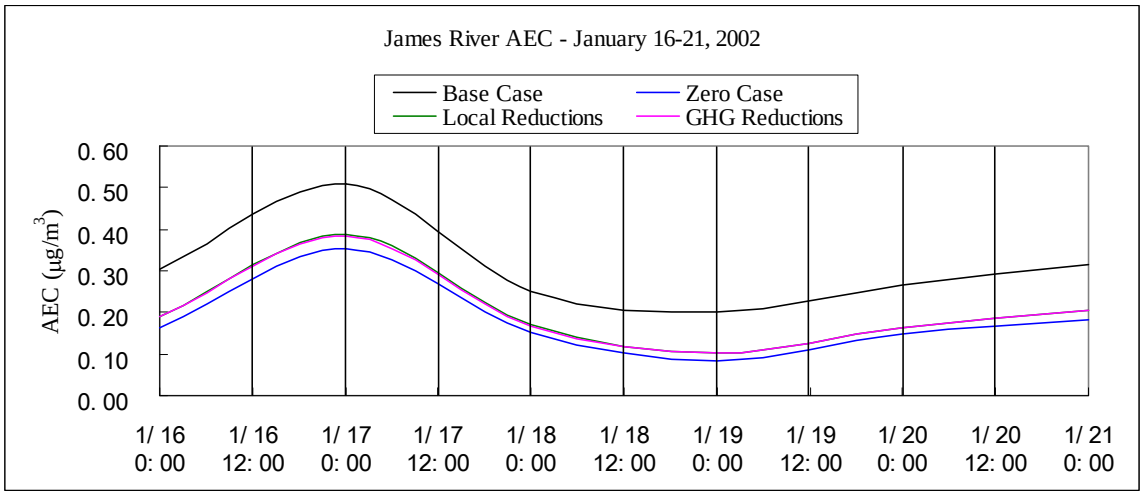

Salem PM2.5 - August 8-13, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
8/ 8 0: 00
8/ 8 12: 00
8/ 9 0: 00
8/ 9 12: 00
8/ 10 0: 00
8/ 10 12: 00
8/ 11 0: 00
8/ 11 12: 00
8/ 12 0: 00
8/ 12 12: 00
8/ 13 0: 00

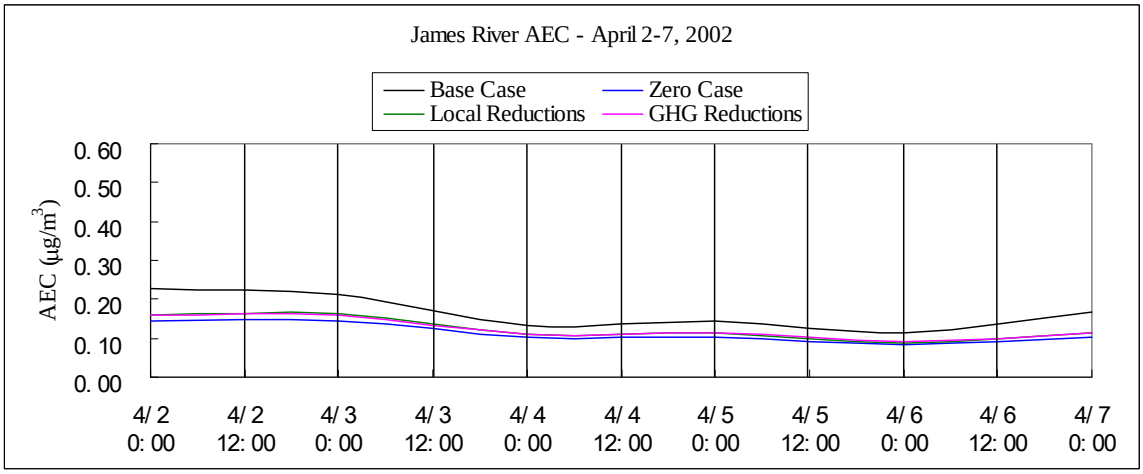

Luray PM2.5 - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
10/ 18 0: 00
10/ 18 12: 00
10/ 19 0: 00
10/ 19 12: 00
10/ 20 0: 00
10/ 20 12: 00
10/ 21 0: 00
10/ 21 12: 00
10/ 22 0: 00
10/ 22 12: 00
10/ 23 0: 00

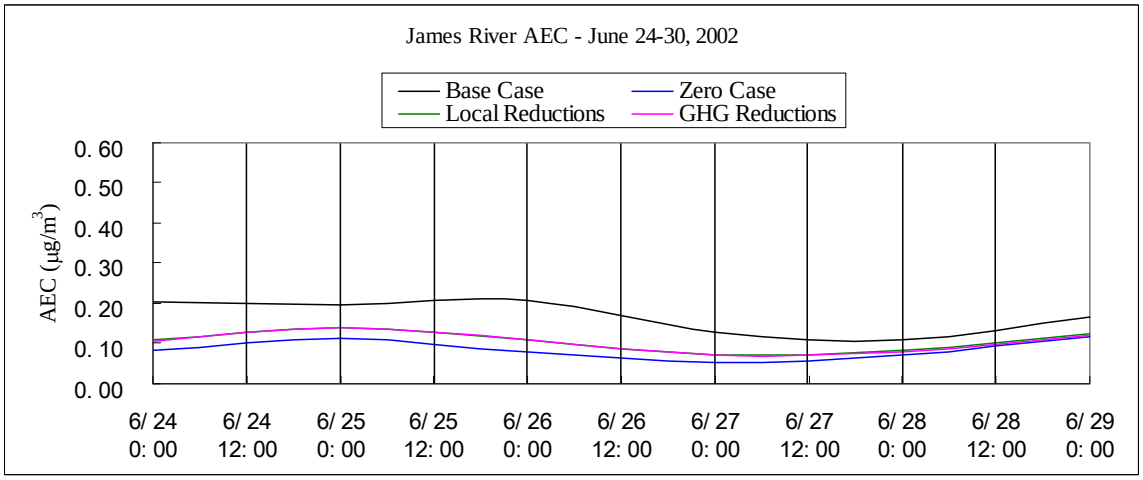

Roanoke PM2.5 - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
10/ 18 0: 00
10/ 18 12: 00
10/ 19 0: 00
10/ 19 12: 00
10/ 20 0: 00
10/ 20 12: 00
10/ 21 0: 00
10/ 21 12: 00
10/ 22 0: 00
10/ 22 12: 00
10/ 23 0: 00

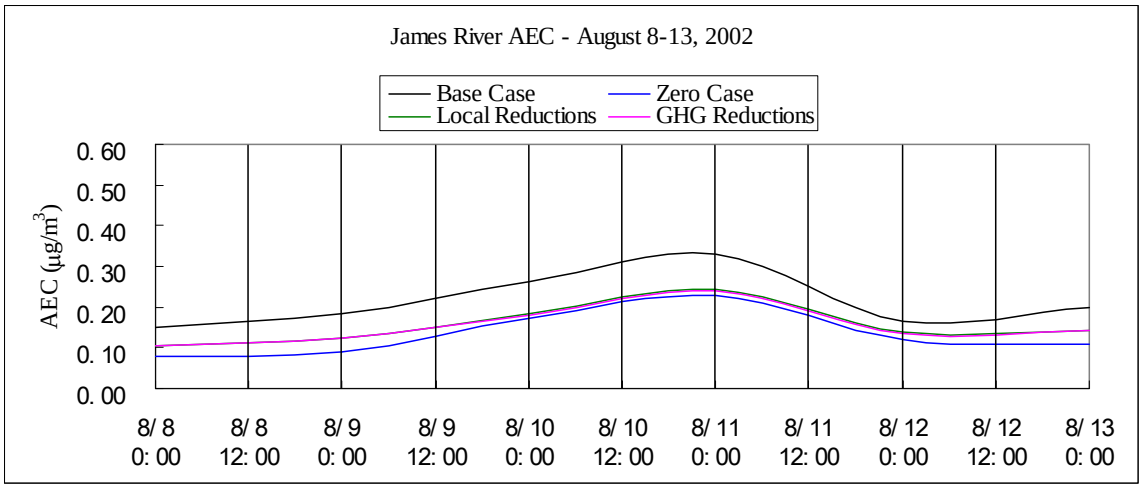

Salem PM2.5 - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
PM2.5 (µg/m3)
25. 00
20. 00
15. 00
10. 00
5. 00
0. 00
10/ 18 0: 00
10/ 18 12: 00
10/ 19 0: 00
10/ 19 12: 00
10/ 20 0: 00
10/ 20 12: 00
10/ 21 0: 00
10/ 21 12: 00
10/ 22 0: 00
10/ 22 12: 00
10/ 23 0: 00

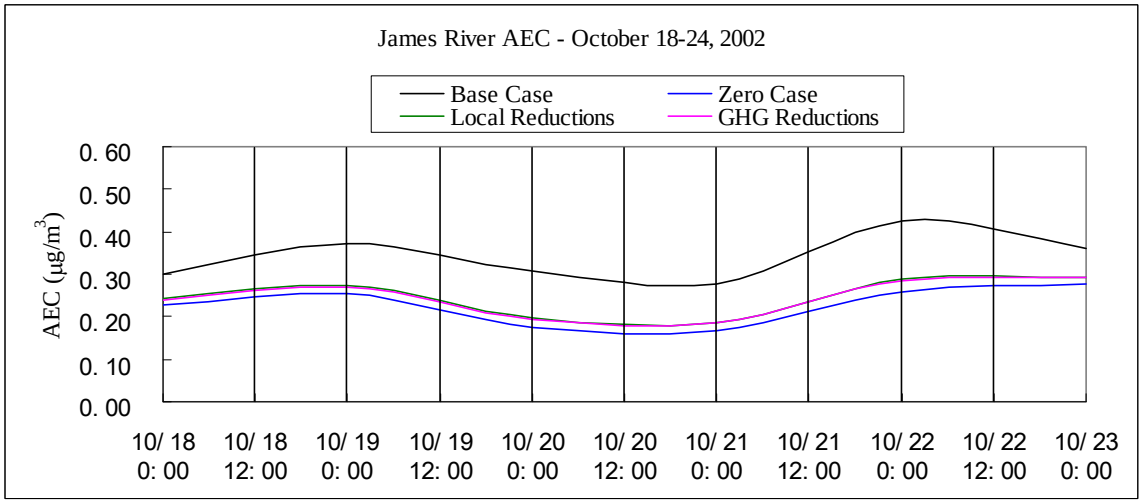
c)


James River AEC - January 16-21, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AEC (µg/m3)
0. 60
0. 50
0. 40
0. 30
0. 20
0. 10
0. 00
1/ 16 0: 00
1/ 16 12: 00
1/ 17 0: 00
1/ 17 12: 00
1/ 18 0: 00
1/ 18 12: 00
1/ 19 0: 00
1/ 19 12: 00
1/ 20 0: 00
1/ 20 12: 00
1/ 21 0: 00

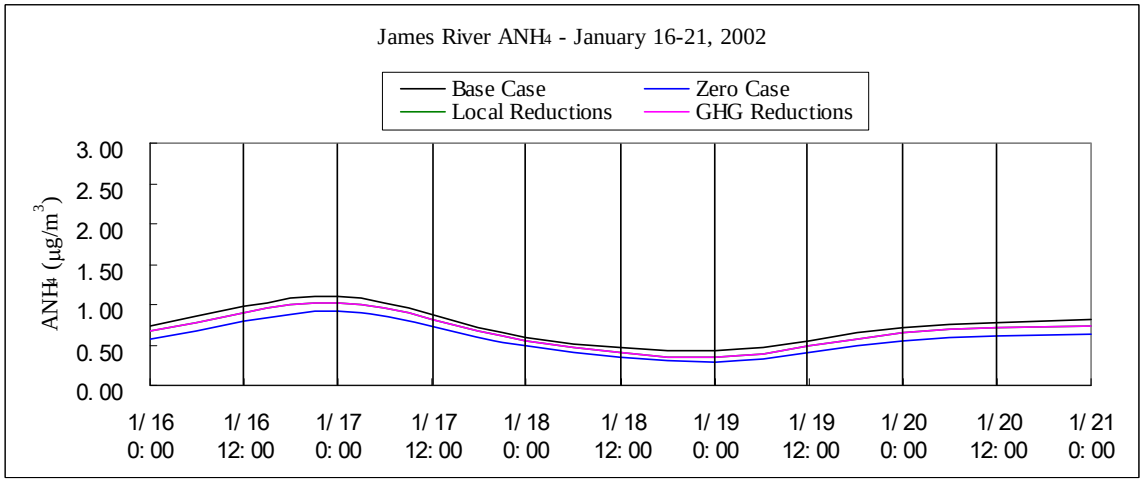

James River AEC - April 2-7, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AEC (µg/m3)
0. 60
0. 50
0. 40
0. 30
0. 20
0. 10
0. 00
4/ 2 0: 00
4/ 2 12: 00
4/ 3 0: 00
4/ 3 12: 00
4/ 4 0: 00
4/ 4 12: 00
4/ 5 0: 00
4/ 5 12: 00
4/ 6 0: 00
4/ 6 12: 00
4/ 7 0: 00

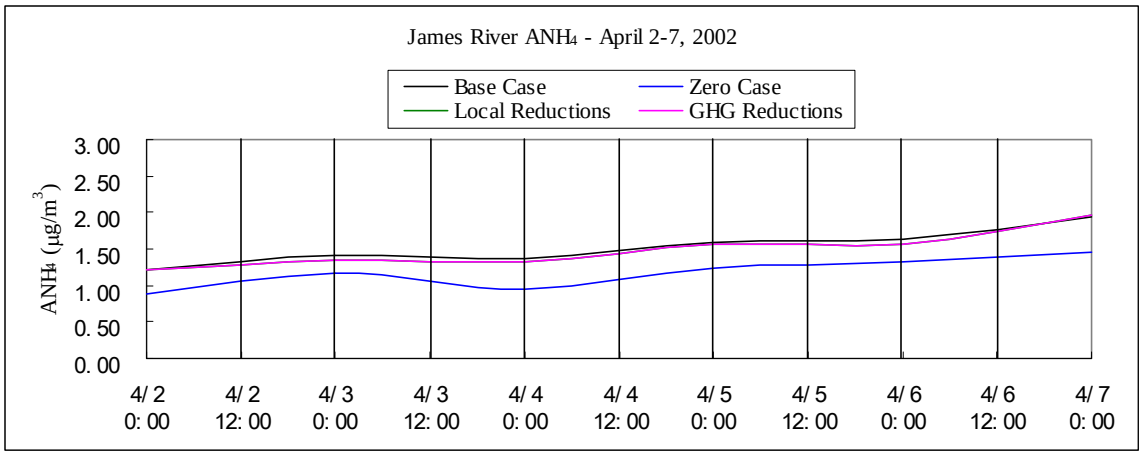

James River AEC - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AEC (µg/m3)
0. 60
0. 50
0. 40
0. 30
0. 20
0. 10
0. 00
6/ 24 0: 00
6/ 24 12: 00
6/ 25 0: 00
6/ 25 12: 00
6/ 26 0: 00
6/ 26 12: 00
6/ 27 0: 00
6/ 27 12: 00
6/ 28 0: 00
6/ 28 12: 00
6/ 29 0: 00

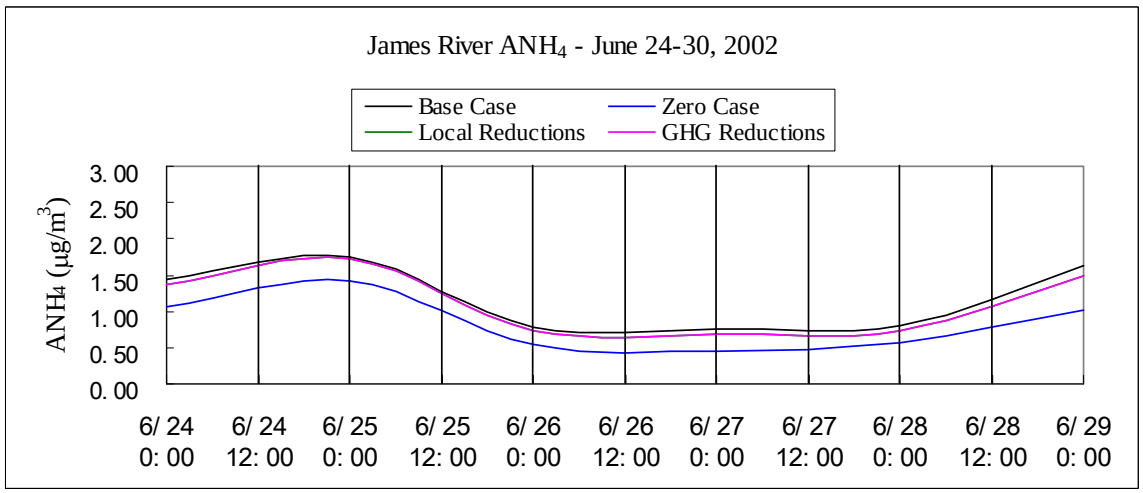

James River AEC - August 8-13, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AEC (µg/m3)
0. 60
0. 50
0. 40
0. 30
0. 20
0. 10
0. 00
8/ 8 0: 00
8/ 8 12: 00
8/ 9 0: 00
8/ 9 12: 00
8/ 10 0: 00
8/ 10 12: 00
8/ 11 0: 00
8/ 11 12: 00
8/ 12 0: 00
8/ 12 12: 00
8/ 13 0: 00

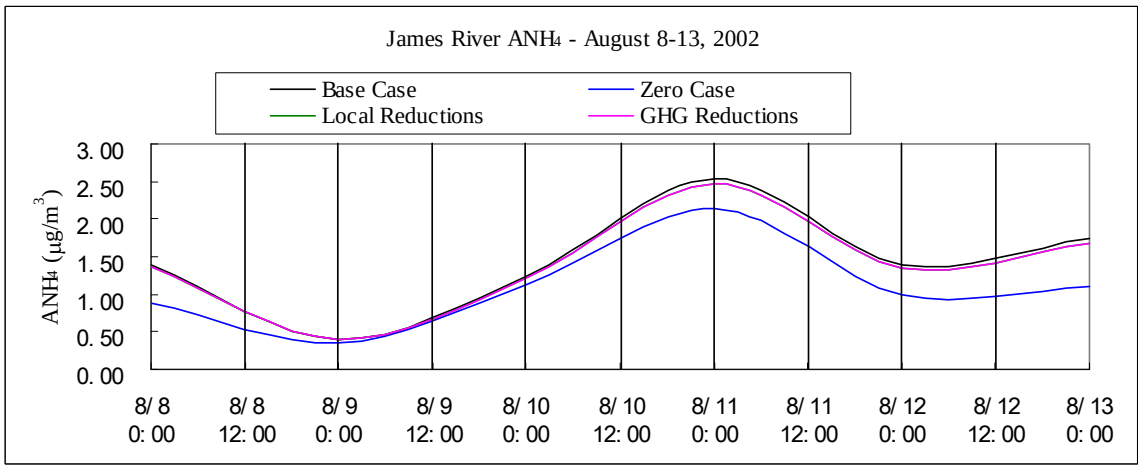

James River AEC - October 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AEC (µg/m3)
0. 60
0. 50
0. 40
0. 30
0. 20
0. 10
0. 00
10/ 18 0: 00
10/ 18 12: 00
10/ 19 0: 00
10/ 19 12: 00
10/ 20 0: 00
10/ 20 12: 00
10/ 21 0: 00
10/ 21 12: 00
10/ 22 0: 00
10/ 22 12: 00
10/ 23 0: 00

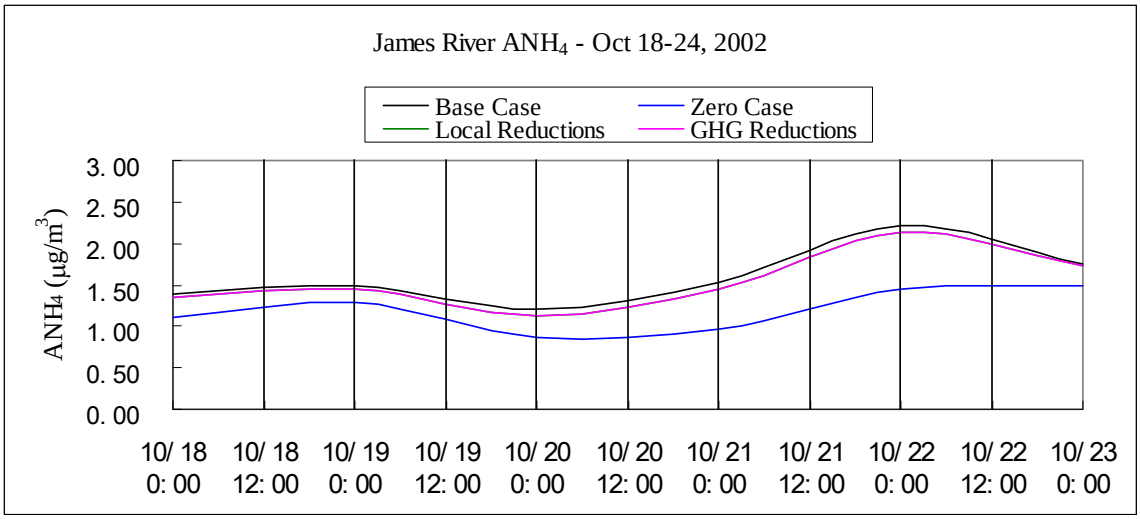
d)


James River ANH4 - January 16-21, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANH4 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
1/ 16 0: 00
1/ 16 12: 00
1/ 17 0: 00
1/ 17 12: 00
1/ 18 0: 00
1/ 18 12: 00
1/ 19 0: 00
1/ 19 12: 00
1/ 20 0: 00
1/ 20 12: 00
1/ 21 0: 00

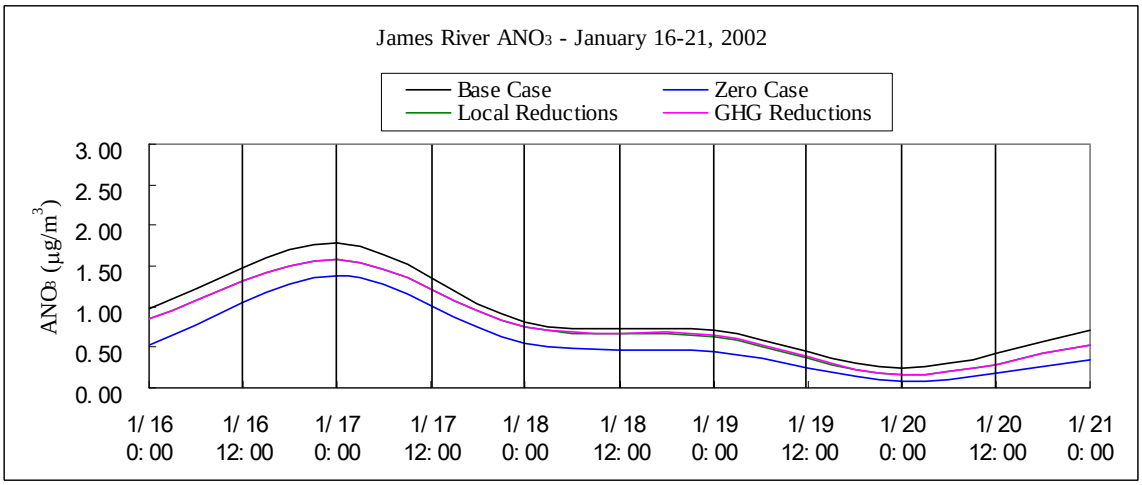

James River ANH4 - April 2-7, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANH4 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
4/ 2 0: 00
4/ 2 12: 00
4/ 3 0: 00
4/ 3 12: 00
4/ 4 0: 00
4/ 4 12: 00
4/ 5 0: 00
4/ 5 12: 00
4/ 6 0: 00
4/ 6 12: 00
4/ 7 0: 00

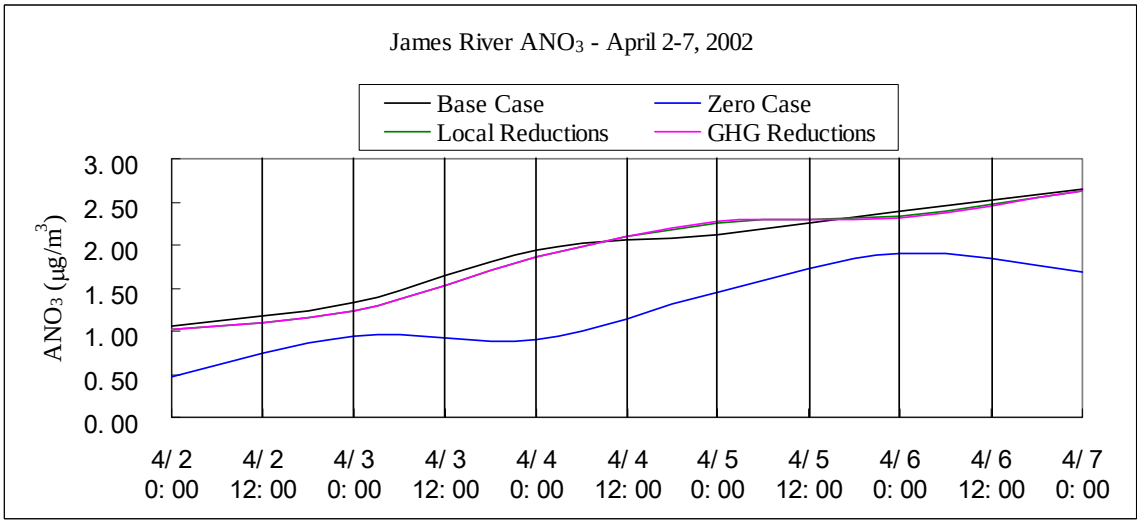

James River ANH4 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANH4 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
6/ 24 0: 00
6/ 24 12: 00
6/ 25 0: 00
6/ 25 12: 00
6/ 26 0: 00
6/ 26 12: 00
6/ 27 0: 00
6/ 27 12: 00
6/ 28 0: 00
6/ 28 12: 00
6/ 29 0: 00

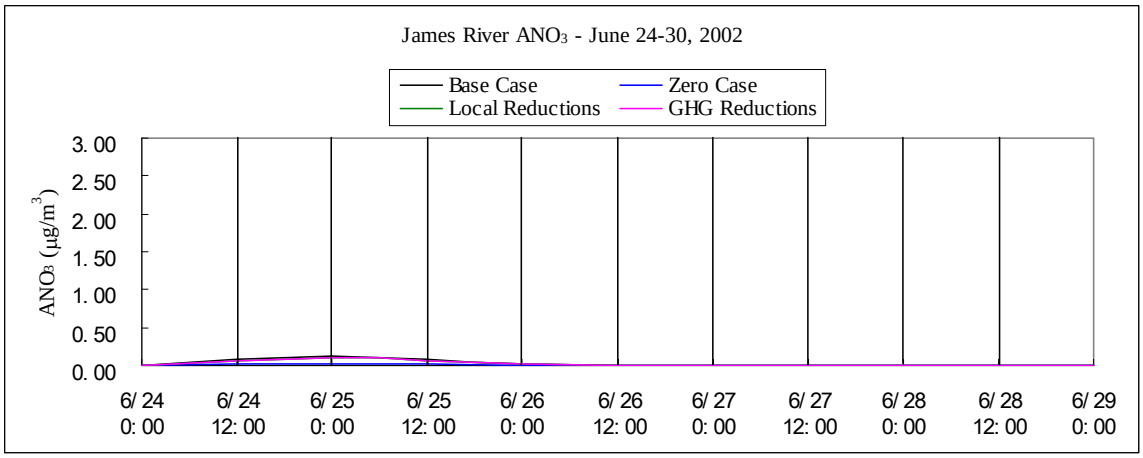

James River ANH4 - August 8-13, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANH4 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
8/ 8 0: 00
8/ 8 12: 00
8/ 9 0: 00
8/ 9 12: 00
8/ 10 0: 00
8/ 10 12: 00
8/ 11 0: 00
8/ 11 12: 00
8/ 12 0: 00
8/ 12 12: 00
8/ 13 0: 00

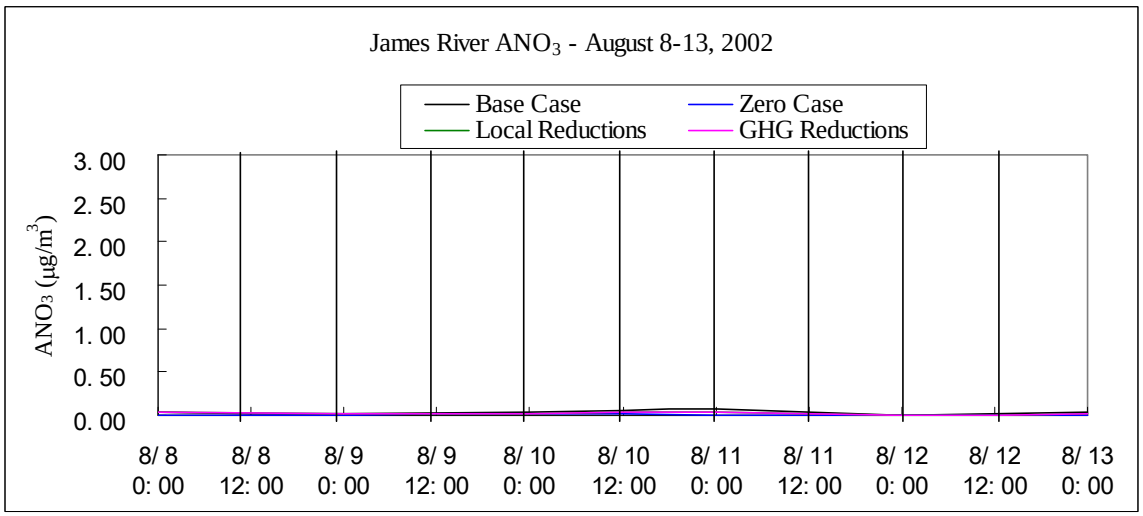

James River ANH4 - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANH4 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
10/ 18 0: 00
10/ 18 12: 00
10/ 19 0: 00
10/ 19 12: 00
10/ 20 0: 00
10/ 20 12: 00
10/ 21 0: 00
10/ 21 12: 00
10/ 22 0: 00
10/ 22 12: 00
10/ 23 0: 00

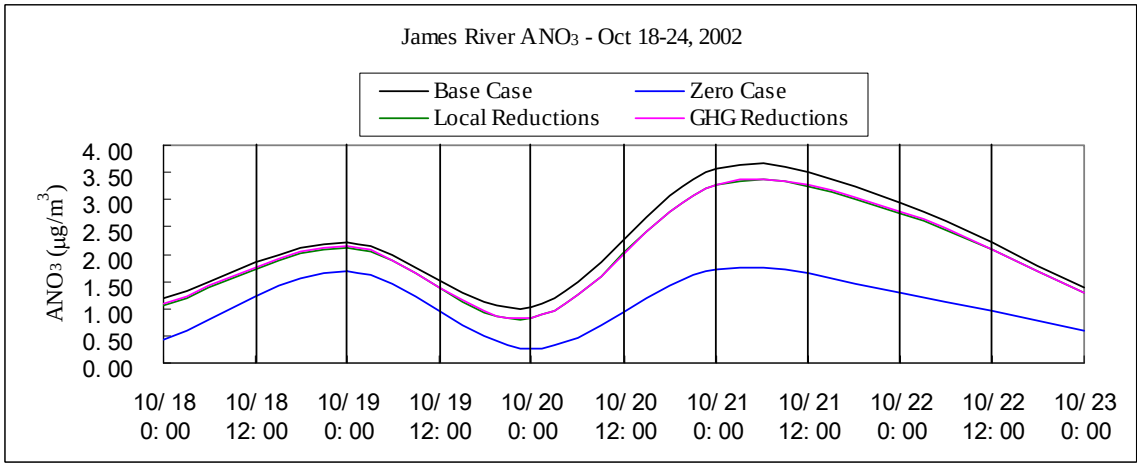
e)


James River ANO3 - January 16-21, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANO3 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
1/ 16 0: 00
1/ 16 12: 00
1/ 17 0: 00
1/ 17 12: 00
1/ 18 0: 00
1/ 18 12: 00
1/ 19 0: 00
1/ 19 12: 00
1/ 20 0: 00
1/ 20 12: 00
1/ 21 0: 00

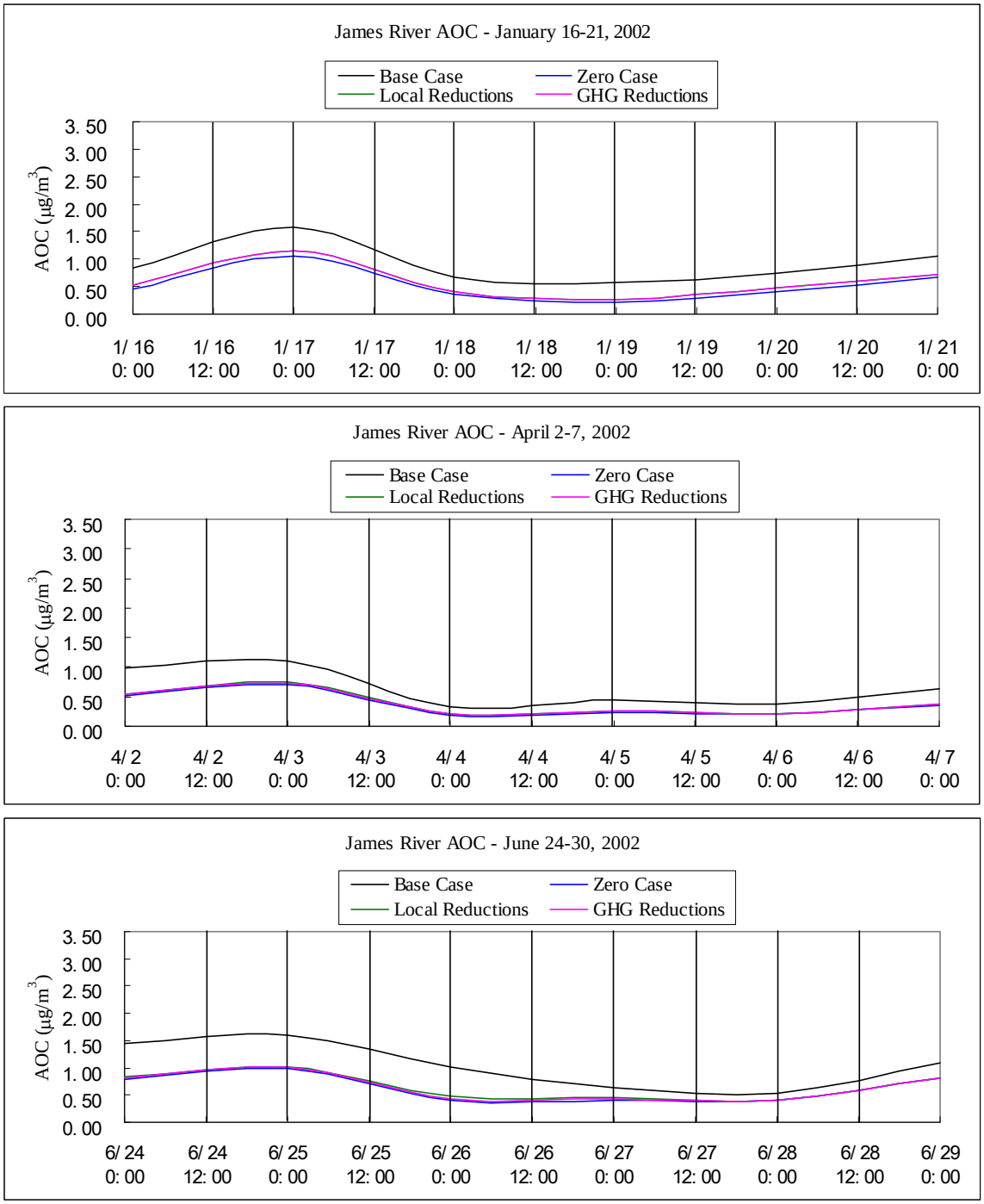

James River ANO3 - April 2-7, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANO3 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
4/ 2 0: 00
4/ 2 12: 00
4/ 3 0: 00
4/ 3 12: 00
4/ 4 0: 00
4/ 4 12: 00
4/ 5 0: 00
4/ 5 12: 00
4/ 6 0: 00
4/ 6 12: 00
4/ 7 0: 00

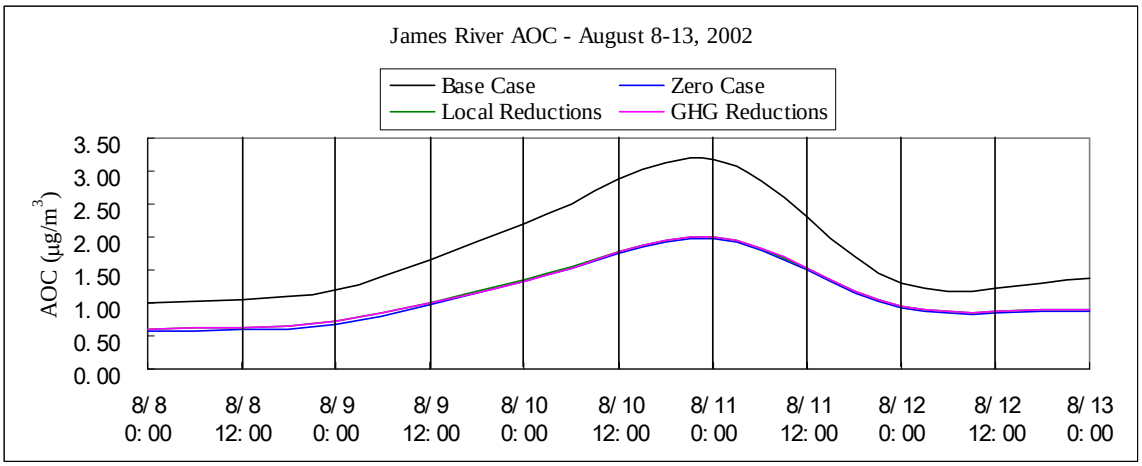

James River ANO3 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANO3 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
6/ 24 0: 00
6/ 24 12: 00
6/ 25 0: 00
6/ 25 12: 00
6/ 26 0: 00
6/ 26 12: 00
6/ 27 0: 00
6/ 27 12: 00
6/ 28 0: 00
6/ 28 12: 00
6/ 29 0: 00

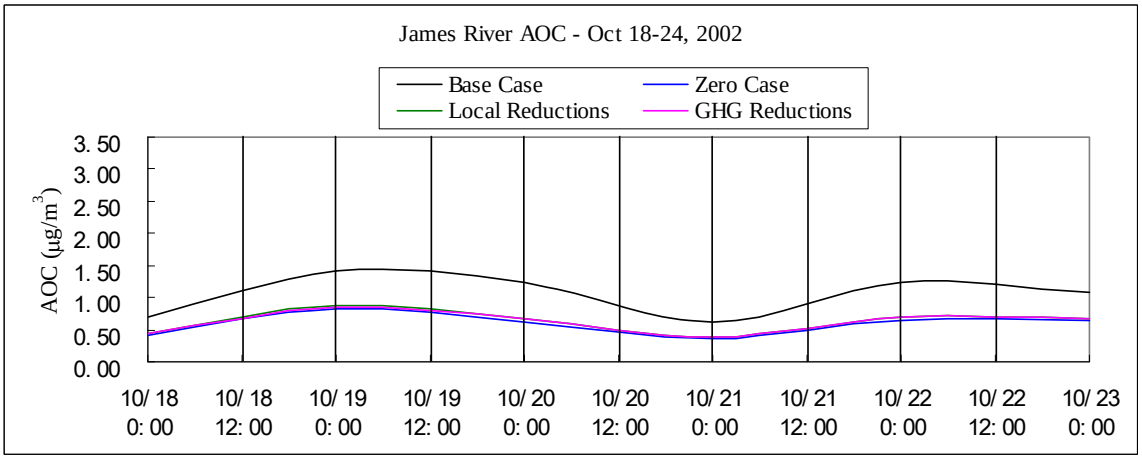

James River ANO3 - August 8-13, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANO3 (µg/m3)
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
8/ 8 0: 00
8/ 8 12: 00
8/ 9 0: 00
8/ 9 12: 00
8/ 10 0: 00
8/ 10 12: 00
8/ 11 0: 00
8/ 11 12: 00
8/ 12 0: 00
8/ 12 12: 00
8/ 13 0: 00


James River ANO3 - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ANO3 (µg/m3)
4. 00
3. 50
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
10/ 18 0: 00
10/ 18 12: 00
10/ 19 0: 00
10/ 19 12: 00
10/ 20 0: 00
10/ 20 12: 00
10/ 21 0: 00
10/ 21 12: 00
10/ 22 0: 00
10/ 22 12: 00
10/ 23 0: 00

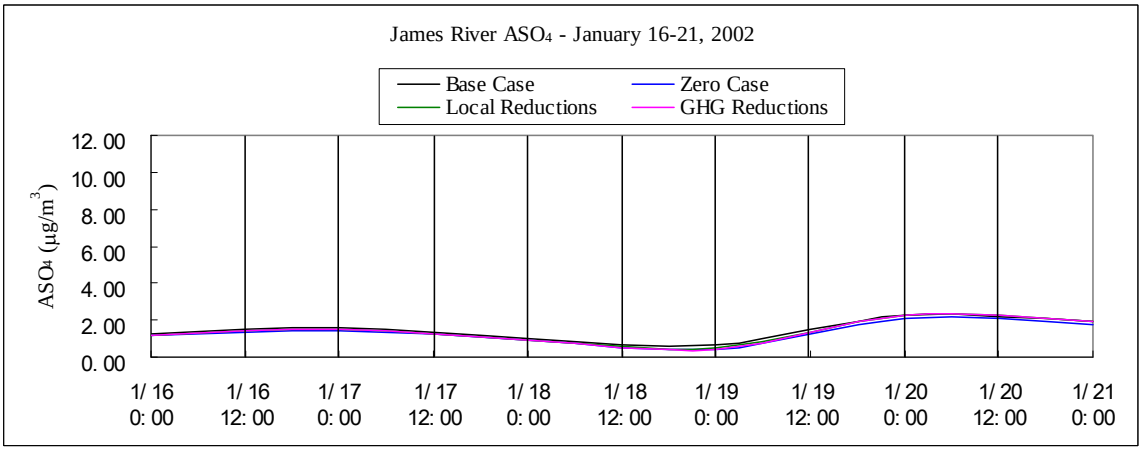
f)

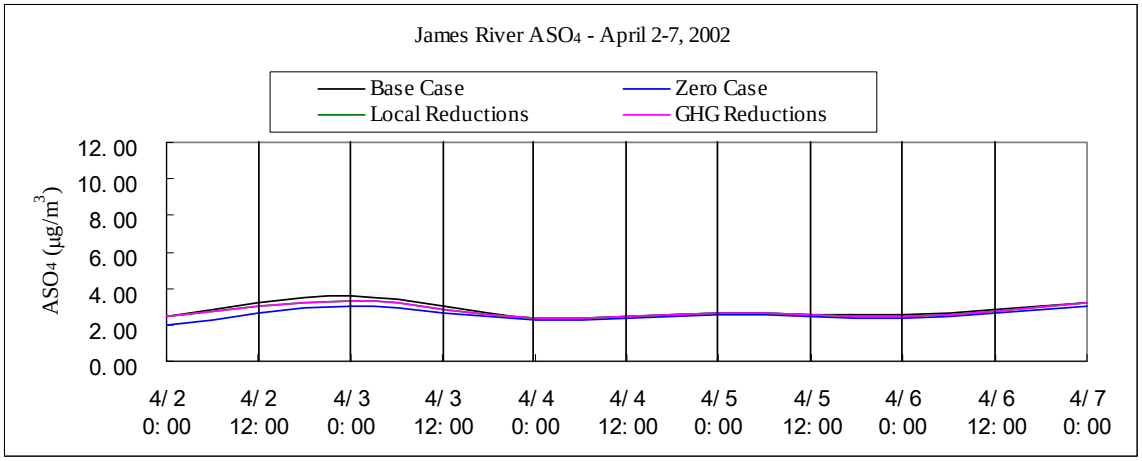

James River AOC - January 16-21, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AOC (µg/m3)
3. 50
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
1/ 16 0: 00
1/ 16 12: 00
1/ 17 0: 00
1/ 17 12: 00
1/ 18 0: 00
1/ 18 12: 00
1/ 19 0: 00
1/ 19 12: 00
1/ 20 0: 00
1/ 20 12: 00
1/ 21 0: 00
James River AOC - April 2-7, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AOC (µg/m3)
3. 50
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
4/ 2 0: 00
4/ 2 12: 00
4/ 3 0: 00
4/ 3 12: 00
4/ 4 0: 00
4/ 4 12: 00
4/ 5 0: 00
4/ 5 12: 00
4/ 6 0: 00
4/ 6 12: 00
4/ 7 0: 00
James River AOC - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AOC (µg/m3)
3. 50
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
6/ 24 0: 00
6/ 24 12: 00
6/ 25 0: 00
6/ 25 12: 00
6/ 26 0: 00
6/ 26 12: 00
6/ 27 0: 00
6/ 27 12: 00
6/ 28 0: 00
6/ 28 12: 00
6/ 29 0: 00

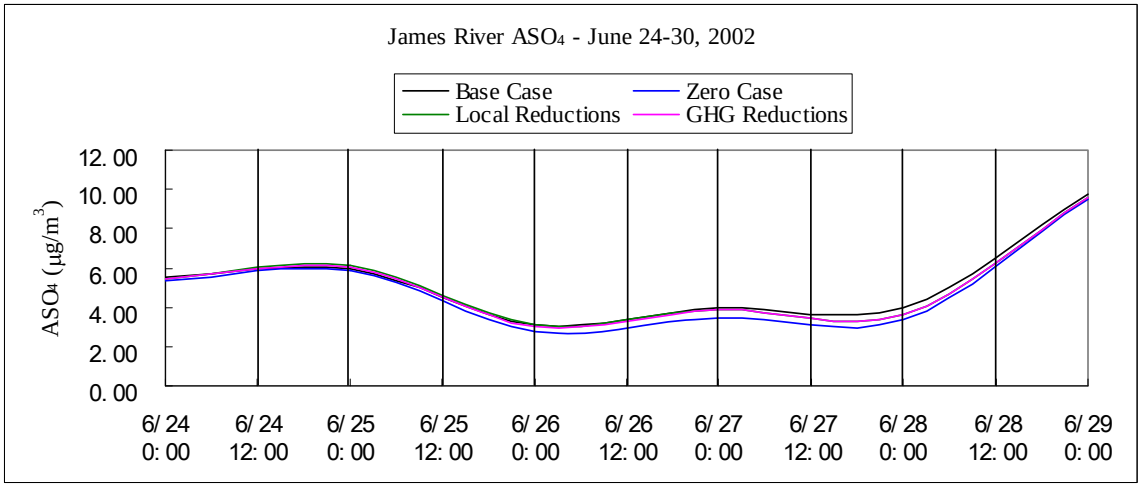

James River AOC - August 8-13, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AOC (µg/m3)
3. 50
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
8/ 8 0: 00
8/ 8 12: 00
8/ 9 0: 00
8/ 9 12: 00
8/ 10 0: 00
8/ 10 12: 00
8/ 11 0: 00
8/ 11 12: 00
8/ 12 0: 00
8/ 12 12: 00
8/ 13 0: 00

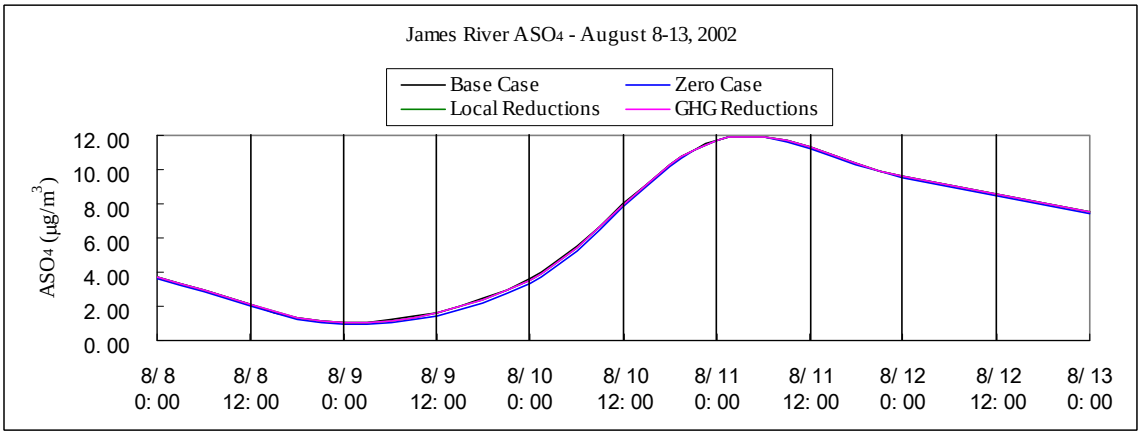

James River AOC - Oct 18-24, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
AOC (µg/m3)
3. 50
3. 00
2. 50
2. 00
1. 50
1. 00
0. 50
0. 00
10/ 18 0: 00
10/ 18 12: 00
10/ 19 0: 00
10/ 19 12: 00
10/ 20 0: 00
10/ 20 12: 00
10/ 21 0: 00
10/ 21 12: 00
10/ 22 0: 00
10/ 22 12: 00
10/ 23 0: 00

g)


James River ASO4 - January 16-21, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ASO4 (µg/m3)
12. 00
10. 00
8. 00
6. 00
4. 00
2. 00
0. 00
1/ 16 0: 00
1/ 16 12: 00
1/ 17 0: 00
1/ 17 12: 00
1/ 18 0: 00
1/ 18 12: 00
1/ 19 0: 00
1/ 19 12: 00
1/ 20 0: 00
1/ 20 12: 00
1/ 21 0: 00


James River ASO4 - April 2-7, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ASO4 (µg/m3)
12. 00
10. 00
8. 00
6. 00
4. 00
2. 00
0. 00
4/ 2 0: 00
4/ 2 12: 00
4/ 3 0: 00
4/ 3 12: 00
4/ 4 0: 00
4/ 4 12: 00
4/ 5 0: 00
4/ 5 12: 00
4/ 6 0: 00
4/ 6 12: 00
4/ 7 0: 00


James River ASO4 - June 24-30, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ASO4 (µg/m3)
12. 00
10. 00
8. 00
6. 00
4. 00
2. 00
0. 00
6/ 24 0: 00
6/ 24 12: 00
6/ 25 0: 00
6/ 25 12: 00
6/ 26 0: 00
6/ 26 12: 00
6/ 27 0: 00
6/ 27 12: 00
6/ 28 0: 00
6/ 28 12: 00
6/ 29 0: 00


James River ASO4 - August 8-13, 2002
Base Case
Zero Case
Local Reductions
GHG Reductions
ASO4 (µg/m3)
12. 00
10. 00
8. 00
6. 00
4. 00
2. 00
0. 00
8/ 8 0: 00
8/ 8 12: 00
8/ 9 0: 00
8/ 9 12: 00
8/ 10 0: 00
8/ 10 12: 00
8/ 11 0: 00
8/ 11 12: 00
8/ 12 0: 00
8/ 12 12: 00
8/ 13 0: 00

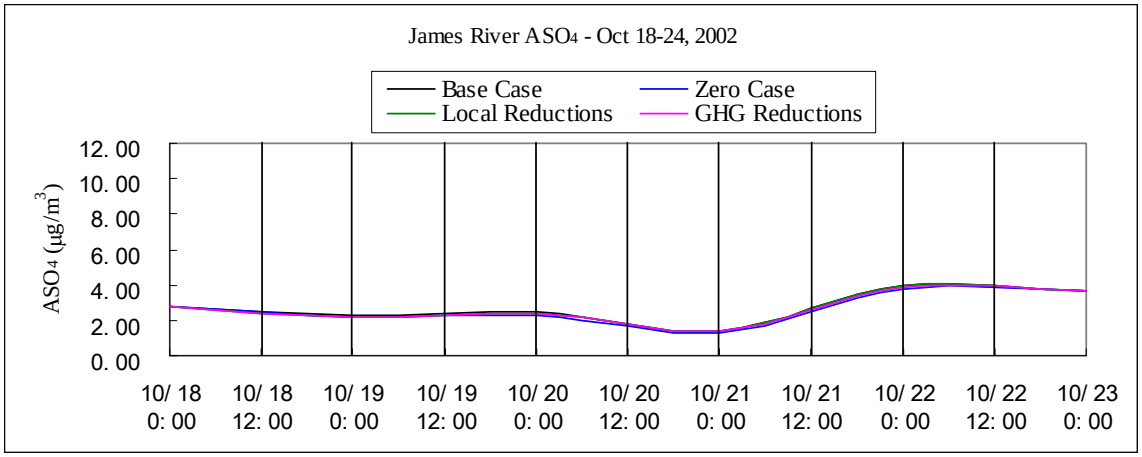


Figure 3.9: Time series plots of modeled concentrations. Plots are for a) O_3, b) $PM_{2.5}$, and various $PM_{2.5}$ constituents: c) AEC, d) ANH_4, e) ANO_3, f) AOC, and g) ASO_4.

3.7 Air Mass Trajectories

Back trajectories from the Shenandoah Valley can help identify the source areas of some of its air pollution. Such an analysis is especially important for O_3 as it originated more from regional transport than local sources. Air mass trajectories were generated using HYSPLIT by the University of Virginia (UVA). The researchers found that in the valley there was a strong correlation between O_3 concentrations and SSC combined with air mass trajectories [50]. For afternoon O_3 concentrations at various locations for different SSC types, concentrations were highest on dry tropical days followed by moist tropical days [50]. This was consistent with our findings relating O_3 concentrations and SSC type. Certain back trajectories led to higher O_3 levels while others led less O_3 and O_3 precursors. Generally, trajectories from the west and northwest led to elevated levels of O_3 while those from the south and southwest led to lower O_3 concentrations [50].

3.8 Conclusions

In this study we created scenarios with alternative emissions to distinguish between the impacts of locally emitted versus regionally transported air pollution and to predict how local air quality control policies would affect ambient air quality. We first verified our model output by comparing it with the benchmark model created by VISTAS and with measured pollutant concentrations. We found that our model compared well with the VISTAS benchmark. Compared with measured data there were differences but they were within reasonable limits. Limitations associated with representing a single point measurement by a 12 km × 12 km grid cell prediction mean that some differences between modeled and measured data are expected.

In the Zero Case model in which anthropogenic emissions were zeroed, $PM_{2.5}$ concentrations fell significantly, but O_3 concentrations did not. This result implies that local emissions were largely responsible for $PM_{2.5}$ in the valley but that O_3 must be more regional in nature. The Local Reductions and GHG Reductions Cases considered policies being adopted or being considered by local governments across the valley region. The Local Reductions Case was a conglomeration of nine policies aimed at reducing criteria pollutant concentrations in the valley while the GHG Reductions Case merged ten policies local governments could adopt to reduce their carbon footprint. Some of the policies in both cases overlapped. Both these cases had similar results with the GHG Reductions case predicting slightly larger reductions in $PM_{2.5}$ concentrations in the southern region of the valley in some cases. As with the Zero Case $PM_{2.5}$ concentrations fell in both cases, though not as much as they did in the Zero Case, but O_3 concentrations were constant or increased.

An overall theme repeated in the results from different scenarios was that $PM_{2.5}$ in the Shenandoah Valley can be controlled through local actions, though not eliminated, while O_3 cannot. VOC emissions are hard to control since biogenic sources emit over half of them. Similarly NO_x emissions may also be hard to control since mobile sources represent the majority of its emissions, and a busy interstate highway runs through the valley. Since much of the traffic on this highway is commercial and represents businesses outside the valley, emissions reductions will require statewide or national actions.

Further research is still necessary to corroborate the themes we found. There may be certain emissions policies that we overlooked that may in fact reduce O_3 in the valley. Further cooperation between SHENAIR's technical team and policy team will be necessary to pinpoint the best strategies for air quality in the Shenandoah Valley. Also expanding SHENAIR or focusing on a scale that encompasses a larger geographic region may be necessary for the valley to achieve the decrease in air pollution concentrations it desires.

4. Conclusions

In our research we first evaluated air pollutant emissions in the Shenandoah Valley region. We categorized emissions of seven pollutants into 14 source categories. Windblown dust, agriculture, and fuel combustion were primarily responsible for $PM_{2.5}$ emissions while both on-road and off-road mobile sources also contributed a significant amount. Emissions of VOCs, an O_3 precursor, were dominated by biogenic sources, the only non-anthropogenic source category. Mobile sources, particularly on-road vehicles, were responsible for an overwhelming share of NO_x emissions, the other O_3 precursors. Mobile sources were also the primary anthropogenic emitters of VOCs.

We then modeled ambient air pollution concentrations in the valley using a three-dimensional chemical transport model, CMAQ. We first compared or model output with the benchmark model created by VISTAS and with measured pollutant concentrations from VDEQ monitoring sites. We found that our model compared well with the VISTAS benchmark. Compared with measured data there were differences but they were within reasonable limits. Limitations associated with representing a single point measurement by a 12 km × 12 km grid cell prediction mean that some differences between modeled and measured data are expected.

We proceeded to create a Base Case model which reflected pollutant concentrations in the Shenandoah Valley in 2002 based on the VISTAS emissions inventories. The Base Case served as the basis for which we compared alternative emissions scenarios. Focusing on O_3 and $PM_{2.5}$, the two most troublesome pollutants in the valley region, we created a Zero Case, a Local Reductions Case, and a Greenhouse Gas Reductions Case. For the Zero Case we set anthropogenic emissions within the valley to zero to determine how much transported pollution and biogenic emissions were responsible for valley air pollution. We found that while $PM_{2.5}$ concentrations fell, O_3 concentrations did not and in fact, increased at times. This was evidence that local emissions were largely responsible for $PM_{2.5}$ in the valley but that O_3 must be more regional in nature. Turning to the Local Reductions and GHG Reductions Cases we modeled two different scenarios which took into account policies being adopted or being considered by local governments across the valley region. The Local Reductions Case was a conglomeration of nine policies aimed at reducing criteria pollutant concentrations in the valley while the GHG Reductions Case merged ten policies local governments could adopt to reduce their carbon footprint. Some of the policies in both cases overlapped. We found that both these cases had similar results with the GHG Reductions case predicting slightly larger reductions in $PM_{2.5}$ concentrations in the southern region of the valley in some cases. As with the Zero Case $PM_{2.5}$

concentrations fell in both cases, though not as much as they did in the Zero Case, but O_3 concentrations were constant or increased.

An overall theme we repeatedly saw was that $PM_{2.5}$ in the Shenandoah Valley can be controlled through local actions, though not eliminated, while O_3 cannot. VOC emissions are hard to control since biogenic sources emit over half of them. Similarly NO_x emissions may also be hard to control since mobile sources represent the majority of its emissions and a busy interstate highway runs through the valley. Since much of the traffic on this highway is commercial and represents businesses outside the valley, emissions reductions will require statewide or national actions.

Further research is still necessary to corroborate the themes we found. There may be certain emissions policies that we overlooked that may in fact reduce O_3 in the valley. Further cooperation between SHENAIR's technical team and policy team will be necessary to pinpoint the best strategies for air quality in the Shenandoah Valley. Also expanding SHENAIR or focusing on a scale that encompasses a larger geographic region may be necessary for the valley to achieve the decrease in air pollution concentrations it desires.

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Appendix A

Tons of pollutants emitted in each city, county or state by source type:

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Elec. Util.	747	85,080	6,796	233,690	3,892	2,649	130
Fuel Comb. Industrial	5,329	75,803	64,382	137,447	18,479	8,453	100
Fuel Comb. Other	54,490	15,642	98,781	5,507	11,572	11,235	13
Chemical & Allied Product Mfg	1,529	8,061	320	2,126	449	392	2,157
Metals Processing	513	936	3,579	5,251	1,575	1,349	0
Petroleum & Related Industries	500	182	23,384	170	254	152	0
Other Industrial Processes	13,085	9,279	12,001	17,702	13,060	5,725	725
Solvent Utilization	111,499	0	0	2	225	210	4
Storage & Transport	26,118	11	16	0	745	504	6
Waste Disposal & Recycling	4,062	1,864	16,564	1,581	3,152	1,276	108
Highway Vehicles	157,988	219,835	2,136,287	8,195	4,498	3,066	7,769
Off-highway	74,865	63,219	660,105	8,662	8,727	8,287	47
Biogenic	582,342	6,411	0	0	0	0	0
Miscellaneous	1,322	565	26,333	151	47,113	7,372	43,992
Virginia State Totals	***1,034,395***	***486,893***	***3,048,555***	***420,489***	***113,746***	***50,678***	***55,056***

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Elec. Util.	1,140	222,437	10,117	500,381	4,472	2,162	121
Fuel Comb. Industrial	1,097	33,831	8,684	37,118	1,583	1,332	97
Fuel Comb. Other	9,272	15,217	29,477	3,987	3,811	3,680	13
Chemical & Allied Product Mfg	5,755	1,626	50,834	9,052	949	830	79
Metals Processing	1,393	1,569	28,836	5,619	8,748	7,515	142
Petroleum & Related Industries	2,163	1,085	1	7,549	475	475	0
Other Industrial Processes	1,802	5,347	2,002	2,315	6,279	3,073	55
Solvent Utilization	35,989	18	15	0	48	44	0
Storage & Transport	12,431	3	14	0	1,951	947	0
Waste Disposal & Recycling	5,097	599	9,395	99	4,152	3,731	7
Highway Vehicles	41,703	58,339	526,841	2,437	1,366	983	1,888
Off-highway	18,566	33,239	133,113	2,111	1,850	1,728	9
Biogenic	269,751	2,188	0	0	0	0	0
Miscellaneous	351	149	6,943	39	13,575	2,071	9,923
West Virginia State Totals	***406,515***	***375,652***	***806,278***	***570,712***	***49,264***	***28,575***	***12,340***

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Industrial	11	401	132	312	26	22	3
Fuel Comb. Other	242	103	892	120	126	123	0
Other Industrial Processes	166	3,331	157	1,610	402	201	36
Solvent Utilization	1,383	0	0	0	0	0	0
Storage & Transport	297	0	0	0	232	93	0
Waste Disposal & Recycling	156	27	442	4	204	174	0
Highway Vehicles	1,904	3,305	24,996	127	77	57	87
Off-highway	441	1,338	3,890	101	69	65	0
Biogenic	3,586	53	0	0	0	0	0
Miscellaneous	2	0	39	0	1,508	186	185
Berkeley County	***8,191***	***8,562***	***30,550***	***2,277***	***2,649***	***926***	***313***
	5.88%	*13.50%*	*6.97%*	*7.72%*	*13.23%*	*11.82%*	*1.51%*

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Industrial	1	124	33	273	3	2	0
Fuel Comb. Other	151	53	548	94	80	77	0
Other Industrial Processes	2	0	0	1	110	22	0
Solvent Utilization	722	0	0	0	0	0	0
Storage & Transport	157	0	0	0	0	0	0
Waste Disposal & Recycling	95	17	284	2	119	110	0
Highway Vehicles	791	927	9,868	43	22	15	36
Off-highway	428	1,738	2,972	127	79	74	0
Biogenic	1,308	68	0	0	0	0	0
Miscellaneous	0	0	3	0	1,585	197	325
Jefferson County	***3,658***	***2,929***	***13,710***	***541***	***2,001***	***500***	***363***
	2.63%	*4.62%*	*3.13%*	*1.84%*	*10.00%*	*6.38%*	*1.75%*

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Elec. Util.	0	6	1	10	0	0	0
Fuel Comb. Industrial	37	571	643	1,466	219	81	0
Fuel Comb. Other	805	95	1,409	17	122	120	0
Petroleum & Related Industries	3	1	1	4	28	6	0
Other Industrial Processes	708	203	4	263	143	62	0
Solvent Utilization	1,363	0	0	0	0	0	0
Storage & Transport	593	0	0	0	5	1	0
Waste Disposal & Recycling	24	13	66	7	50	20	0
Highway Vehicles	2,532	4,583	35,739	136	85	64	93

Off-highway	2,228	974	29,142	101	134	127	1
Biogenic	6,343	48	0	0	0	0	0
Miscellaneous	7	3	161	0	842	107	327
Frederick County	***14,647***	***6,502***	***67,170***	***2,009***	***1,632***	***590***	***422***
	10.52%	*10.25%*	*15.32%*	*6.81%*	*8.15%*	*7.53%*	*2.03%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	42	616	735	1,634	245	91	0
Fuel Comb. Other	310	81	554	28	42	41	0
Other Industrial Processes	33	0	0	0	23	15	0
Solvent Utilization	926	0	0	0	0	0	0
Storage & Transport	90	0	0	0	0	0	0
Waste Disposal & Recycling	15	6	28	5	25	8	0
Highway Vehicles	513	363	5,100	14	6	4	14
Off-highway	102	187	1,566	16	10	9	0
Biogenic	893	14	0	0	0	0	0
Miscellaneous	0	0	2	0	92	11	3
Winchester City	***2,927***	***1,268***	***7,986***	***1,700***	***445***	***182***	***18***
	2.10%	*2.00%*	*1.82%*	*5.77%*	*2.22%*	*2.32%*	*0.09%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	8	124	149	341	50	18	0
Fuel Comb. Other	164	21	289	4	33	33	0
Other Industrial Processes	1	0	0	0	100	20	0
Solvent Utilization	270	0	0	0	0	0	0
Storage & Transport	93	0	0	0	0	0	0
Waste Disposal & Recycling	4	1	9	1	9	4	0
Highway Vehicles	538	821	7,821	33	18	13	26
Off-highway	178	204	1,673	32	23	22	0
Biogenic	1,777	53	0	0	0	0	0
Miscellaneous	0	0	11	0	433	55	268
Clarke County	***3,037***	***1,227***	***9,954***	***412***	***669***	***167***	***294***
	2.18%	*1.93%*	*2.27%*	*1.40%*	*3.34%*	*2.13%*	*1.42%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	45	573	657	1,400	213	81	1
Fuel Comb. Other	463	77	825	12	100	99	0
Metals Processing	0	0	0	0	9	9	0
Other Industrial Processes	11	279	235	2	237	82	0

Solvent Utilization	1,079	0	0	0	5	4	0
Storage & Transport	513	0	0	0	17	5	0
Waste Disposal & Recycling	18	6	29	5	29	13	0
Highway Vehicles	1,474	2,671	22,901	91	50	36	72
Off-highway	299	344	2,239	38	35	33	0
Biogenic	8,215	82	0	0	0	0	0
Miscellaneous	5	1	90	0	534	73	1,724
Shenandoah County	***12,125***	***4,037***	***26,979***	***1,550***	***1,233***	***440***	***1,798***
	8.71%	*6.37%*	*6.15%*	*5.26%*	*6.16%*	*5.61%*	*8.66%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	7	102	122	260	39	15	0
Fuel Comb. Other	423	55	742	11	75	74	0
Chemical & Allied Product Mfg	90	0	0	0	0	0	0
Other Industrial Processes	16	2	31	0	69	22	0
Solvent Utilization	406	0	0	0	0	0	0
Storage & Transport	124	0	0	0	0	0	0
Waste Disposal & Recycling	9	3	15	2	13	6	0
Highway Vehicles	822	1,299	11,766	48	27	19	38
Off-highway	324	285	2,175	50	35	33	0
Biogenic	4,631	35	0	0	0	0	0
Miscellaneous	2	0	31	0	198	24	96
Warren County	***6,859***	***1,785***	***14,885***	***374***	***460***	***196***	***135***
	4.93%	*2.81%*	*3.40%*	*1.27%*	*2.30%*	*2.50%*	*0.65%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	16	251	283	655	97	36	0
Fuel Comb. Other	304	53	543	6	62	61	0
Other Industrial Processes	3	0	0	0	53	10	0
Solvent Utilization	337	0	0	0	0	0	0
Storage & Transport	93	0	0	0	0	0	0
Waste Disposal & Recycling	11	3	17	2	17	8	0
Highway Vehicles	398	527	5,053	22	12	8	17
Off-highway	387	198	3,710	24	25	23	0
Biogenic	4,342	61	0	0	0	0	0
Miscellaneous	202	92	4,295	25	701	393	2,799
Page County	***6,097***	***1,187***	***13,903***	***737***	***969***	***542***	***2,817***
	4.38%	*1.87%*	*3.17%*	*2.50%*	*4.84%*	*6.92%*	*13.57%*

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Elec. Util.	0	0	0	4	0	0	0
Fuel Comb. Industrial	90	1,084	1,271	2,859	416	159	2
Fuel Comb. Other	904	120	1,592	24	154	152	0
Petroleum & Related Industries	0	6	0	21	0	0	0
Other Industrial Processes	105	2	0	0	131	43	3
Solvent Utilization	1,313	0	0	0	0	0	0
Storage & Transport	173	0	0	0	21	3	0
Waste Disposal & Recycling	36	12	56	9	54	23	0
Highway Vehicles	1,936	3,079	27,917	116	64	46	92
Off-highway	426	638	3,785	74	64	61	0
Biogenic	9,332	122	0	0	0	0	0
Miscellaneous	33	14	696	4	1,549	258	9,393
Rockingham County	***14,352***	***5,082***	***35,321***	***3,115***	***2,458***	***748***	***9,491***
	10.31%	*8.01%*	*8.06%*	*10.57%*	*12.28%*	*9.54%*	*45.71%*

Fuel Comb. Industrial	39	545	682	1,498	223	82	0
Fuel Comb. Other	554	116	987	31	42	41	0
Chemical & Allied Product Mfg	18	0	0	0	2	1	0
Other Industrial Processes	6	0	0	0	40	8	0
Solvent Utilization	667	0	0	0	0	0	0
Storage & Transport	285	0	0	0	2	0	0
Waste Disposal & Recycling	21	34	50	43	31	11	0
Highway Vehicles	669	983	8,850	37	20	14	29
Off-highway	297	188	3,291	14	15	14	0
Biogenic	515	33	0	0	0	0	0
Miscellaneous	0	0	2	0	194	24	10
Harrisonburg City	***3,076***	***1,901***	***13,863***	***1,625***	***573***	***198***	***40***
	2.21%	*3.00%*	*3.16%*	*5.51%*	*2.86%*	*2.53%*	*0.19%*

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Industrial	47	697	821	1,909	286	110	0
Fuel Comb. Other	879	111	1,540	21	148	146	0
Metals Processing	12	0	0	0	2	2	0
Other Industrial Processes	28	0	0	0	104	38	0
Solvent Utilization	1,062	0	0	0	0	0	0
Storage & Transport	199	0	0	0	0	0	0

Waste Disposal & Recycling	26	10	49	8	44	18	0
Highway Vehicles	2,420	4,114	36,243	148	82	58	116
Off-highway	427	638	5,069	78	67	64	0
Biogenic	9,896	101	0	0	0	0	0
Miscellaneous	17	7	356	2	1,049	157	3,730
Augusta County	***15,020***	***5,682***	***44,080***	***2,169***	***1,787***	***596***	***3,847***
	10.79%	*8.96%*	*10.05%*	*7.36%*	*8.93%*	*7.60%*	*18.53%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	2	35	43	100	14	5	0
Fuel Comb. Other	307	51	540	13	48	47	0
Other Industrial Processes	3	0	0	0	0	0	0
Solvent Utilization	222	0	0	0	0	0	0
Storage & Transport	130	0	0	0	0	0	0
Waste Disposal & Recycling	12	2	10	1	5	1	0
Highway Vehicles	310	423	4,058	17	9	6	13
Off-highway	150	75	1,754	14	10	9	0
Biogenic	1,450	31	0	0	0	0	0
Miscellaneous	0	0	1	0	93	11	0
Staunton City	***2,590***	***619***	***6,408***	***147***	***183***	***82***	***14***
	1.86%	*0.98%*	*1.46%*	*0.50%*	*0.91%*	*1.05%*	*0.07%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	27	1,029	507	2,125	177	73	0
Fuel Comb. Other	255	37	447	8	36	36	0
Chemical & Allied Product Mfg	117	0	0	0	45	36	0
Metals Processing	0	0	0	0	1	1	0
Other Industrial Processes	3	0	0	0	0	0	0
Solvent Utilization	286	0	0	0	0	0	0
Storage & Transport	119	0	0	0	2	1	0
Waste Disposal & Recycling	8	3	14	2	11	3	0
Highway Vehicles	322	428	3,952	17	9	6	13
Off-highway	160	158	1,902	23	14	13	0
Biogenic	930	17	0	0	0	0	0
Miscellaneous	0	0	0	0	52	5	0
Waynesboro City	***2,231***	***1,674***	***6,824***	***2,177***	***352***	***180***	***14***
	1.60%	*2.64%*	*1.56%*	*7.38%*	*1.76%*	*2.30%*	*0.07%*

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Industrial	18	371	322	1,026	158	69	0
Fuel Comb. Other	275	32	482	5	54	54	0
Other Industrial Processes	56	0	0	0	56	17	0
Solvent Utilization	352	0	0	0	0	0	0
Storage & Transport	431	0	0	0	4	1	0
Waste Disposal & Recycling	8	3	15	2	14	6	0
Highway Vehicles	1,326	2,476	21,195	83	46	33	65
Off-highway	341	269	1,665	47	36	33	0
Biogenic	7,811	65	0	0	0	0	0
Miscellaneous	93	42	1,975	11	502	201	544
Rockbridge County	***10,716***	***3,261***	***25,657***	***1,177***	***873***	***417***	***610***
	7.70%	*5.14%*	*5.85%*	*3.99%*	*4.36%*	*5.32%*	*2.94%*

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Industrial	0	8	9	22	3	1	0
Fuel Comb. Other	88	19	157	6	11	11	0
Other Industrial Processes	1	0	0	0	0	0	0
Solvent Utilization	55	0	0	0	0	0	0
Storage & Transport	26	0	0	0	0	0	0
Waste Disposal & Recycling	1	0	2	0	1	0	0
Highway Vehicles	53	59	571	2	1	1	2
Off-highway	14	7	268	0	0	0	0
Biogenic	537	7	0	0	0	0	0
Miscellaneous	0	0	0	0	16	2	0
Lexington City	***779***	***102***	***1,009***	***32***	***35***	***16***	***2***
	0.56%	*0.16%*	*0.23%*	*0.11%*	*0.17%*	*0.20%*	*0.01%*

Tier Name	VOC	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	NH_3
Fuel Comb. Industrial	6	104	119	271	40	15	0
Fuel Comb. Other	81	10	143	1	13	13	0
Other Industrial Processes	7	0	0	0	0	0	0
Solvent Utilization	568	0	0	0	1	1	0
Storage & Transport	29	0	0	0	0	0	0
Waste Disposal & Recycling	8	1	5	0	4	1	0
Highway Vehicles	58	65	634	2	1	1	2
Off-highway	17	67	227	12	5	5	0
Biogenic	318	6	0	0	0	0	0

Miscellaneous	0	0	1	0	8	0	0
Buena Vista City	***1,095***	***256***	***1,131***	***288***	***76***	***39***	***2***
	0.79%	*0.40%*	*0.26%*	*0.98%*	*0.38%*	*0.50%*	*0.01%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	13	191	228	539	78	29	0
Fuel Comb. Other	425	78	754	7	74	73	0
Petroleum & Related Industries	1	0	0	0	0	0	0
Other Industrial Processes	71	2,104	1,394	2,958	472	343	6
Solvent Utilization	443	0	0	0	11	11	0
Storage & Transport	288	0	0	0	48	48	0
Waste Disposal & Recycling	9	3	18	2	17	9	0
Highway Vehicles	1,731	4,169	23,805	110	74	58	59
Off-highway	294	403	2,849	74	45	43	0
Biogenic	8,150	55	0	0	0	0	0
Miscellaneous	3	1	51	0	248	31	236
Botetourt County	***11,431***	***7,008***	***29,103***	***3,694***	***1,073***	***647***	***302***
	8.21%	*11.05%*	*6.64%*	*12.53%*	*5.36%*	*8.26%*	*1.45%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	39	462	566	1,276	192	75	0
Fuel Comb. Other	1,129	223	2,016	37	215	212	0
Metals Processing	82	73	550	43	43	43	0
Other Industrial Processes	125	7	6	10	47	16	0
Solvent Utilization	986	0	0	0	9	9	0
Storage & Transport	374	0	0	0	0	0	0
Waste Disposal & Recycling	39	10	51	7	33	10	0
Highway Vehicles	2,318	3,093	29,406	111	62	44	85
Off-highway	436	921	5,701	174	106	99	0
Biogenic	4,360	30	0	0	0	0	0
Miscellaneous	91	41	1,926	11	495	194	88
Roanoke County	***9,984***	***4,863***	***40,226***	***1,672***	***1,208***	***708***	***175***
	7.17%	*7.67%*	*9.18%*	*5.67%*	*6.03%*	*9.03%*	*0.84%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	35	512	620	1,403	209	77	0
Fuel Comb. Other	323	70	572	23	47	46	0
Metals Processing	13	0	0	0	2	2	0
Other Industrial	72	11	40	22	45	43	0

Processes							
Solvent Utilization	596	0	0	0	0	0	0
Storage & Transport	114	0	0	0	0	0	0
Waste Disposal & Recycling	14	5	27	4	24	8	0
Highway Vehicles	536	417	5,818	18	8	5	17
Off-highway	231	306	3,502	46	26	24	0
Biogenic	913	6	0	0	0	0	0
Miscellaneous	0	0	1	0	77	8	2
Salem City	***2,852***	***1,331***	***10,583***	***1,519***	***442***	***218***	***20***
	2.05%	*2.10%*	*2.41%*	*5.15%*	*2.21%*	*2.78%*	*0.10%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Industrial	40	681	762	1,958	241	89	0
Fuel Comb. Other	1,226	249	2,167	78	192	188	0
Chemical & Allied Product Mfg	54	0	0	0	13	13	0
Other Industrial Processes	14	0	0	0	17	17	0
Solvent Utilization	1,471	0	0	0	2	2	0
Storage & Transport	439	0	0	0	0	0	0
Waste Disposal & Recycling	29	12	55	9	39	12	0
Highway Vehicles	2,550	2,568	30,132	86	43	29	74
Off-highway	382	624	5,930	134	66	61	0
Biogenic	1,325	10	0	0	0	0	0
Miscellaneous	1	0	8	0	285	31	10
Roanoke City	***7,535***	***4,146***	***39,055***	***2,267***	***901***	***445***	***85***
	5.41%	*6.54%*	*8.91%*	*7.69%*	*4.50%*	*5.68%*	*0.41%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Elec. Util.	0	6	1	14	0	0	0
Fuel Comb. Industrial	523	8,481	8,704	21,327	2,929	1,130	6
Fuel Comb. Other	9,308	1,654	17,199	546	1,674	1,647	0
Chemical & Allied Product Mfg	279	0	0	0	60	50	0
Metals Processing	107	73	550	43	57	57	0
Petroleum & Related Industries	4	7	1	25	28	6	0
Other Industrial Processes	1,431	5,939	1,867	4,866	2,049	959	45
Solvent Utilization	14,507	0	0	0	28	27	0
Storage & Transport	4,567	0	0	0	331	152	0
Waste Disposal & Recycling	543	171	1,242	115	743	445	0

Highway Vehicles	23,201	36,370	315,825	1,261	716	517	950
Off-highway	7,562	9,562	83,310	1,179	864	812	1
Biogenic	76,631	896	0	0	0	0	0
Miscellaneous	456	201	9,649	53	10,461	1,968	19,740
Shenandoah Region Totals	***139,201***	***63,422***	***438,397***	***29,482***	***20,019***	***7,837***	***20,762***
	9.66%	*7.35%*	*11.37%*	*2.97%*	*12.28%*	*9.89%*	*30.81%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Elec. Util.	0	6	1	14	0	0	0
Fuel Comb. Industrial	511	7,956	8,539	20,742	2,900	1,106	3
Fuel Comb. Other	8,915	1,498	15,759	332	1,468	1,447	0
Chemical & Allied Product Mfg	279	0	0	0	60	50	0
Metals Processing	107	73	550	43	57	57	0
Petroleum & Related Industries	4	7	1	25	28	6	0
Other Industrial Processes	1,263	2,608	1,710	3,255	1,537	736	9
Solvent Utilization	12,402	0	0	0	28	27	0
Storage & Transport	4,113	0	0	0	99	59	0
Waste Disposal & Recycling	292	127	516	109	420	161	0
Highway Vehicles	20,506	32,138	280,961	1,091	617	445	827
Off-highway	6,693	6,486	76,448	951	716	673	1
Biogenic	71,738	776	0	0	0	0	0
Miscellaneous	454	201	9,607	53	7,368	1,585	19,230
Virginia Shenandoah Region Totals	***127,353***	***51,931***	***394,137***	***26,664***	***15,369***	***6,411***	***20,086***
	12.31%	*10.67%*	*12.93%*	*6.34%*	*13.51%*	*12.65%*	*36.48%*

Tier Name	**VOC**	**NO_x**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Fuel Comb. Elec. Util.	0	0	0	0	0	0	0
Fuel Comb. Industrial	12	525	165	585	29	24	3
Fuel Comb. Other	393	156	1,440	214	206	200	0
Chemical & Allied Product Mfg	0	0	0	0	0	0	0
Metals Processing	0	0	0	0	0	0	0
Petroleum & Related Industries	0	0	0	0	0	0	0
Other Industrial Processes	168	3,331	157	1,611	512	223	36
Solvent Utilization	2,105	0	0	0	0	0	0
Storage & Transport	454	0	0	0	232	93	0
Waste Disposal & Recycling	251	44	726	6	323	284	0

Highway Vehicles	2,695	4,232	34,864	170	99	72	123
Off-highway	869	3,076	6,862	228	148	139	0
Biogenic	4,893	120	0	0	0	0	0
Miscellaneous	2	0	42	0	3,093	383	510
West Virginia Shenandoah Region Totals	***11,849***	***11,491***	***44,260***	***2,818***	***4,650***	***1,426***	***676***
	2.91%	*3.06%*	*5.49%*	*0.49%*	*9.44%*	*4.99%*	*5.48%*

Appendix B

Per capita emissions by county/city.

County/City	**VOC**	**NO_x**	**CO**	**SO2**	**PM_{10}**	**$PM_{2.5}$**	**NH_3**
Berkeley County	0.0877	0.0917	0.3271	0.0244	0.0284	0.0099	0.0034
Jefferson County	0.0867	0.0694	0.3250	0.0128	0.0474	0.0119	0.0086
Frederick County	0.2474	0.1098	1.1345	0.0339	0.0276	0.0100	0.0071
Winchester City	0.1165	0.0505	0.3179	0.0677	0.0177	0.0072	0.0007
Clarke County	0.2400	0.0970	0.7868	0.0326	0.0529	0.0132	0.0232
Shenandoah County	0.3457	0.1151	0.7692	0.0442	0.0352	0.0125	0.0513
Warren County	0.2172	0.0565	0.4713	0.0118	0.0146	0.0062	0.0043
Page County	0.2631	0.0512	0.5999	0.0318	0.0418	0.0234	0.1215
Rockingham County	0.2119	0.0750	0.5215	0.0460	0.0363	0.0110	0.1401
Harrisonburg City	0.0760	0.0470	0.3426	0.0402	0.0142	0.0049	0.0010
Augusta County	0.2289	0.0866	0.6718	0.0331	0.0272	0.0091	0.0586
Staunton City	0.1086	0.0260	0.2686	0.0062	0.0077	0.0034	0.0006
Waynesboro City	0.1143	0.0858	0.3496	0.1115	0.0180	0.0092	0.0007
Rockbridge County	0.5150	0.1567	1.2330	0.0566	0.0420	0.0200	0.0293
Lexington City	0.1134	0.0149	0.1469	0.0047	0.0051	0.0023	0.0003
Buena Vista City	0.1725	0.0403	0.1781	0.0454	0.0120	0.0061	0.0003
Botetourt County	0.3748	0.2298	0.9543	0.1211	0.0352	0.0212	0.0099
Roanoke County	0.1164	0.0567	0.4690	0.0195	0.0141	0.0083	0.0020
Salem City	0.1152	0.0538	0.4276	0.0614	0.0179	0.0088	0.0008
Roanoke City	0.0813	0.0448	0.4216	0.0245	0.0097	0.0048	0.0009

Appendix C

Names and locations of point sources, excluding power plants, in the Shenandoah Valley.

Plant Name	**State**	**County**	**County Name**	**SIC**
American Safety Razor Company	51	015	Augusta County	3421
Alcoa Packaging LLC	51	015	Augusta County	3081
Hollister Inc	51	015	Augusta County	3842
Hershey Chocolate of Virginia Inc	51	015	Augusta County	2066
Neuman Aluminum USA	51	015	Augusta County	3499
Blue Ridge Lumber	51	015	Augusta County	2431
Adams Construction Co-Blue Ridge	51	023	Botetourt County	2951
Columbia Gas Transmission Corporation Gala Compres	51	023	Botetourt County	4922

Roanoke Cement Company	51	023	Botetourt County	3241
O N Minerals - Plant 2	51	023	Botetourt County	3274
General Shale Brick, Inc.	51	023	Botetourt County	3251
O'Neal Inc	51	023	Botetourt County	5051
Arkay Packaging Corporation	51	023	Botetourt County	2759
Dynax America Corp USA	51	023	Botetourt County	3714
Mundet-Hermetite Inc	51	530	Buena Vista City	2754
Bontex, Inc.	51	530	Buena Vista City	3069
Everbrite LLC	51	530	Buena Vista City	3993
Torque-Traction Integration Technologies Inc	51	530	Buena Vista City	3714
Stuart M Perry Incorporated	51	069	Frederick County	1422
Valley Proteins, Inc.	51	069	Frederick County	2077
Lear Corporation - Winchester Division	51	069	Frederick County	3082
Crown Cork & Seal USA Inc	51	069	Frederick County	3411
O-N Minerals (Chemstone) Company - Clear Brook	51	069	Frederick County	3274
Unimin Corporation	51	069	Frederick County	3295
CED Enterprises Inc	51	069	Frederick County	2819
Cives Steel Company	51	069	Frederick County	3441
General Electric Company, Winchester Lamp Plant	51	069	Frederick County	3641
Stowe Woodward Company	51	069	Frederick County	3069
Allied Wood Products Inc	51	069	Frederick County	2421
Pactiv Corporation	51	069	Frederick County	3086
Team/IBS Inc	51	069	Frederick County	2493
Quebecor World Inc	51	069	Frederick County	2752
Green Bay Packaging Inc	51	069	Frederick County	2672
Miller Milling Co	51	069	Frederick County	2041
Trex Company Inc	51	069	Frederick County	3089
Trelleborg Engineered Products Inc - Seaward Div	51	069	Frederick County	3089
Frederick County Landfill	51	069	Frederick County	4953
HP Hood Inc	51	069	Frederick County	2026
Intrapac (Harrisonburg) Inc	51	660	Harrisonburg City	3354
JMU - James Madison University	51	660	Harrisonburg City	8221
Walker Manufacturing Company	51	660	Harrisonburg City	3714
Quarles Petroleum Inc	51	660	Harrisonburg City	5171
Banta Book Group	51	660	Harrisonburg City	2752
Gemini Coatings of Virginia Inc	51	660	Harrisonburg City	2851
City of Harrisonburg - Resource Recovery Facility	51	660	Harrisonburg City	4952
Pilgrim's Pride Corporation	51	660	Harrisonburg City	2048
Harmony Shenandoah Valley LLC	51	660	Harrisonburg City	2875
George's Foods LLC	51	660	Harrisonburg City	2048
Double Envelope Company	51	161	Roanoke County	2677
Walker Machine And Foundry	51	161	Roanoke County	3321
Motiva Enterprises LLC Roanoke	51	161	Roanoke County	5171
Couvrette Building Systems	51	161	Roanoke County	3444
Valleydale Foods, Inc.	51	161	Roanoke County	2013
Halmode Apparel	51	161	Roanoke County	2335
Koppers Incorporated Salem Plant	51	161	Roanoke County	2491
Salem Frame Co	51	161	Roanoke County	2426
Marathon Petroleum Co Roanoke Terminal	51	161	Roanoke County	5171
Progress Press Inc	51	161	Roanoke County	2752
RR Donnelley & Sons	51	161	Roanoke County	2752
Maple Leaf Bakery	51	161	Roanoke County	2051
Smith Gap Regional Landfill	51	161	Roanoke County	4953
Moore Wallace USA Inc	51	139	Page County	2761
VF Jeanswear - Wrangler	51	139	Page County	2326
Columbia Gas Transmission Corporation	51	139	Page County	4922
Yokohama Tire Corp	51	775	Salem City	3011
Old Virginia Brick Co	51	775	Salem City	3251

John W Hancock Jr Incorporated	51	775	Salem City	3441
Graham White Mfg Co	51	775	Salem City	3493
Mohawk Industries Inc - Lees Carpets Division	51	163	Rockbridge County	2273
Stillwater Incorporated Goshen Plant	51	163	Rockbridge County	2231
The Burke Parsons Bowlby Corporation	51	163	Rockbridge County	2491
RES dba Steel Dynamics Roanoke Bar Division	51	770	Roanoke City	3312
Norfolk Southern Railway Company East End Shops	51	770	Roanoke City	4011
Akzo Nobel Coatings Inc	51	770	Roanoke City	2851
Hooker Furniture Corp	51	770	Roanoke City	2511
Kinder Morgan Southeast Terminals - Roanoke Termin	51	770	Roanoke City	4226
Custom Wood Products LLC Aerial Way Plt	51	770	Roanoke City	2434
Riverton Corporation	51	187	Warren County	3272
E I DuPont de Nemours & Co Inc - Front Royal	51	187	Warren County	2851
Toray Plastics	51	187	Warren County	3086
Adams Construction Company	51	165	Rockingham County	2951
Virginia Poultry Growers Cooperative Inc - Hinton	51	165	Rockingham County	2015
Valley Proteins Inc - Linville	51	165	Rockingham County	2077
Pilgrims Pride Corporation - Timberville	51	165	Rockingham County	2015
Merck & Co Inc - Stonewall Plant	51	165	Rockingham County	2834
Ethan Allen Inc - Bridgewater Division	51	165	Rockingham County	2511
Virginia Poultry Growers Cooperative Inc- Broadway	51	165	Rockingham County	2015
Transprint USA	51	165	Rockingham County	2759
R R Donnelley & Sons Co Inc	51	165	Rockingham County	2732
Coors Brewing Company - Shenandoah Brewery	51	165	Rockingham County	2082
Arsenal of Virginia Inc	51	165	Rockingham County	3799
Tyson Foods, Inc.	51	171	Shenandoah County	2015
Bowman Apple Products Co Inc	51	171	Shenandoah County	2033
Howell Metal Co	51	171	Shenandoah County	3351
O-N Minerals (Chemstone) Company - Strasburg	51	171	Shenandoah County	3274
Johns Manville	51	171	Shenandoah County	3295
Lear Operations Corporation - Strasburg	51	171	Shenandoah County	3089
Merillat LP	51	171	Shenandoah County	2434
Mountain View Rendering Company	51	171	Shenandoah County	2011
Agmark Intermodal Systems Inc	51	171	Shenandoah County	5153
Columbia Gas Transmission Corp - Strasburg Com Sta	51	171	Shenandoah County	4922
Carpers Wood Creations Inc	51	171	Shenandoah County	2511
Wayn-Tex LLC	51	820	Waynesboro City	2221
Shenandoah Forest LLC	51	820	Waynesboro City	2421
INVISTA S.a r.l. - Waynesboro	51	820	Waynesboro City	2824
Virginia Metalcrafters Inc	51	820	Waynesboro City	3366
Neuman Aluminium Impact Extrusion Inc	51	820	Waynesboro City	3499
Henkel-Harris Co Inc - South Pleasant Valley Road	51	840	Winchester City	2511
National Fruit Product Co Inc	51	840	Winchester City	2033
Plumly Flooring LLC	51	840	Winchester City	2426
O'Sullivan Films Inc	51	840	Winchester City	3081
Federal-Mogul Friction Products	51	840	Winchester City	3714
Aker Plastics Co., Inc.	54	003	Berkeley County	-
Brentwood Industries, Inc.	54	003	Berkeley County	-
Capitol Cement Corporation	54	003	Berkeley County	-
Guardian Fiberglass, Inc.	54	003	Berkeley County	-
North Mountain Sanitary Landfill	54	003	Berkeley County	-
Quad/Graphics, Inc.	54	003	Berkeley County	-
Quebecor World - Martinsburg	54	003	Berkeley County	-
Spectratech International, Inc.	54	037	Jefferson County	-
Halltown Paperboard Company	54	037	Jefferson County	-

Appendix D

Policy analysis for the Local Reductions Case.

	Proposed Measure	Policy	Valley Impact	Agency actions
1	Idling reduction			
	a. Large diesel engine trucks	1) Provide electrified parking at truck stops, distribution centers, and other operations served by or having diesel engine fleets.	Emissions/exposure reduction of NO_x and $PM_{2.5}$	**Local Government Planning** - Conditional use requirement for new facilities or expansion of existing facilities. Example: Baugh Northeast Co-op Distribution Center, Warren County. **State/Federal** – Capital funding support for installation of commercial hook-ups and industry retrofits by tax credits or loan as well as expansion of locations. **For public entities** – Provide grants for fleet centers or extension of public service commercial locations. **Private sector** - Corporate policies and training to implement programs.
		2) Install individual truck auxiliary power generators and/or electrified parking adaptors.	Emissions/exposure reduction of NO_x and $PM_{2.5}$	**State/Federal** - Capital funding support for installation of equipment by individual operators by tax credits or loan.
	b. Passenger vehicles and small trucks	Reduce small vehicle idling time by 10%.	Emissions/exposure reduction of NO_x and $PM_{2.5}$; fuel savings	**Valley AIRNow, Clean Air Connection, SHENAIR LGC** – Regional idling reduction information and education program with direct assistance to Local Governments under Green Valley Initiative. **Private sector** - Corporate policies and training to implement programs that change driver habits to become conscious of idling reduction practices.
2	Clean Fleet CNG (Compressed Natural Gas) for Public Transit and School Systems and State and Federal vehicles based in Valley	Replace vehicles and convert where feasible public fleets to CNG.	Emissions/exposure reduction of VOC, NO_x, and $PM_{2.5}$	**Local Government/School Systems** – Plan for and support conversion process regionally to build distribution infrastructure and take advantage or regional availability of CNG availability. **State/Federal** – Provide capital funding support for a Valley Regional program as was done for the WMATA Clean Fleet Program in the NoVA/D.C. Metro region. Deploy CNG vehicles for agencies operating from and in the Shenandoah Valley.
3	Cleaner small equipment engines	Encourage the use of electric or push mowers, CNG or LPG mowers and CNG or LPG substitution for gas engines where practical.	Emissions of CO, NO_x, and PM in the Valley from lawnmower use would fall, and people using the mowers would be exposed to less pollution.	**Private sector** - Provide sales and service for such equipment in the region. **Local/State/Federal** – Use such equipment at facilities. Town of Woodstock evaluating LPG mower. **Valley AIRNow, Clean Air Connection, SHENAIR LGC** – Small engine information and education program with direct assistance to Local Governments under Green Valley Initiative

4	Reformulated gasoline	Mandate or encourage the sale of low Reid vapor pressure gasoline at gas stations in the Valley.	Vehicles refueling in the Valley would have lower VOC and NO_x emissions.	**State** - DEQ implement on a seasonal or year round-basis as conditions require. **Federal** – Possible EPA role
5	Fuel and VOC source storage emissions	Encourage the sale and use of tighter storage containers and low emissions fuel tanks for public, corporate and private equipment and vehicles.	VOC emissions from home garages and storage facilities in the Valley would be reduced.	**Private sector** - Provide sales and service for such equipment in the region. Corporate programs for VOC source storage tanks. **Valley AIRNow, Clean Air Connection, SHENAIR LGC** – Small engine information and education program with direct assistance to Local Governments under Green Valley Initiative.
6	Low- or zero-VOC paint	Mandate the use of low-VOC and/or zero-VOC paint.	Reduced VOC emissions locally from all painting projects. Workers and building occupants would benefit from lower exposures to VOCs.	**Private sector** – Stock appropriate paints and provide customer information on use. **State** – DEQ regulation to implement for Valley. **Federal** – Possible EPA role **Valley AIRNow, Clean Air Connection, SHENAIR LGC** – Paint/VOC information and education program with direct assistance to Local Governments under Green Valley Initiative.
7	Public mobility /trip reduction	Increase trip alternatives to the SOV (single occupancy vehicle) with ridesharing, transit, taxi or other paid service; walking and wheeling by bike or other and reduce trip length with employment closer to home including substitution of communications for transportation via telework.	Vehicle emissions of CO, NO_x, VOCs, and PM could be reduced.	**Private sector** – Provide these options to workers; provide services or purchase services from private or public providers. **Public Sector** – Providers and Ridesharing agencies provide information to individuals and companies about options. **Local governments** – Plan for workforce housing in relationship to employment centers locally and regionally, including transportation and broadband infrastructure. **State/Federal** – Policies and grants to support investment that support trip efficiency
8	Fluorescent and LED lighting	Encourage rapid phase-in of compact fluorescent and LED lighting for public and private locations.	Lower electricity demand would reduce power plant emissions, primarily outside the Shenandoah Valley and offset increases for other Valley electrification programs.	**Private sector** – Stock lighting fixtures and bulbs using bulk purchasing and sales to reduce cost. **Local/State/Federal** – Phase-in use of these lighting options. Use cooperative procurement to reduce costs. Establish convenient disposal system for CFL and standard fluorescent bulbs. **Valley AIRNow, Clean Air Connection, SHENAIR LGC** –Light source information and education program with direct assistance to Local Governments under Green Valley Initiative.

9	Green buildings	Increase building and home energy efficiency and plan for future buildings and homes to incorporate environmentally friendly measures.	Reduce average household fossil fuel use and accompanying emissions in the Valley as well as that for public and business buildings. Lower average electricity demand could balance increased electricity demand from other programs and help manage power plant emissions outside the Shenandoah Valley.	**Private sector** – Develop Green Building (LEED) competencies in design, retrofitting and building within the region. **Private/Non-Profit/Public** – For new construction and renovation include Green/LEED specs in contracts. **SHENAIR LGC** – Coordinate and support Local Governments through the Green Valley Initiative. **Public Solid Waste Management** –Implement parallel source reduction plans incorporating Green building and related strategies.

Appendix E

This document will help you process VISTAS emissions inventories in SMOKE v2.4. It is based on the current setup of SMOKE on the workstation and also on the current input inventories and data files. Updating to a new version of SMOKE, changing its configuration, and/or changing or modifying input files may require SMOKE to be operated differently than what is outlined in this document.

1. First an environment variable needs to be set and all the work must be done in C-shell. To do this input the following commands:
   csh
   setenv SMK_HOME /opt/smoke
2. Now the assigns file needs to be sourced. This will automatically set the remaining environment variables needed to operate SMOKE.
   cd $SMK_SUBSYS/smoke/assigns/
   source ASSIGNS.vistas.cmaq.cb4p25.rpo12.ag
   The assigns file, along with two other files it calls: *set_dirs_baseg_2002.scr* and *set_case.scr*, set all the necessary environment variables and path directories necessary for SMOKE. These can be modified but be sure to source the assigns file again after these changes in order for them to take effect.
3. To modify the assigns file or any other file I like to use *gedit*. You could also use another text editor such as *vi* or *emacs*. To do this type
   gedit ASSIGNS.vistas.cmaq.cb4p25.rpo12.ag &
   The **&** sign allows the process to be run in the background and is only needed if the *gedit* program is not already open. It allows you continue working in the console without having to close *gedit*. If *gedit* is already open the **&** is not necessary though it doesn't hurt.
4. In *gedit* make sure the following is set in the assigns file:

   setenv INVID baseg_2002
   setenv INVOP baseg_2002
   setenv INVEN baseg_2002
   setenv ABASE baseg_2002
   setenv BBASE baseg_2002
   setenv MBASE baseg_2002
   setenv PBASE baseg_2002
   setenv EBASE baseg_2002
   setenv METSCEN baseg_2002
   setenv GRID vista12
   setenv IOAPI_GRIDNAME_1 VISTA12_168X177
   setenv IOAPI_ISPH 19
   setenv SPC cmaq.cb4p25
5. You can modify the length of the SMOKE run by changing the "mobile episode variables" and "per-period environment variables". For example, if you want to run SMOKE for 3 days (72 hours) starting on January 1, 2002 set the following:

   setenv EPI_STDATE 2002001
   setenv EPI_STTIME 000000

setenv EPI_RUNLEN 0720000
setenv EPI_NDAY 3
setenv G_STDATE 2002001
setenv G_STTIME 000000
setenv G_TSTEP 10000
setenv G_RUNLEN 250000
setenv ESDATE 20020101
setenv MSDATE 20020101
setenv NDAYS 1
setenv MDAYS 1
setenv YEAR 2002

Only the variables EPI_STDATE, EPI_RUNLEN, EPI_NDAY, G_STDATE, ESDATE, MSDATE, and YEAR need to be changed.

6. **Area Sources:**

To run area source emissions make sure the following are set under "Area-source input files" in the assigns file:

setenv ARINV $INVDIR/area/arinv_vistas_2002g_2453922_w_pmfac.txt
setenv REPCONFIG $INVDIR/other/repconfig.ar.temporal.txt
#setenv NRINV $INVDIR/nonroad/nrinv_vistas_2002g_2453908.txt
setenv ARTOPNT $INVDIR/other/ar2pt_14OCT03_1999.txt
setenv AGPRO $GE_DAT/amgpro.12km_vista12_epa_update.agv1
setenv AGREF $GE_DAT/amgref_us_100604.ag
setenv ATPRO $GE_DAT/atpro_vistas_basef_15jul05.txt
setenv ATREF $GE_DAT/atref_vistas_basef_15jul05.txt

Make sure the files being set here actually exist under the correct path directories. The **ARINV** variable is the raw input emissions inventory. The file shown here is the VISTAS area sources emissions inventory downloaded from Alpine Geophysics' ftp site. The **REPCONFIG** variable is the file that properly creates reports after the SMOKE run. **NRINV** is the file for the raw VISTAS non-road emissions inventory. MAKE SURE THIS IS COMMENTED OUT WITH THE # SYMBOL WHEN PROCESSING AREA SOURCES. The remaining variables that are set refer to other input files. Some of these can be changed as there may be updated versions of them, especially the **$GE_DAT** files. Once again, if you change any of these variables be sure to source your assigns file again.

To execute the area sources run go to the executables folder:

cd $SCRIPTS/run

Run *smk_ar_12k.ag*, but before doing so make sure that this executable file calls the correct assigns file. To do this open *smk_ar_12k.ag* using *gedit* and make sure at the top it says:

setenv ASSIGNS_FILE
$SMKROOT/assigns/ASSIGNS.vistas.cmaq.cb4p25.rpo12.ag

Once this is done run the executable file:

./smk_ar_12k.ag

7. **Non-road Sources:**

To run non-road source emissions make sure the following are set under "Area-source input files" in the assigns file:

#setenv ARINV $INVDIR/area/arinv_vistas_2002g_2453922_w_pmfac.txt
setenv REPCONFIG $INVDIR/other/repconfig.ar.temporal.txt
setenv NRINV $INVDIR/nonroad/nrinv_vistas_2002g_2453908.txt
setenv ARTOPNT $INVDIR/other/ar2pt_14OCT03_1999.txt
setenv AGPRO $GE_DAT/amgpro.12km_vista12_epa_update.agv1
setenv AGREF $GE_DAT/amgref_us_100604.ag
setenv ATPRO $GE_DAT/atpro_vistas_basef_15jul05.txt
setenv ATREF $GE_DAT/atref_vistas_basef_15jul05.txt

Make sure the files being set here actually exist under the correct path directories. The **NRINV** variable is the raw input emissions inventory. The file shown here is the VISTAS non-road sources emissions inventory downloaded from Alpine Geophysics' ftp site. The **REPCONFIG** variable is the file that properly creates reports after the SMOKE run. **ARINV** is the file for the raw VISTAS non-road emissions inventory. MAKE SURE THIS IS COMMENTED OUT WITH THE # SYMBOL WHEN PROCESSING NON-ROAD SOURCES. The remaining variables that are set call other input files. Some of these can be changed as there may be updated versions of them, especially the **$GE_DAT** files. Once again, if you change any of these variables be sure to source your assigns file again.

To execute the non-road sources run go to the executables folder:
cd $SCRIPTS/run
Run *smk_nr_12k.ag*, but before doing so make sure that this executable file calls the correct assigns file. To do this open *smk_nr_12k.ag* using *gedit* and make sure at the top it says:
setenv ASSIGNS_FILE
$SMKROOT/assigns/ASSIGNS.vistas.cmaq.cb4p25.rpo12.ag
Once this is done run the executable file:
./smk_nr_12k.ag

8. **Biogenic Sources:**

To run biogenic source emissions make sure the following are set under "Biogenic input files" in the assigns file:

setenv BGUSE $SMKDAT/inventory/beld2/beld.5.us36.txt
setenv METLIST $INVDIR/biog/metlist.tmpbio.txt
setenv RADLIST $INVDIR/biog/radlist.tmpbio.txt
setenv BFAC $GE_DAT/bfac.summer.txt
setenv S_BFAC $GE_DAT/bfac.summer.txt
setenv W_BFAC $GE_DAT/bfac.winter.txt
setenv BCUSE $GE_DAT/landuse.dat
setenv B3FAC $GE_DAT/b3fac.beis3_efac_v0.98.txt
setenv B3XRF $GE_DAT/b3tob2B.xrf
setenv BELD3_TOT $INVDIR/biog/b3_t.VISTAS12_168X177.beld3.ncf
setenv BELD3_A $INVDIR/biog/b3_a.VISTAS12_168X177.beld3.ncf
setenv BELD3_B $INVDIR/biog/b3_b.VISTAS12_168X177.beld3.ncf
setenv SOILINP $STATIC/soil.beis312.$GRID.$SPC.ncf

Technically there are no raw emission inventories for biogenic sources.
Land-use/Land-cover (LULC) data is used to calculate biogenic emissions over a

specified area. The **$GE_DAT** files may be updated and may change. The **BELD3_*** files are specifically related to VISTAS LULC and were downloaded from Alpine Geophysics' ftp site.

To execute the biogenic sources run go to the executables folder:
cd $SCRIPTS/run
Run *smk_bg_12k.ag*, but before doing so make sure that this executable file calls the correct assigns file. To do this open *smk_bg_12k.ag* using *gedit* and make sure at the top it says:
setenv ASSIGNS_FILE
$SMKROOT/assigns/ASSIGNS.vistas.cmaq.cb4p25.rpo12.ag
Once this is done run the executable file:
./smk_bg_12k.ag

9. **Point Sources:**

To run point source emissions make sure the following are set under "Point source input files" in the assigns file:

```
setenv PTINV     $INVDIR/point/negu_ptinv_vistas_2002typ_baseg_2453909.txt
#setenv PTDAY       $INVDIR/point/
setenv PTHOUR    $INVDIR/point/pthour_2002typ_baseg_jan_28jun2006.ems
setenv PELVCONFIG      $INVDIR/point/pelvconfig.top50.txt
setenv REPCONFIG       $INVDIR/other/repconfig.pt.temporal.txt
setenv PTPRO           $GE_DAT/ptpro_typ_jan_vistasg_28jun2006.txt
setenv PTREF           $GE_DAT/ptref_typ_vistas_baseg_28jun2006.txt
setenv PSTK            $GE_DAT/pstk.m3.txt
```

PTINV calls the raw VISTAS point source emissions inventory. It was downloaded from Alpine Geophysics' ftp site. Notable for point sources is that **PTHOUR** and **PTPRO** need to be changed depending on which month you are running. The portion of each filename that says "**jan**" needs to be changed to the first three letters of the month in which the run is taking place.

To execute the point sources run go to the executables folder:
cd $SCRIPTS/run
Run *smk_pnt_vistaII_12k.ag*, but before doing so make sure that this executable file calls the correct assigns file. To do this open *smk_pnt_ vistaII_12k.ag* using *gedit* and make sure at the top it says:
setenv ASSIGNS_FILE
$SMKROOT/assigns/ASSIGNS.vistas.cmaq.cb4p25.rpo12.ag
Once this is done run the executable file:
./smk_pnt_ vistaII_12k.ag

10. **Mobile Sources:**

To run mobile sources emissions make sure the following are set under "Mobile source input files" in the assigns file:

```
setenv MBINV       $INVDIR/mobile/mbinv_vistas_02g_vmt_12jun06.txt
setenv VMTMIX      $INVDIR/mobile/vmtmix.txt
```

setenv MEPROC $INVDIR/mobile/meproc.txt
setenv MCODES $INVDIR/mobile/mcodes.baseg.txt
setenv MCREF $INVDIR/mobile/mcref.baseg.36k.ag.txt
setenv MVREF $INVDIR/mobile/mvref.baseg.36k.ag.txt
setenv M6MAP $INVIDR/mobile/m6map.txt
setenv METLIST $INVDIR/mobile/metlist.premobl.12k.txt
setenv SPDREF $INVDIR/mobile/spdref.2002g.txt
setenv SPDPRO $INVDIR/mobile/spdprof.2002g.txt
setenv REPCONFIG $INVDIR/mobile/other/repconfig.mb.temporal.txt
#setenv MGPRO $GE_DAT/amgpro.12km_vista12_epa_update.us
setenv MGREF $GE_DAT/amgref_us_091503.ag
setenv MTPRO $GE_DAT/mtpro_vistas_basef_04jul05.txt
setenv MTREF $GE_DAT/mtref_us_can_vistas_basef_04jul05.txt

There are two ways in which mobile sources can be processed: one uses VMT data while another uses emissions inventory data. VISTAS uses VMT data and this is input for the variable **MBINV**. The remaining input files may be updated and may change. The file for **MGPRO** is called by **SRGDESC** which is set under "Shared input files". If you want to change the **MGPRO** file do so in by modifying whichever file is called by **SRGDESC**. Be sure to source your assigns file again after changes.

One of the actions needed before processing mobile emissions is the creation of **METCOMBO*** files in the meteorology data. To do this first set the time period of the **METCOMBO*** files you wish to create in the assigns file. Then in the **$SCRIPTS/run** folder make sure the *metcombinevistas.csh* sources the assigns file you are using. Before running metcombinevistas.csh you will have to go to your **$METDAT** directory and create copies of all the **METCRO2D*** and **METCRO3D*** meteorology files you want to combine so that they have Julian calendar dates in their names rather than regular calendar dates. For example, if you want to create **METCOMBO*** files for January 1, 2002 do the following:

cd $METDAT
ln –s METCRO2D*20020101 METCRO2D*2002001
ln –s METCRO3D*20020101 METCRO3D*2002001
cd $SCRIPTS/run
./metcombinevistas.csh

After creating the METCOMBO* files you will need to go back and rename them to their regular calendar names since they will have been created with Julian calendar names. You can also delete the **METCRO2D*** and **METCRO3D*** with the Julian calendar names if you choose to do so. DO NOT DELETE THE **METCRO2D*** AND **METCRO3D*** FILES WITH THE REGULAR CALENDAR NAMES.

Another detail to work out is to make sure all the necessary files exist in the **$SMK_M6PATH** and **$INVDIR/mobile/m6_$YEAR** directories. **$SMK_M6PATH** must contain all the necessary external data files and **$INVDIR/mobile/m6_$YEAR** needs all the **.in* files for SMOKE-Mobile6 to run properly. All the files currently necessary for **$SMK_M6PATH** are in there and if you add new files to the folder make sure they are in the unix/linux format by using the **dos2unix** command on them. The files necessary for the **$INVDIR/mobile/m6_$YEAR** exist for a specific month and must be changed when changing months. All the files needed for this directory can be found

under **$INVDIR/mobile/inputs**. Not having these files or having them in the incorrect format in either **$SMK_M6PATH** or **$INVDIR/mobile/m6_$YEAR** will most likely cause the program Emisfac to fail.

To execute the mobile sources run go to the executables folder:

cd $SCRIPTS/run

Run *smk_mb_vistaII_12k.ag*, but before doing so make sure that this executable file calls the correct assigns file. To do this open *smk_mb_ vistaII_12k.ag* using *gedit* and make sure at the top it says:

setenv ASSIGNS_FILE
$SMKROOT/assigns/ASSIGNS.vistas.cmaq.cb4p25.rpo12.ag

Once this is done run the executable file:

./smk_mb_ vistaII_12k.ag

11. **Some Common Problems:**

A common problem that may occur when running SMOKE may be that previously generated intermediate files and log files interfere with the new creation of the same files if you are running SMOKE for the same period again. To deal with this problem remove previously generated intermediate files and log files before a run:

cd $SCENARIO
rm {names of intermediate files}
cd $LOGS
rm {names of log files}

Some intermediate files are also created in the **$INVDIR** and **$STATIC** directories. BE CAREFUL WHEN DELETING FILES IN THESE DIRECTORIES. They both also contain crucial input files. A good way to distinguish between the two is to use the command **ls –lt**. This allows you to see the time and date when files were created so you can see which files were created during a previous run versus files that have been in the directory for a long time. If you are still unsure DO NOT DELETE the file. Run SMOKE and see the errors in the log files. If they say a certain intermediate file is in the way then delete that file only. If you are still unsure, you can move the suspect file to a backup version:

mv existing_file existing_file.bak

12. **Future Year Inventories or Control Scenarios:**

To process future year emission inventories you must first run current year emissions inventories for the same dates you wish to run. This is because the files created in the **$STATIC** and **$SCENARIO** folders are necessary for future year runs. A growth & control file named *gcntl.{current year}_{future year}.txt* is necessary for each source type you are trying to process. The file name must be as shown above and it must be in the same folder as the raw emissions inventory input for the respective source.

The gcntl file is set up with four main columns. The first column refers to the country/state/county (CSC) code. These refer to the specific locations for which the file applies. If you are working only in the USA the code may include only state and county. The second column is for SCC codes. These refer to specific types of emission sources. Each type of source is assigned a specific SCC code. The third column refers to the

projection factor. This is the number that will actually do the growth and control projections because it will be multiplied to the current year's emission inventory for the specific county and SCC. The fourth column refers to the pollutant for which you want to apply the projection factor. If you want to apply the projection factor to all pollutants enter -9 in the column. There are additional columns which may be added to the gcntl file if necessary though these are not needed. Refer to the SMOKE manual's section 8.6 for further information on these.

Running future year scenarios in SMOKE will create folders with the same names as the current year runs except with ***_$FYEAR** at the end of them. For example if your output for the current year is set to **$SMKDAT/run_baseg_2002/output** your output for a year 2050 run will go to the **$SMKDAT/run_baseg_2002_50/output** under the current settings.

For mobile sources it will be necessary to have all the files being used in the **$SMK_M6PATH** and **$INVDIR/mobile/m6_$YEAR** directories to also exist in the equivalent future year directories.