VDEQ Mercury Study

Mercury Deposition Modeling for the Virginia Mercury Study

Final Report

October 20, 2008

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List of Acronyms and Abbreviations

AEP = American Electric Power

AERMET = AERMOD Meteorological Preprocessor

AERMOD = AMS/ EPA Regulatory Model

AMS = American Meteorological Society

AQS = Air Quality System

ARL = Air Resources Laboratory

CAIR = Clean Air Interstate Rule

CAMR = Clean Air Mercury Rule

CART = Classification and Regression Tree

CASTNet = Clean Air Status and Trends Network

CB = Carbon bond

CMAQ = Community Multiscale Air Quality

CO = Carbon monoxide

CTM = Chemical Transport Model

Dep = Deposition

EGU = Electric Generating Unit

EC = Elemental carbon

EPA = Environmental Protection Agency

FF = Fabric filter

FGD = Flue gas desulfurization

HB1055 = Virginia House Bill 1055

Hg = Mercury

HG0 = Elemental mercury

HG2 = Reactive gaseous mercury (also divalent gaseous mercury)

HGP = Particle bound mercury

IC/BC = Initial and boundary conditions

IMPROVE = Interagency Monitoring of Protected Visual Environments

MACT = Maximum Available Control Technology

Max = Maximum

MCIP = Meteorology-Chemistry Interface Processor

MDN = Mercury Deposition Network

Min = Minimum

MM5 = Fifth Generation Mesoscale Model

NADP= National Acid Deposition Program

NAMMIS = North American Mercury Model Inter-comparison Study

NEI = National Emissions Inventory

NH_3 = Ammonia

NH_4 = Ammonium

NO_3 = Nitrate

NOAA = National Oceanographic and Air Administration

NO_x = Nitrogen oxides

NRV = Natural, recycled and volcanic

NWS = National Weather Service

OC = Organic carbon

$PM_{2.5}$ = Fine particular matter (with a diameter of less than or equal to 2.5 microns)

PM_{10} = Particulate matter (with a diameter of less than or equal to 10 microns)

PMF = Positive Matrix Factorization

PPTM = Particle and Precursor Tagging Methodology

PSU/NCAR = Pennsylvania State University/National Center for Atmospheric Research

REMSAD = REgional Modeling System for Aerosols and Deposition

SMOKE = Sparse-Matrix Operator Kernel Emissions

SO_2 = Sulfur dioxide

SO4 = Sulfate

TRI = Toxics Release Inventory

VA08 = Site identifier for the Culpeper, Virginia MDN monitoring site

VA28 = Site identifier for the Shenandoah National Park, Virginia MDN monitoring site

VA98 = Site identifier for the Harcum, Virginia MDN monitoring site

VDEQ = Virginia Department of Environmental Quality

VOC = Volatile organic compound

WBAN = Weather Bureau Army Navy

List of Units

g km^{-2} = grams per square kilometer (Note: g km^{-2} = $\mu g m^{-2}$)

in = inches

km = kilometer

lb/yr = pounds per year

m = meter

ppb = parts per billion

$\mu g\ m^{-2}$ = micrograms per square meter (Note: $\mu g\ m^{-2}$ = g km^{-2})

$\mu g\ m^{-3}$ = micrograms per cubic meter

ng m^{-2} = nanograms per square meter

tpy = tons per year

Executive Summary

The key objectives of the Virginia atmospheric mercury deposition modeling analysis were to

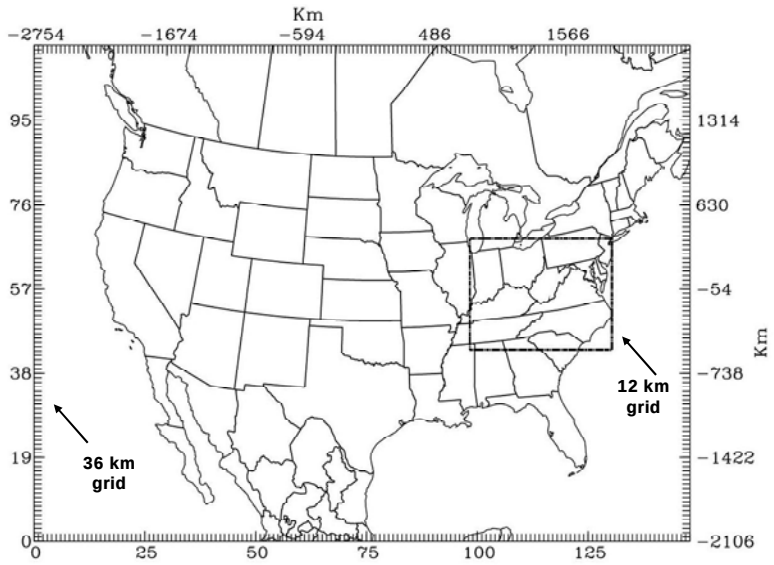
- Examine and quantify the contribution of global, regional and local emissions sources to mercury deposition throughout the Commonwealth;,
- Examine the effects of future-year emissions changes on airborne mercury deposition; and
- Provide information to support the further analysis of the impact of mercury deposition on the environment.

The modeling analysis was designed to account for the different scales and chemical interactions important to mercury deposition. The Community Multiscale Air Quality (CMAQ) modeling system was applied to simulate and quantify the effects of national and regional emissions on mercury deposition. The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere. The CMAQ modeling system supports the detailed simulation of mercury (Hg), including the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury. The CMAQ Particle and Precursor Tagging Methodology (PPTM) for mercury was used in this study to provide detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition.

The EPA Gaussian model AERMOD was applied for 15 of the highest-emitting point sources in the Virginia emissions inventory to further assess the local contributions of these sources.

Both CMAQ and AERMOD were applied for an annual simulation period corresponding to a base year of 2001. This base year was selected based on meteorology. However, mercury emissions for 2002 were used for the Virginia sources since the 2002 emissions data represent the most recent, complete and quality assured emission inventory for Virginia. The base year for this study is therefore referred to as 2001/2002. The CMAQ modeling used both 36- and 12-km horizontal resolution, as shown in Figure ES-1.

Figure ES-1. CMAQ 36- and 12-km Resolution Nested-Grid Modeling Domain.



The evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species. Good model performance is achieved for ozone and $PM_{2.5}$ species. For mercury, simulated annual wet deposition amounts on average are within 10 percent of the observed values for both the 36- and 12-km domains.

The models were also applied for three future years: 2010, 2015 and 2018, using projected emissions data. Projection to the future years has provided information on the potential effects of future emissions changes and the effectiveness of potential emissions controls on mercury deposition. Analysis of the mercury deposition modeling results focused on Virginia and the major water basins.

Table ES-1 displays the base- and future-year emissions for Virginia. Emissions totals are given in Table ES-1a and percent reductions are given in Table ES-1b. Emissions are provided for Electric Generating Unit (EGU) sources, non-EGU sources, non-point (area) sources, and all sources (total). The non-point source category includes such sources as residential/industrial fuel combustion, fluorescent lamp breakage, health services, agricultural production, waste disposal, landfills, and other combustion sources.

Table ES-1a. Mercury Emissions Totals (lbs/year) for the Commonwealth of Virginia.

Region	EGU				Non-EGU				Non-Point				Total Emissions			
	2002	2010	2015	2018	2001/ 2002	2010	2015	2018	2002	2010	2015	2018	2002	2010	2015	2018
Virginia	1380	860	840	780	980	660	600	620	380	280	300	300	2740	1800	1740	1700

Table ES-1b. Percent Change in Mercury Emissions Totals Compared to the 2002 Base Year for the Commonwealth of Virginia.

Region	EGU			Non-EGU			Non-Point			Total Emissions		
	2010	2015	2018	2010	2015	2018	2010	2015	2018	2010	2015	2018
Virginia	-37.7	-39.1	-43.5	-32.6	-38.8	-36.7	-26.3	-21.1	-21.1	-34.3	-36.5	-37.9

The majority of the emissions reductions are expected by 2010. For Virginia, mercury emissions from EGUs are expected to be reduced by ~40 percent by 2010, mainly from controls mandated by the EPA Clean Air Interstate Rule (CAIR)[1], with additional reductions in 2015 and 2018 from the Clean Air Mercury Rule (CAMR)[2] and other state-specific rules. For the non-EGU sector in Virginia, mercury emissions are expected to be reduced by about 32 percent in 2010, decrease further in 2015, but slightly increase in 2018. The increases are due to future-year growth projections. For the non-point sector in Virginia, mercury emissions are expected to decrease by about 24 percent in 2010 (due to new MACT standards, etc.) and basically stay the same beyond that. For Virginia, total mercury emissions are expected to decrease by about 34 percent in 2010, and slightly more than that by 2015 and 2018.

[1] Although CAIR was vacated by the U.S. Court of Appeals on 11 July 2008, the modeling analysis included the provisions of the original rule.

[2] Although the United States Court of Appeals for the D.C. District ruled on 8 February 2008 that EPA's CAMR was illegal, the original provisions of CAMR compliance were simulated in the future-year modeling analysis for this study.

Table ES-2 summarizes CMAQ-simulated base and future-year mercury deposition (per unit area) for Virginia.

Table ES-2. Mercury Deposition Totals (g km^{-2}) for Virginia.

Region	2001/2002	2010	2015	2018
Virginia	22.7	18.6	18.2	18.1

Compared to the base year, the percent reduction in simulated mercury deposition is 18 percent for 2010, 19.9 percent for 2015, and 20.5 percent for 2018.

In this study, AERMOD was used to examine the effects of emissions changes on local deposition. Table ES-3 displays the average emissions for each year examined for the AERMOD sources (the fifteen facilities in Virginia with the most mercury emissions in 2002).

Table ES-3. Average Mercury Emissions (lbs/yr) for the Top 15 Mercury Emitters in the Commonwealth of Virginia, Based on Emissions for 2002.

	2001/2002	2010	2015	2018
All 15 Sources	130.7	75.4	69.1	65.5

Compared to the base year, the mercury emissions from the top 15 emitting sources are reduced by 40.7 percent for 2010, 44.2 percent for 2015, and 47.5 percent for 2018. These 15 sources include both EGU and non-EGU sources and emissions from both sectors are substantially reduced in all three future years. The corresponding percent reduction in mercury deposition from these sources (averaged over all 15 sources) is 40.6, 44.1 and 51.4 percent, respectively, for 2010, 2015 and 2018. For this subset of sources, the local reduction in mercury deposition from non-EGU sources is, on average, greater than that for EGU sources. This reduction in local deposition is consistent with a greater reduction in emissions for the non-EGU sources.

Source apportionment (CMAQ/PPTM) was applied for selected sources and source regions for the base year and 2018. The first CMAQ/PPTM scenario examined the contributions from mercury air emissions sources in 1) Virginia, 2) surrounding states (in the remainder of the 12-km modeling domain), 3) all other U.S. states (outside of the 12-km domain), 4) Canada and Mexico, 5) global emissions sources, and 6) natural emissions to mercury deposition in Virginia. The second CMAQ/PPTM scenario quantified the contributions from EGU and non-EGU facilities in Virginia and the surrounding states.

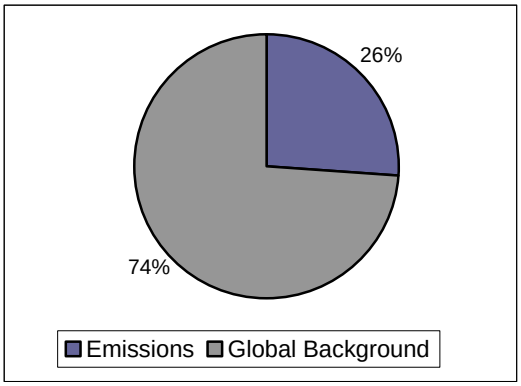
CMAQ/PPTM results for the entire state are presented in Figure ES-2. In this figure, the total deposition for the grid cell is given at the top of the page. The pie chart in the upper left-hand corner of the display summarizes the percent contribution to total deposition from emissions versus global background concentrations (represented in the modeling by the initial and boundary conditions (IC/BCs)). Global background refers to mercury that is circulated around the earth, and sources both within and outside of the modeling domain may contribute to the global background concentrations. The bar chart in the upper right-hand corner attributes total (overall) and emissions-based deposition to wet and dry deposition. Note that the total or overall deposition is the sum of the deposition from both emissions and global background sources. In the next two pie charts, the contributions from emissions sources are broken out in detail. The middle pie chart includes all tags. The lower pie chart does not include the global background and natural emissions source tags. Without the global background and natural emissions contributions, the

lower pie chart allows a more detailed comparison of the local and regional anthropogenic source contributions. Deposition is given in terms of the deposition per square kilometer.

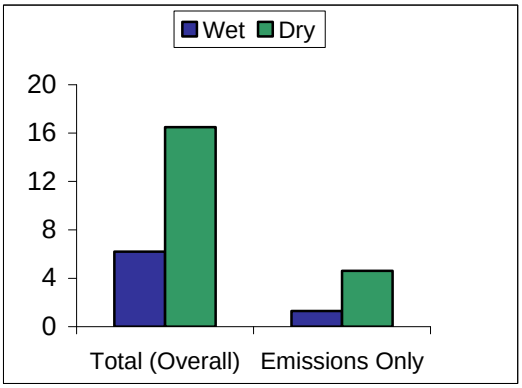
Figure ES-2. Summary of CMAQ/PPTM Mercury Tagging Results for Virginia.

Simulated Annual Hg Deposition for 2001 for Virginia: 22.69 g/km²

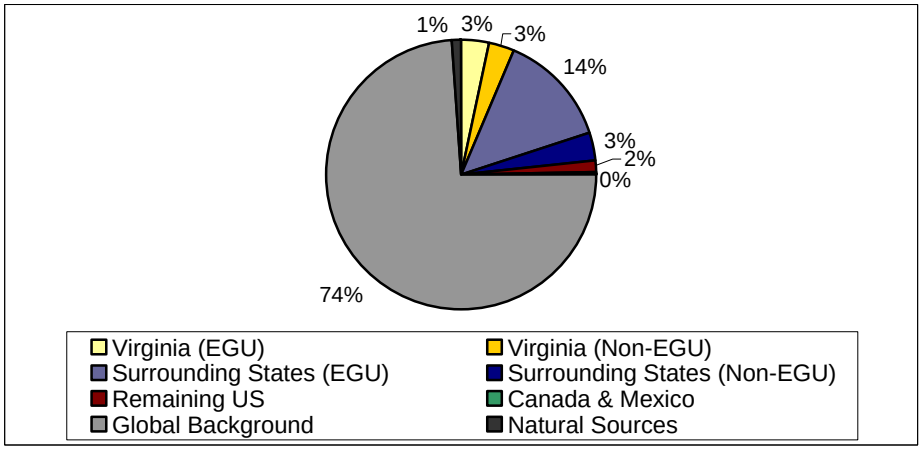
Emissions vs. Global Background Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

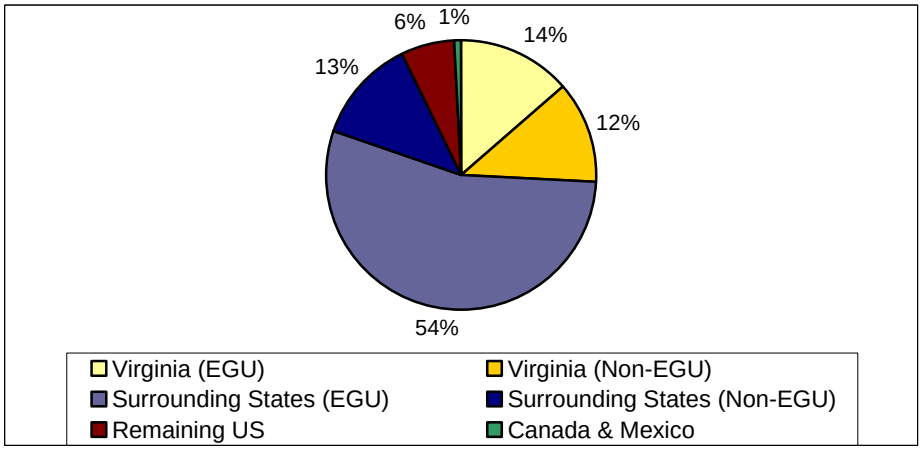
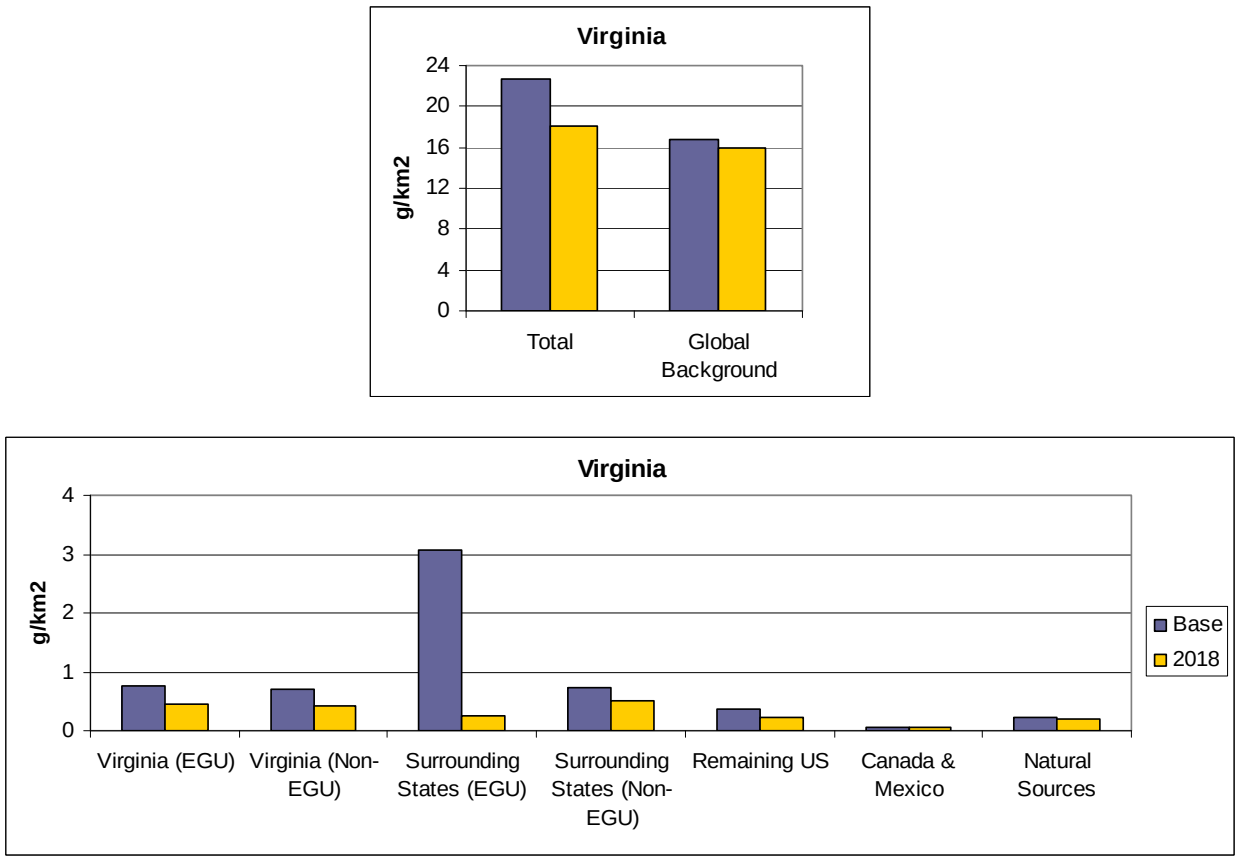


Figure ES-3 displays the relative contribution from each of the tagged source regions and source categories to mercury deposition for Virginia for both 2001/2002 and 2018. Global background (represented in the modeling by the initial and boundary condition (IC/BC) tag) is a primary contributor to simulated mercury deposition. The second largest contribution is from EGU sources in the surrounding states. This is followed by EGU sources in Virginia, non-EGU sources in Virginia, non-EGU sources in the surrounding states, sources in the remainder of the U.S., and natural sources.

Figure ES-3. CMAQ/PPTM 12-km Mercury Tagging Results for Virginia for 2001/2002 and 2018.



The contributions from all sources are lower for 2018. Although the IC/BC and natural emissions inputs are the same for both years, their contributions are lower for 2018 due to lower regional-scale ozone concentrations in the future year. Ozone and other oxidants influence mercury chemistry and lower ozone concentrations lead to less oxidation of certain forms of mercury and less mercury deposition. Of primary interest for this analysis is the change in contribution from the non-background/anthropogenic sources.

Overall mercury deposition for Virginia is lower by 20.4 percent for 2018, compared to the base year. The change in deposition is the result of changes in emissions from the various source categories and regions and the tagging results can be used to attribute the changes in deposition to the tagged source categories and regions. The greatest reduction comes from EGU sources located outside of Virginia (in the 12-km modeling domain that encompasses several nearby states), and 61 percent of the reduction in mercury deposition for Virginia is attributable to reductions in emissions from EGU sources in these nearby states. In addition, 7.2

percent of the overall simulated mercury reduction for Virginia is attributable to reductions in the emissions from EGU sources located within the state, 5.7 percent is attributable to reductions in the emissions from non-EGU sources in the state, 4.6 percent is attributable to reductions in non-EGU sources in nearby states, and 2.8 percent is attributable to emissions reductions in the remainder of the U.S. While the global background and natural emissions estimates, as input to the model, are the same for both years, there is also a reduction in the contribution from these tags. This is due to lower regional-scale concentrations of ozone and other species in the future year, which results in less mercury deposition. About 18 percent of the overall reduction in deposition for Virginia is attributed to a lower contribution from the boundary conditions and less than one percent of the overall reduction is attributed to a lower contribution from natural emissions. Since the emissions changes are similar for all three future-years, it is expected that the attribution of the changes for 2018 can be also applied for 2010 and 2015.

When compared in a relative sense, the CMAQ and AERMOD modeling results agree very well. The AERMOD results indicate that mercury reductions from a given facility within the state will reduce local mercury deposition by a percentage that is similar to the emissions reductions. On a statewide basis, the CMAQ results indicate that the average reduction in mercury deposition from facilities within the state is comparable, on a percentage basis, to the average emissions reduction. Both models indicate that in-state controls are effective in reducing the in-state contribution to mercury deposition.

1. Introduction

This report summarizes the methods and results of a mercury deposition modeling study for the Commonwealth of Virginia. In this study, the Community Multiscale Air Quality (CMAQ) modeling system was used to estimate the regional, national, and global contributions to airborne mercury deposition for Virginia and to examine the effects of expected future-year emissions changes on the modeled deposition amounts. The American Meteorological Society (AMS)/Environmental Protection Agency (EPA) Regulatory Model (AERMOD) was used to simulate the effects of local emissions and emissions changes for selected areas and sources.

The modeling results provide a basis for quantifying the contribution of emissions sources to mercury deposition and evaluating the effectiveness of control measures in reducing mercury deposition. By quantifying deposition, the modeling results also provide a link between the analysis of mercury emissions and the assessment of the impacts of airborne mercury on the environment.

1.1. Background and Discussion of the Mercury Deposition Problem for Virginia

Human exposure to mercury is most commonly associated with the consumption of contaminated fish. Due to measured high levels of mercury in fish, at least 44 U.S. states have, in recent years, issued fish consumption advisories. These advisories typically suggest limits on the consumption of certain types of fish or not eating fish from certain bodies of water because of unsafe levels of mercury contamination. States have identified more than 6,000 individual bodies of water as mercury impaired and have issued mercury fish advisories for more than 2,000 individual bodies of water.

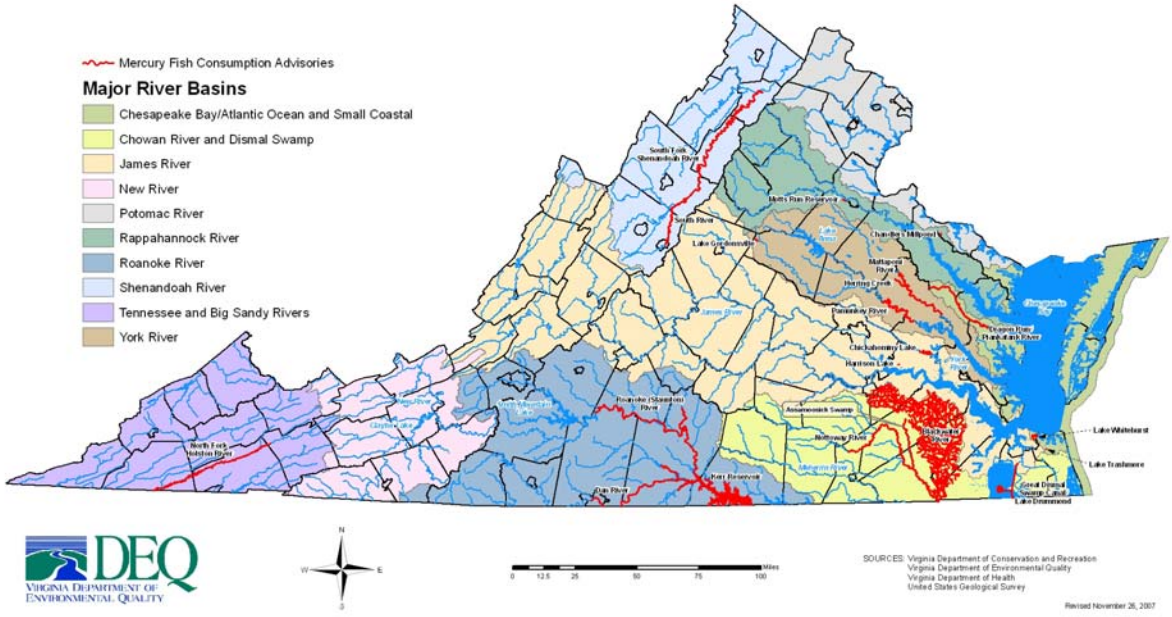
Until 2002, significant mercury contamination in Virginia surface waters was known only in three rivers (the North Fork of the Holston River, the South River, and the South Fork of the Shenandoah River) and was associated with historical industrial releases. Since then, however, state monitoring efforts have identified mercury contamination in a number of surface waters without readily identifiable sources.

The Virginia Department of Environmental Quality (VDEQ) expanded its mercury monitoring in 2002 based on an increasing scientific understanding of mercury's environmental chemistry and discoveries in other states (e.g., Florida, Maryland) of mercury pollution in water bodies without direct sources. The 2002 monitoring effort focused mostly on river basins in eastern Virginia. As a result of this effort, Virginia found elevated mercury levels in some fish in the Blackwater River, the Great Dismal Swamp Canal, the Dragon Run Swamp, and the Piankatank River. Consistent with findings from Florida and elsewhere, these water bodies in Virginia possess characteristics favorable for the formation of the highly bio-accumulative form of mercury, methyl mercury. These characteristics include low dissolved oxygen, high organic matter, and low pH, and are most prevalent in "backwaters" of the southeastern portion of the state.

Since that time, monitoring efforts have continued and fish consumption advisories have been issued for several bodies of water in Virginia. VDEQ has compiled a list of "mercury sensitive waters," the characteristics of which are consistent with mercury methylation and bioaccumulation of mercury in fish. These are primarily located along the coastal plain and include: Lake Gordonsville (in Louisa Co.), Lake Whitehurst (in Norfolk), Lake Trashmore (in Virginia Beach), a portion of the Mattaponi River, a portion of Herring Creek, a portion of the Pamunkey River, Chickahominy Lake (in Charles City Co.), Harrison Lake (in Charles City Co.), portions of the Blackwater River, a portion of the Dismal Swamp Canal, and Dragon Run

Swamp. Other areas suspected of being “mercury sensitive waters” for which monitoring was conducted in 2006-2007 include additional portions of the Blackwater River, the Nottoway River, and the Meherrin River. Figure 1-1 displays the waterways with fish consumption advisories.

Figure 1-1. Major River Basins and Waters under Fish Consumption Advisories for Mercury in Virginia.



The primary source of mercury to these water bodies is suspected to be atmospheric deposition. There are currently two Mercury Deposition Network (MDN) sites located in Virginia, in Shenandoah National Park and Harcum. A third site, located near Culpeper, was operational between late 2002 and 2006. Wet deposition data from these sites have contributed to the regional characterization of mercury transport and deposition throughout the state. Supplemental monitoring of dry deposition at the Harcum site in 2005 revealed that dry deposition of reactive gaseous (divalent) mercury along the Piankatank River (near the Chesapeake Bay) and in upstream areas is an important contributor to the high mercury levels observed in the water and fish in the area.

Global, regional, and local sources of air mercury emissions contribute to the deposition, and understanding these contributions is an important step toward identifying measures that will effectively reduce mercury deposition and environmental mercury levels.

The key objectives of the mercury deposition modeling analysis were to examine and quantify the contribution of global, regional and local emissions sources to mercury deposition throughout the Commonwealth, to examine the effects of future-year emissions changes on airborne mercury deposition, and to provide information to support the further analysis of the impact of mercury deposition on the environment.

The results of this study are currently being used by VDEQ to assess the effectiveness of planned emissions controls, evaluate the need for additional measures to reduce mercury emissions in Virginia, and develop a long-term management strategy for meeting water quality criteria and protecting human health.

1.2. Overview of Mercury Deposition Modeling

Several different types of modeling and analysis tools have been developed and applied to the study of mercury deposition. Modeling tools differ primarily in terms of overall numerical formulation (e.g. grid based (Eulerian), trajectory (Lagrangian), plume (Gaussian) formulations), treatment of mercury chemistry and other processes (such as deposition and the effects of meteorology), and applicable scales (e.g. global, regional, local). In addition, data analysis techniques such as receptor modeling have also been used to study mercury deposition. A portion of the literature review contained in Appendix C of this report summarizes the ongoing development of mercury capabilities in air quality modeling and some recent national- and regional-scale applications.

Grid-based models are designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere. Two state-of-the-science, regional air quality modeling systems for mercury deposition are CMAQ and the REgional Modeling System for Aerosols and Deposition (REMSAD), both of which were developed under funding from EPA and both of which have been used for national- and regional-scale regulatory assessments. The CMAQ model was designed as a "one-atmosphere" model and can be used to simulate ozone, particulate matter, and mercury. CMAQ supports the detailed simulation of the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury.

According to Bullock et al. (2008), the CMAQ model reflects the current state-of-the-science in simulating the atmospheric processes that influence the dispersion, advection, chemical transformation, and deposition of mercury. The CMAQ model includes three mercury (Hg) species: elemental mercury (Hg^0 or HG0), reactive gaseous mercury (RGM or HG2), and particulate mercury (PHg or HGP). Throughout the remainder of this report, these three forms of mercury are referred to as HG0, HG2, and HGP. Reactive gaseous mercury is known to be comprised almost entirely of divalent mercury (Hg^{2+}), since Hg compounds at other valence states tend to be chemically unstable in the atmosphere. Particle-bound mercury is also primarily comprised of divalent mercury, but may also include elemental mercury.

In addition to the state-of-the-science chemical mechanism for mercury, other key features of the CMAQ model in simulating mercury deposition include state-of-the-science advection, dispersion and deposition algorithms, the latest version of the Carbon Bond chemical mechanism (CB05), and the CMAQ Particle and Precursor Tagging Methodology (PPTM).

PPTM for mercury (Douglas et al., 2006) provides detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified.

Several areas of potential uncertainty that affect grid-based models such as CMAQ include: representation of emissions (including natural emissions), boundary conditions (global emissions) and meteorology; uncertainties in the chemical reaction rates; representing the dispersion and chemistry in plumes; and accounting for the deposition of elemental mercury and re-emission of mercury.

Trajectory models are an alternative to grid-based modeling. In these models, the transport of emissions from specific sources (or to specific receptor locations) is estimated using forward (or backward) trajectories. The movement of air parcels along the trajectories is guided by

meteorological parameters (such as wind and stability) and the contents of each air parcel may be subject to dispersion and chemical transformation (depending upon the complexity of the model). Examples of trajectory based models include CALPUFF and HYSPLIT. Use of the HYSPLIT model for mercury deposition modeling is discussed in Cohen et al. (2004) and in Cohen (2004). The authors estimate contributors to mercury deposition to the Great Lakes and the Chesapeake Bay. The results tend to differ from grid-based modeling estimates in that very distant sources are estimated to contribute to deposition loading. Trajectory modeling is not well suited for simulating contributions from distant sources since the uncertainty of any given trajectory increases with the time (and thus distance between the source and receptor).

Gaussian dispersion (or plume) models are designed to simulate the local-scale dispersion and deposition of pollutants. Currently, the most widely used model of this type is AERMOD (EPA, 2004). AERMOD is a steady-state Gaussian dispersion model designed to simulate the local-scale dispersion of pollutants from low-level or elevated sources in simple or complex terrain. It is an EPA "preferred" model (40 CFR Part 51, Appendix W, *Guideline on Air Quality Models*). Recent versions of AERMOD (EPA, 2006a) include algorithms for simulating deposition of gaseous and particulate pollutants. AERMOD can also be used to simulate the effects of local emission changes for selected areas and sources. Typical applications of AERMOD limit the analysis of results to within approximately 10 kilometers (km) of the source location.

AERMOD does not include a chemical mechanism for mercury. That is, AERMOD can be used to simulate the dispersion and deposition of mercury, but not the chemical transformation of mercury. However, this may not be an important limiting factor for near-source assessments. Wet and dry deposition can be estimated using AERMOD. The wet deposition algorithms use a washout ratio that is dependent on precipitation rate and the properties of the pollutant being simulated. Dry deposition is based on aerodynamic resistance calculations and the deposition velocities are calculated based on surface type and local meteorological conditions. An important limitation of Gaussian models such as AERMOD is the simple representation of the meteorological conditions (important but complex meteorological features cannot be represented). Representing the effects of complex terrain (such as that found in western Virginia) and land-use are also sources of uncertainty.

Receptor modeling, as applied to mercury deposition, uses a combination of observed wet deposition data, air quality data, meteorological data, and information about emissions source characteristics (e.g., location, emissions process, speciation) to identify potential sources or source categories that may be contributing to observed deposition. Examples of statistical-based receptor modeling approaches include the Positive Matrix Factorization (PMF) and UNMIX tools. One limitation of receptor modeling is that meteorological conditions are generally not considered or are represented by a few simple parameters. In some cases, receptor modeling has been combined with trajectory modeling as a way to better incorporate the effects of meteorology and narrow down the source-receptor relationships. However, as noted earlier, the uncertainties associated with trajectory modeling, which increase with distance from the receptor location, may also add to the uncertainties in the hybrid source-receptor modeling results. Other limitations of source-receptor modeling include the need for very high resolution, comprehensive data to establish the contributing source profiles and reliance on statistical rather than physical and chemical relationships to infer source attribution.

1.3. Summary of the Mercury Deposition Modeling Approach for Virginia

The Virginia mercury deposition modeling includes the use of several different types of air quality and deposition models. These include a state-of-the-science regional modeling system with source-contribution-assessment capabilities to simulate and quantify the effects of national and regional emissions on mercury deposition, and a Gaussian model for the detailed assessment of local contributions. In addition, boundary conditions for the regional model are based on the output from a global model. The approach was designed to account for the different scales and chemical interactions important to mercury deposition. Model selection is discussed in detail in the modeling protocol, which is included as Appendix A.

At the regional scale, the latest version (version 4.6) of the Community Multiscale Air Quality (CMAQ) modeling system was applied. The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere. The CMAQ modeling system supports the detailed simulation of mercury (Hg), including the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury.

The CMAQ Particle and Precursor Tagging Methodology (PPTM) for mercury was used in this study to provide detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Using this methodology, mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources.

The CMAQ modeling domain for this study includes an outer grid that encompasses the entire contiguous U.S. as well as portions of Canada and Mexico and, therefore, all or nearly all mercury emissions sources in North America. The horizontal resolution of the outer, coarse grid is 36 kilometers (km). The domain also includes a higher-resolution inner grid that encompasses Virginia and several surrounding states. Boundary concentrations for the regional-scale modeling (applied to the outermost grid) were estimated based on global model simulation results.

At the local scale, the EPA Gaussian model AERMOD was applied for selected point sources in the Virginia emissions inventory. Initially, AERMOD was used to screen the mercury emissions sources to determine the potential for impacts outside the vicinity of the source. AERMOD was also used to simulate the effects of local emission changes for selected areas and sources.

Both CMAQ and AERMOD were applied for an annual simulation period corresponding to a base year which, as detailed later in this report, is primarily 2001 but some of the emissions inputs are for 2002. Throughout the report, the base-year scenario is referred to as either the “base year” or the “2001/2002 base year.” The models were also applied for three future years: 2010, 2015 and 2018. PPTM was applied for selected sources and source regions for the 2001/2002 base year and 2018. Emissions inputs for the application of CMAQ and AERMOD were prepared using the latest available emissions data and projections, as obtained from VDEQ and EPA. Model-ready meteorological input files for 2001 and other requisite input files for CMAQ were provided by EPA. Meteorological inputs for AERMOD were prepared using available meteorological data for this same period.

The components of the base- and future-year modeling analyses are summarized in Figure 1-2. Figure 1-2a displays the components of the base-year modeling analysis. This includes the evaluation of model performance as well as diagnostic and sensitivity tests to examine the response of each modeling system to changes and/or uncertainties in the inputs. Figure 1-2b displays the components of the future-year modeling. The combination of modeling tools selected for this study has allowed us to address the variety of factors influencing mercury deposition in Virginia. Projection to the future years has provided information on the potential effects of future emissions changes and the effectiveness of potential emissions controls on mercury deposition.

Figure 1-2a. Schematic Diagram of the Virginia Mercury Deposition Modeling Analysis: Base-Year Modeling.

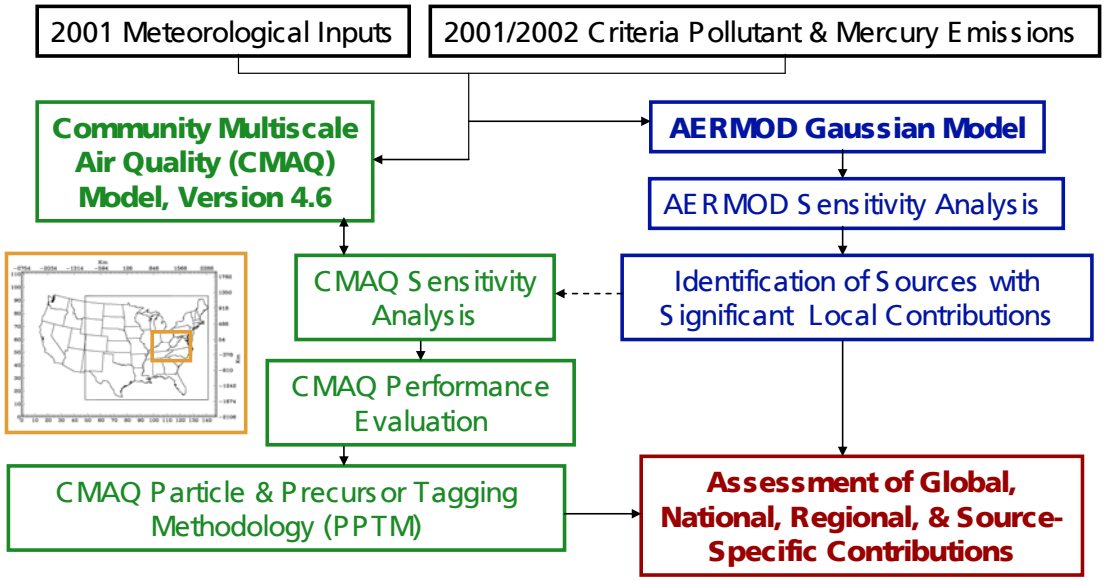
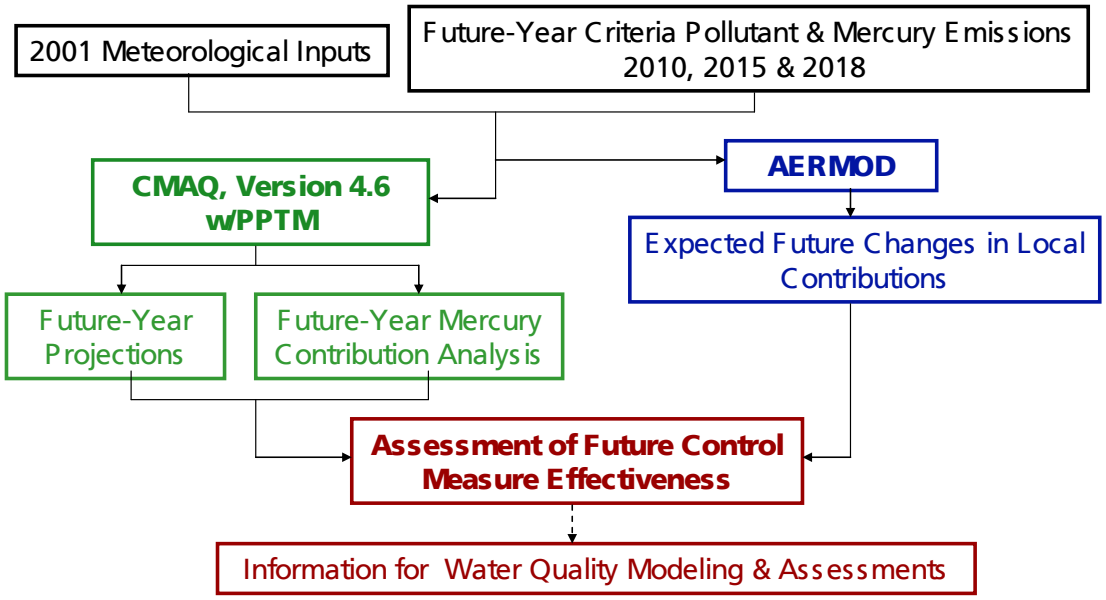


Figure 1-2b. Schematic Diagram of the Virginia Mercury Deposition Modeling Analysis: Future-Year Modeling.



1.4. Report Contents

The methods and results of the mercury deposition modeling are presented in the remainder of this report. Section 2 provides a conceptual description of mercury deposition for Virginia. Sections 3 and 4 provide details of the grid-based (CMAQ) and source-specific (AERMOD) modeling methodologies, respectively. Section 5 presents the CMAQ modeling results. Section 6 presents the AERMOD modeling results. Section 7 summarizes the results and findings from the mercury deposition assessment. The report also contains three appendixes. The modeling protocol is included as Appendix A. The conceptual model report, prepared earlier in the study, is provided as Appendix B. Finally, the emissions data analysis report, summarizing a review of the mercury emissions data that were used in the modeling, is provided in Appendix C.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2. Conceptual Description of Mercury Deposition for Virginia

A conceptual description for mercury deposition for Virginia was developed at the beginning of this study and is presented in Appendix B. This conceptual description is based on observed mercury deposition data, meteorological data, and emissions inventory information. It also draws on mercury deposition modeling results from prior studies. The key elements of the conceptual description are summarized and updated in this section of the report, based on the latest data and mercury deposition modeling results (which are presented later in this report).

Mercury wet deposition data are available for three Mercury Deposition Network (MDN) sites in Virginia: Culpeper, Shenandoah National Park, and Harcum (NADP, 2008). The period of record for the MDN data is late 2002 through 2006 for Culpeper, late 2002 to the present for Shenandoah, and approximately 2005 to the present for the Harcum site. The Culpeper site was located in north central Virginia. The Shenandoah site is a high elevation monitoring site located within the national park (in northwestern Virginia), and the Harcum site is located along the southern portion of the inner coast of the Chesapeake Bay. The locations of the sites are shown in Figure 2-1, along with the locations of MDN sites in several neighboring states (which will be referenced later in this section). Each measurement of wet deposition represents an approximate seven-day period. Annual mercury wet deposition for these sites is summarized in Table 2-1. The units are nanograms per square meter (ng m^{-2}).

Figure 2-1. Locations of MDN Monitoring Sites in Virginia and Neighboring States.

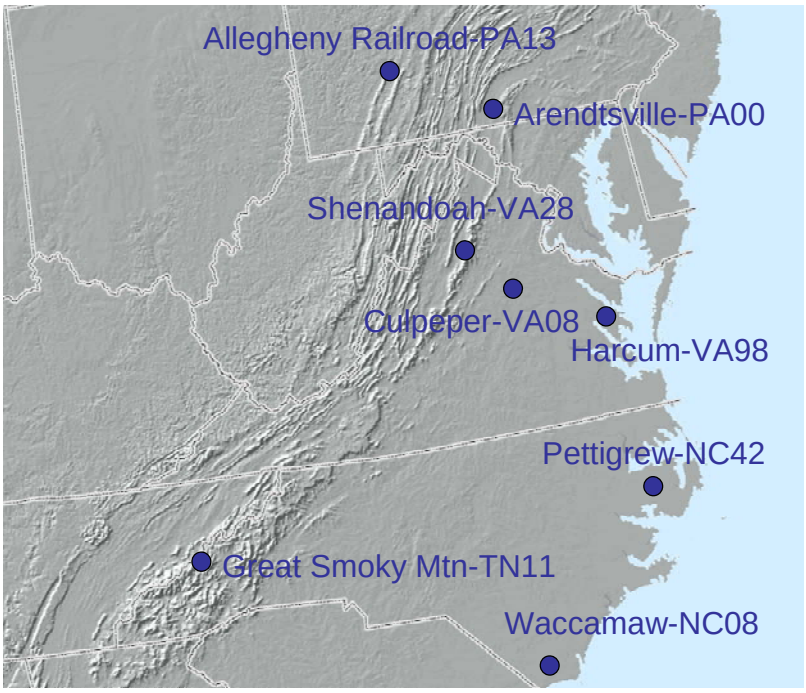
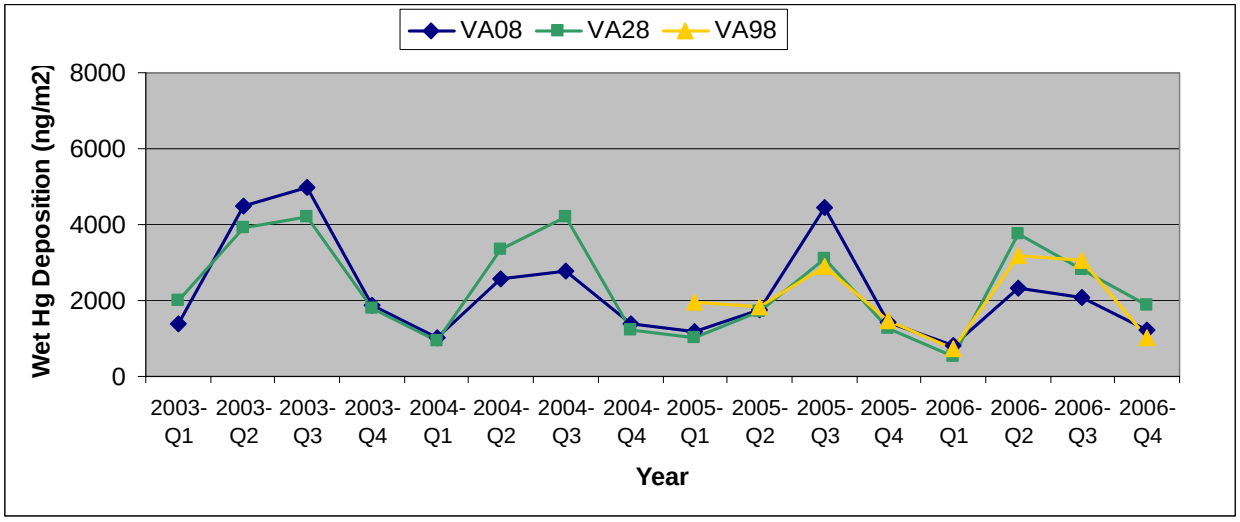


Table 2-1. Summary of Annual Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

Site Name (MDN ID)	Annual Observed Mercury Wet Deposition (ng m^{-2})			
	2003	2004	2005	2006
Culpeper (VA08)	13,097	7,784	8,811	6,463
Shenandoah National Park (VA28)	11,922	9,727	7,074	8,986
Harcum (VA98)	—	—	8,218	8,029

Within each calendar year, there are variations in deposition by week, month, and quarter, primarily in accordance with variations in rainfall amount. Figure 2-2, which displays quarterly deposition amounts, indicates that, like rainfall, mercury deposition has an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively). The deposition amounts are generally similar among the three sites.

Figure 2-2. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for the Three MDN Monitoring Sites in Virginia.



Analysis of both the data and recent modeling results has provided insight into some key questions regarding the nature of mercury deposition. Key questions and issues addressed in the conceptual description are summarized in the remainder of this section.

- **Is mercury deposition primarily a local issue, or are regional, national, and global factors important?**

  Based on a review of the available data and prior modeling results, it is expected that global, national, regional, and local factors contribute to mercury deposition in Virginia. The primary source of mercury to impaired water bodies is believed to be atmospheric deposition, which is comprised of both natural and anthropogenic emissions. These emissions can be directly emitted or they can be re-emitted to the atmosphere after being deposited at another location.

Various atmospheric processes influence the transport and deposition of mercury and these involve a variety of scales ranging from global to local. Specifically:

- Mercury may be transported globally by atmospheric circulation systems and prior (Myers et al., 2006) and current mercury deposition modeling results (from the Virginia mercury study) indicate that global background may comprise 60 to 75 percent of the contribution to mercury deposition at the Virginia MDN sites.
- Mercury may also be subject to regional-scale transport. Modeling also indicates that emissions contributing to the simulated deposition are from Virginia, the neighboring states, and other states within the U.S. Similarities in observed mercury wet deposition among monitoring sites in Virginia and several neighboring states also support the conclusion that mercury deposition is a regional-scale issue.
- Finally, prior and current modeling also reveals local source-specific contributions to mercury deposition at the three monitoring sites.

- **Does mercury deposition vary with time?**

  Annual mercury wet deposition amounts vary by year for monitoring sites in Virginia and the surrounding states.

  In addition, within each calendar year, there are variations in deposition by week, month, and quarter, primarily in accordance with variations in rainfall amount.

  Mercury deposition (and rainfall amount) appears to have an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively). As illustrated later in this section, this annual cycle is consistent with that for precipitation.

- **Does mercury deposition vary from location to location?**

  Measurements of wet mercury deposition data indicate that deposition varies from location to location. For the period 2003-2005, annual mercury deposition for the Virginia MDN sites is about the same as that for nearby sites in southern Pennsylvania, and lower than that for nearby sites in North Carolina and Tennessee. In some cases, deposition characteristics are similar for geographically similar sites within the mid-Atlantic region. For each of the Virginia MDN sites, it is possible to identify a monitoring site (from a neighboring state) that has similar deposition characteristics.

  Prior modeling performed by EPA (EPA, 2005a) and the current regional modeling results for the Virginia mercury study also indicate that mercury deposition varies from location to location and more specifically that annual mercury deposition is related to the distribution of emission sources, especially within the eastern U.S.

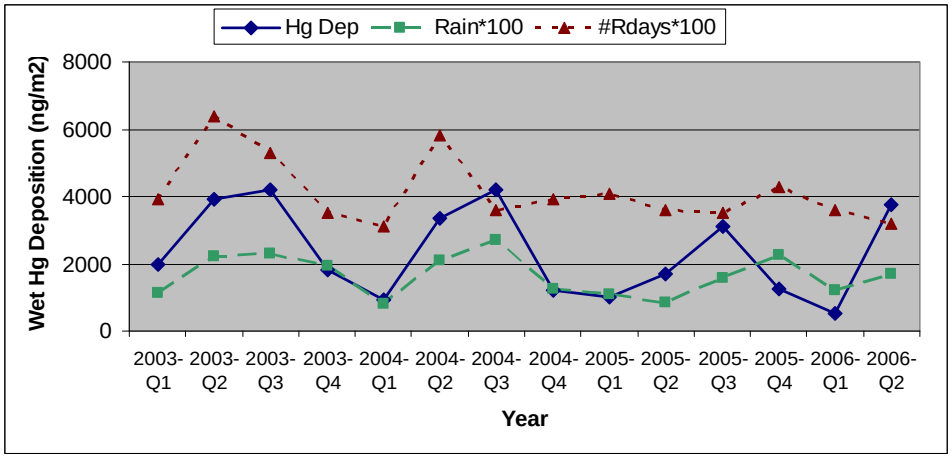
  At the local level, the source-specific modeling indicates that there may be areas of high deposition close to mercury emitting sources.

- **How does meteorology influence mercury deposition in Virginia?**

  A number of different meteorological factors influence mercury deposition in Virginia. Key factors include precipitation, temperature, wind speed, and the potential for recirculation. The relative importance of each of these factors varies among the three monitoring sites. In addition, there are different types of meteorological conditions and combinations of parameters that lead to high deposition.

Precipitation is an important mechanism for wet mercury deposition. Mercury wet deposition is correlated with rainfall, but rainfall amount does not fully explain the observed variations in deposition. As an example, Figure 2-3 compares quarterly mercury wet deposition with rainfall amount and number of days with measurable rainfall for the Shenandoah MDN site (VA28). For plotting purposes, rainfall amount has been multiplied by 100, such that a value of 2000 corresponds to 20 inches of rainfall in a given quarter. The number of rain days has also been multiplied by 100, such that a value of 2000 corresponds to 20 days with rain in a given quarter. Both mercury wet deposition and precipitation are measured at the MDN site. This comparison indicates that mercury deposition is affected by the amount and frequency of precipitation, but that there are also other factors that influence mercury deposition.

Figure 2-3. Quarterly Observed Mercury Wet Deposition (ng m^{-2}), Total Rainfall (Scaled to Inches x 100), and Number of Days with Rainfall (Scaled by 100): Shenandoah National Park (VA28).



For all three MDN sites, there is a positive correlation between rainfall, temperature, and relative humidity such that the greater the values of these parameters, the greater the deposition. Higher deposition is associated with lower wind speeds and a well mixed (or unstable) atmosphere. The conditions are representative of summertime conditions and consistent with the timing of the higher observed deposition amounts.

Wind directions, both near the surface and at upper levels, may influence the regional and local transport of mercury emissions from source regions or individual sources for subsequent deposition at the monitoring sites (and to bodies of water) in Virginia. For all three MDN sites, wind directions are slightly different during high deposition periods compared to all periods and indicate possible regional or local transport of mercury emissions from the east or northeast for Culpeper and Shenandoah, and from the south or southwest for Harcum.

Finally, dry deposition of mercury is influenced by several meteorological factors including the temperature characteristics of the atmosphere and the wind speed.

- **Are there discernable trends in mercury deposition and have recent changes in deposition been accompanied by changes in emissions or primarily driven by meteorological variability?**

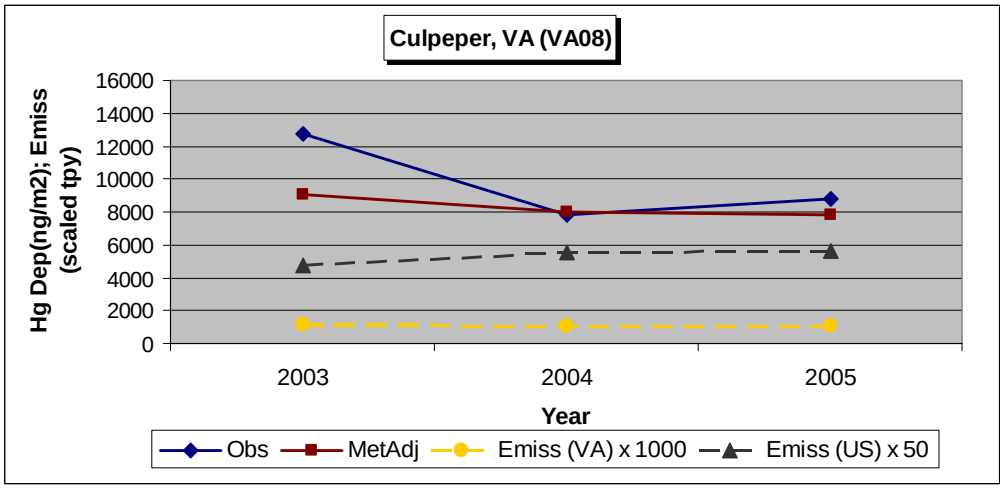
  Variations in meteorology contribute to observed variations in quarterly and annual mercury wet deposition.

  Annual deposition amounts that have been adjusted to account for these variations in meteorology exhibit much less variation among the years. Figure 2-4 shows observed and meteorologically adjusted deposition values along with the EPA Toxics Release Inventory (TRI) emissions (EPA, 2007a) for Virginia and the entire U.S. Note that for plotting purposes, the emissions totals for Virginia (tons per year (tpy)) have been multiplied by 1000 and the emissions totals (tpy) for the U.S. have been multiplied by 50.

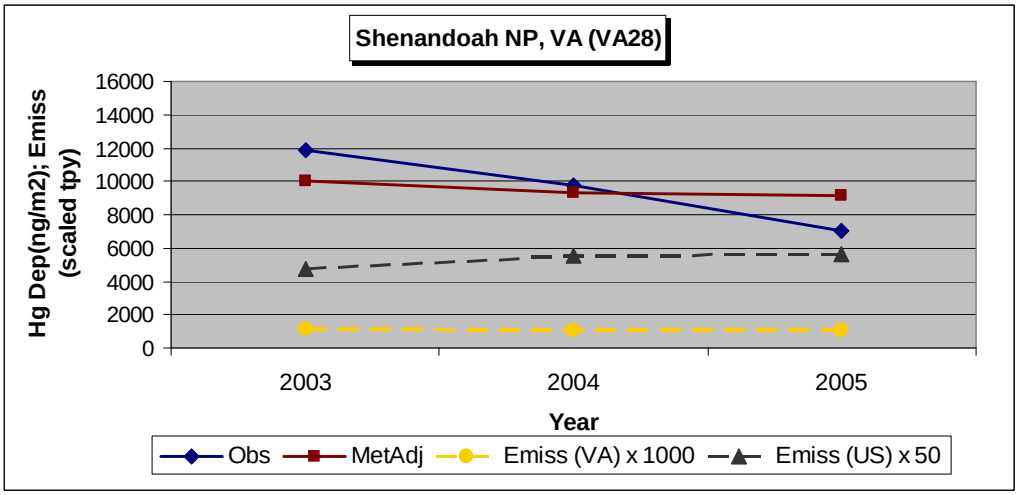
Figure 2-4. Actual and Meteorologically-Adjusted Annual Mercury Wet Deposition (ng m-2) for MDN Monitoring Sites in Virginia Plotted Together with TRI Annual Mercury Emissions Totals (scaled tpy) for Virginia and the Entire U.S.

Note that the Emissions are Scaled to Enable Display of the Different Datasets and Comparison of the Tendencies.

(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



For both sites, the meteorologically adjusted deposition values for 2003-2005 are consistent with changes in the emissions for Virginia. The adjusted deposition values indicate a slight downward trend.

Similarly, for sites in Pennsylvania and North Carolina, the meteorologically adjusted deposition trends for 2000-2005 are consistent with changes in the U.S. emissions. For 2003 to 2005 the trend is slightly upward, in contrast to that for the Virginia sites.

- **What is the relative importance of wet versus dry deposition, and the various forms of mercury?**

  Prior and current regional modeling results suggest that for all three Virginia sites, dry deposition is a significant contributing factor to total mercury deposition. Overall, for these studies, the simulated dry deposition represents about 45 percent or more of the total deposition. Prior modeling also indicates that both wet and dry deposition are predominantly reactive gaseous mercury, and that dry deposition includes about 10 percent particulate mercury.

  The implications regarding dry deposition are consistent with monitoring data. The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) conducted a monitoring study during the summer of 2005 at the Harcum site (NOAA, 2007) and found that dry deposition was significant and was dominated by reactive gaseous mercury.

  Source-specific modeling results also indicate a predominance of dry deposition. Wet deposition is modeled to occur near the source, while dry deposition occurs both near the source and downwind. This type of modeling suggests that, near the source locations, particulate-bound mercury deposition is greatest followed by reactive gaseous mercury deposition.

3. Grid-Based Mercury Deposition Modeling Methodology

The Community Multiscale Air Quality (CMAQ) model was used to simulate mercury deposition at the regional scale. This section of the report describes the methodology for the application of CMAQ.

3.1. Selection and Overview of CMAQ Version 4.6 with PPTM

The selection of CMAQ as the primary modeling tool for the Virginia mercury study was based on the technical formulation, capabilities, and features of the model. In accordance with EPA guidance (EPA, 2006b), its peer-review status and use in previous applications was also considered.

The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere (Byun and Ching, 1999). The CMAQ model was designed as a "one-atmosphere" model and can be used to simulate ozone, particulate matter, and mercury. For mercury, CMAQ supports the detailed simulation of the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury. The latest version of CMAQ, version 4.6, was used for this study.

According to Bullock et al. (2007), the CMAQ model reflects the current state-of-the-science in simulating the atmospheric processes that influence the dispersion, advection, chemical transformation and deposition of mercury. The CMAQ model includes three mercury (Hg) species: elemental mercury (HG0), reactive gaseous mercury (HG2), and particulate-bound mercury (HGP). Reactive gaseous mercury is known to be comprised almost entirely of divalent mercury (Hg^{2+}), since Hg compounds at other valence states tend to be chemically unstable in the atmosphere. Particulate-bound mercury is also primarily comprised of divalent mercury, but may also include elemental mercury.

Mercury simulation capabilities were first incorporated into the CMAQ model by adding gaseous and aqueous chemical reactions involving mercury to the CMAQ chemical mechanism (Bullock and Brehme, 2002). Since that time, the chemical mechanism has been further updated to include additional reactions and updated information on reaction rates. The most recent changes to CMAQ for mercury include an improved dry deposition algorithm and the incorporation of natural mercury emissions. The CMAQ modeling system, including the mercury modeling component, has been peer reviewed (e.g., Amar et al., 2005).

In addition to the state-of-the science chemical mechanism for mercury, other key features of the CMAQ model in simulating mercury deposition include state-of-the-science advection, dispersion and deposition algorithms, the latest version of the Carbon Bond chemical mechanism (CB05), and the CMAQ Particle and Precursor Tagging Methodology (PPTM).

PPTM for mercury (Douglas et al., 2006) provides detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources.

The CMAQ model has been used by EPA to support the development of the Clean Air Mercury Rule (CAMR) (EPA, 2005a). This study included the evaluation of global modeling results to prescribe boundary conditions for CMAQ, evaluation of mercury deposition using MDN data, and assessment of the contribution of mercury emissions from coal-fired power plants on mercury deposition in the U.S.

CMAQ was also included in the North American Mercury Model Intercomparison Study (NAMMIS) (Bullock et al., 2008) and the performance and response of CMAQ was found to be reasonable and also consistent with that for the REgional Modeling System for Aerosols and Deposition (REMSAD), which has been widely applied and tested for mercury (e.g., Myers et al., 2006).

Additional detail regarding the selection of the CMAQ model is provided in the modeling protocol document (Appendix A).

3.2. CMAQ Application Procedures for the Virginia Mercury Deposition Modeling Study

The application of CMAQ, including the simulation period, modeling domain, input preparation, performance evaluation, and base-case and future-year modeling, are discussed in this section.

As noted throughout this section, many of the components of the modeling analysis were based on the CAMR modeling, including the outer modeling domain, simulation period, meteorological inputs, and national-scale emission inventories. Key differences between this analysis and the CAMR modeling analysis include the use of a high-resolution modeling domain over Virginia and the surrounding states, updated emissions estimates, in particular for Virginia, and the use of CMAQ version 4.6 with PPTM.

3.2.1. Simulation Period

The simulation period for the application of CMAQ is calendar year 2001. All of the inputs, with the exception of the mercury emissions for Virginia, represent 2001. In running the model, the simulation period was divided into two parts covering January through June and July through December, respectively. Each part of the simulation also includes an additional five start-up simulation days, which are intended to reduce the influence of uncertainties in the initial conditions on the simulation results.

In selecting this simulation period, meteorological and emissions database availability and meteorological representativeness were considered. Additional detail regarding the selection of the simulation period is provided in the modeling protocol document (Appendix A).

The 2001 simulation period is characterized by normal precipitation amounts during the summer months for Virginia and most of the surrounding areas, but less than normal precipitation during the fall period. Temperatures during the summer months were normal for 2001.

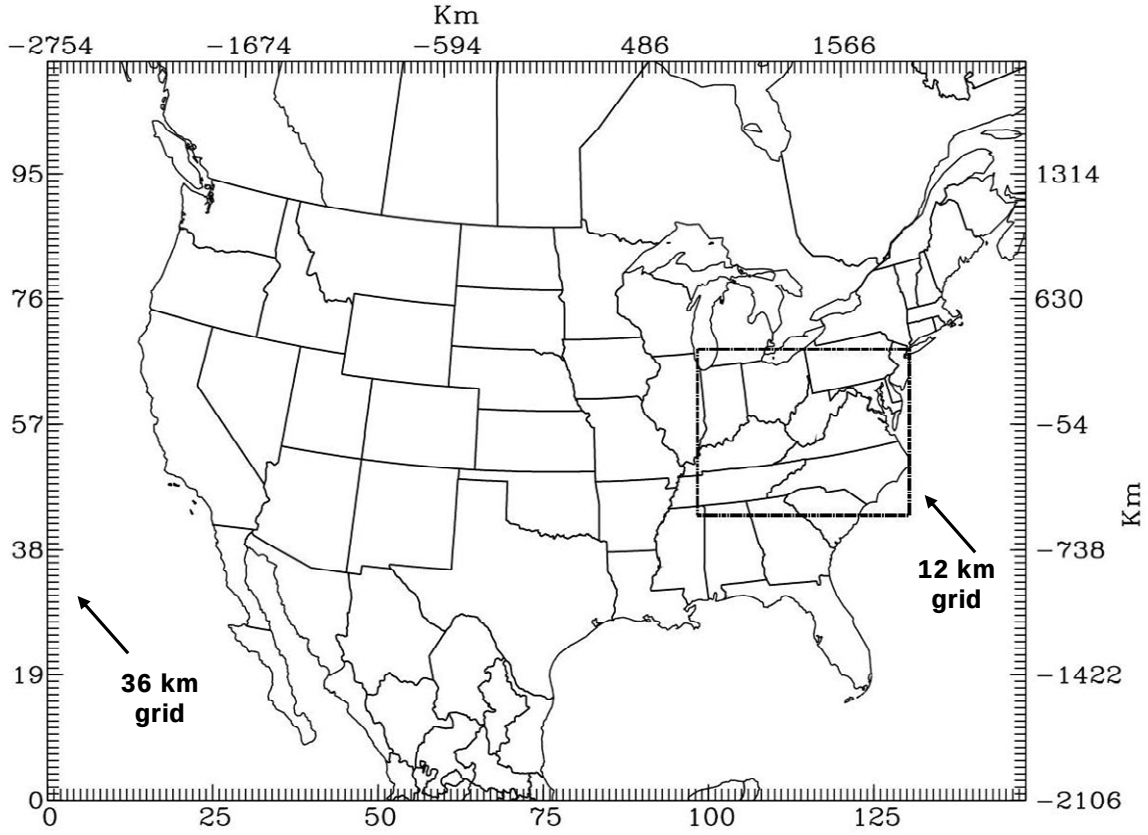
While 2001 was selected as the simulation period, sensitivity testing was conducted using 2002 meteorological inputs to examine the differences in the CMAQ results due to the use of alternative meteorological conditions.

3.2.2. CMAQ Modeling Domain

Horizontal Extent and Grid Spacing

The CMAQ modeling domain is illustrated in Figure 3-1. The outermost domain is based on the regional-scale modeling domain that has been established by EPA for regulatory applications (e.g. CAMR modeling). The outer grid encompasses the entire contiguous U.S. as well as portions of Canada and Mexico and, therefore, all or nearly all mercury emissions sources in North America. The horizontal resolution of the outer, coarse grid is 36 km. The inner grid focuses on Virginia and the surrounding states and has a horizontal grid resolution of 12 km.

Figure 3-1. CMAQ 36- and 12-km Resolution Nested-Grid Modeling Domain.



Vertical Structure

The CMAQ domain includes 14 vertical layers. CMAQ uses a sigma vertical coordinate system, which is a terrain-following vertical coordinate system with numerous numerical advantages. The vertical structure of the modeling domain is such that the highest resolution is achieved near the surface. The top of the modeling domain is approximately 10,000 m. The sigma layers and their approximate heights (under standard pressure conditions) are provided in Table 3-1.

Table 3-1. Vertical Levels that Define the CMAQ Modeling Domain.

Layer Number	Sigma	Height (m)
1	0.995	0
2	0.99	36
3	0.98	72
4	0.96	145
5	0.94	293
6	0.91	444
7	0.86	674
8	0.8	1074
9	0.74	1579
10	0.65	2115
11	0.55	2989
12	0.4	4078
13	0.2	6037
14	0	9733

3.2.3. Input Preparation

The mercury emission inventories used in the CMAQ modeling were prepared specifically for this study. Most of the other inputs were obtained from EPA and were used in prior EPA modeling studies.

Emission inventories

CMAQ requires hourly, gridded emissions for a number of different species, including criteria pollutants, related precursor species and mercury. The criteria pollutant portion of the inventory includes emissions for nitrogen oxides (NO_x), volatile organic compounds (VOC), sulfur dioxide (SO_2), ammonia (NH_3), primary particulates, and numerous other precursor species. These emissions are primarily used to simulate ozone and particulate matter, and certain species are also involved in reactions concerning mercury. The mercury portion of the emission inventory includes emissions for the three forms of mercury elemental (HG0), reactive gaseous (HG2), and particulate (HGP). The criteria pollutant and mercury emissions are typically prepared separately, and then merged to create a model-ready emission inventory.

For this study, CMAQ model-ready emission inventories were prepared for the base year using a combination of data for 2001 and 2002, and for the three future years 2010, 2015 and 2018 using projected emissions for these years.

BASE-YEAR EMISSION INVENTORIES

The 36- and 12-km model-ready criteria-pollutant emission inventories prepared by EPA for the 2001 annual simulation period were used to represent the criteria pollutants. The 36-km criteria pollutant emission inventory was used directly, since the VDEQ 36-km domain is the same as that used by EPA. The 12-km emissions for the VDEQ subdomain were extracted from a larger 12-km domain used by EPA. In both cases, the emissions were re-speciated for use with the CB05 chemical mechanism.

The mercury emissions inventory incorporates the latest mercury emissions data for point sources in Virginia for 2002. These emissions (along with emissions for 2005) were reviewed and updated

as part of this study to ensure that the methods used to calculate the emissions are valid, the data are complete, and that the emissions totals, locations, and stack parameters are correct. (Additional detail regarding the review of Virginia mercury sources is contained in Appendix C).

Baseline mercury emissions for all other areas and source categories were based on the latest version (version 3) of the 2002 National Emissions Inventory (NEI). Currently the NEI inventory does not include mercury emissions for motor vehicle or non-road sources. EPA estimates (EPA, 2007b) that emissions from these source categories represent less than five percent of the overall mercury emissions. In processing the base year emissions, ICF worked with EPA to correct a couple of errors for emissions sources in Pennsylvania where the emissions were unrealistically high. Natural, recycled, and volcanic (NRV) mercury emissions for all areas were extracted from the corresponding EPA 2001 emissions files.

The Sparse-Matrix Operator Kernel Emissions (SMOKE) processing system was used to process the mercury emissions for input to the CMAQ model. Following application of SMOKE, the quality assurance procedures outlined in the quality assurance plan for the project were applied to the emissions processing. SMOKE was then used to merge the criteria pollutant and mercury emissions into a model-ready emissions inventory for CMAQ.

FUTURE-YEAR EMISSION INVENTORIES

Future-year emission inventories were prepared for 2010, 2015, and 2018. Emissions projections were based on information available from EPA (e.g., CAMR (EPA, 2005b)) and from VDEQ (primarily through surveys; see Appendix C for addition information on the surveys).

The future-year criteria pollutant emissions inventories were based on future-year emission inventories prepared by EPA as part of the Clear Skies modeling analyses (EPA, 2003) as updated in 2005. For 2010 and 2015, the criteria pollutant emissions were extracted from EPA's 2010 and 2015 Clear Skies emissions inventory, respectively, and for 2018, the criteria pollutant emissions were extracted from EPA's 2020 Clear Skies emissions inventory. These inventories were projected from an earlier version of the NEI and prepared by EPA for the same 36-km domain used the Virginia mercury study. The emissions were re-speciated for use with the CB05 chemical mechanism and then used to represent the criteria pollutant emissions for the 36-km outer domain for the Virginia modeling study.

For the 12-km domain, the future-year criteria pollutant emissions from the 36-km resolution inventories were allocated to the 12-km grid using spatial allocation factors. The factors were developed using the base-year (2001)12-km emission inventory, as follows. The emissions for each set of nine 12-km grid cells corresponding to each 36-km grid cell were first combined. The percent of the combined emissions contained within each 12-km grid cell was calculated. The future-year emissions for each 36-km grid cell were then allocated to the 12-km grid cells according to this percentage. Using this approach, the spatial distribution of emissions within each 36-km grid cell is the same for the base and future years but the amount of emissions reflects the future year. For all three future-years, the criteria pollutant emissions were re-speciated for use with the CB05 chemical mechanism.

The mercury emission inventories were processed specifically for this study. For all areas of the domain, with the exception of Virginia, the future-year inventories were based on the EPA Clear Skies inventories. For 2010 and 2015, the mercury emissions were extracted from EPA's 2010 and 2015 Clear Skies emissions inventories, respectively, and for 2018, the emissions were extracted from EPA's 2020 Clear Skies emissions inventory. To reflect anticipated future growth in demand for electricity throughout the U.S., the Clear Skies inventories include a number of

generic Electric Generating Units (EGUs). The emissions for these units are small compared to the other sources (less than 50 pounds per year (lbs/yr)).

For Virginia, point source emissions estimates for each future year were provided by VDEQ (and are described in more detail in Appendix C of this report). Emissions for small landfill sources included in the 2002 NEI Version 3, but not in the VDEQ inventory, were incorporated and kept at 2002 levels for the future years. No generic EGUs were included for Virginia, since any new sources are expected to have low emissions and, to date, the locations and/or emissions of potential new sources have not been determined.

For all states, the future-year emissions estimates for mercury take into account the provisions of CAMR. The CAMR, promulgated on May 18, 2005, includes two mechanisms to reduce mercury emissions from electric power plants. First, it sets standards of performance for new and existing coal-fired power plants. Second, it establishes a two-phase, national cap-and-trade program. In the initial phase of the cap-and-trade program, the national mercury emissions will be capped at 38 tons and emissions reductions will occur as a "co-benefit" of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions under the Clean Air Interstate Rule (CAIR) issued on March 10, 2005. In the second phase, due in 2018, coal-fired power plants will be subject to a second cap, which will reduce emissions to 15 tons upon full implementation. Although the United States Court of Appeals for the D.C. District ruled on 8 February 2008 that EPA's CAMR was illegal, the original provisions of CAMR compliance, as estimated by VDEQ for Virginia sources and by EPA in their Clear Skies modeling inventories for all other states, were simulated in the future-year modeling analysis for this study. The future-year modeling conducted for this project was well underway by the time of the ruling.

In addition to CAMR, Virginia-specific laws were also accounted for in the future emissions projections. To participate in the federal cap-and-trade program, states must submit to EPA a State Implementation Plan revision that describes how the state will meet its mercury reduction budget under CAMR. States may adopt a "model rule" or a rule(s) with comparable provisions. Legislation enacted by Virginia in April 2006 (HB1055) authorized the Air Pollution Control Board to adopt and submit to EPA the model rule. As described below, the Virginia legislation also provided authority for state-specific rules to further control mercury emissions from sources regulated under CAMR. These are summarized by the following amendments to the Code of Virginia:

- § 10.1-1328 C—This section directs the Air Pollution Control Board to adopt and submit to EPA the CAMR "model rule" for participation in the federal mercury cap-and-trade trading program. The rule will include a set-aside of mercury allowances for new sources not to exceed 5 percent of the total state budget during the first five years and 2 percent thereafter.
- § 10.1-1328 D—This section is a state-specific (i.e., that exceeds the requirements of CAMR) rule. Its requirements are similar to the CAMR cap-and-trade program, but it applies to additional (smaller) sources and includes additional restrictions on compliance options.
- § 10.1-1328 E—This section directs the Air Pollution Control Board to adopt regulations governing mercury emissions that meet, but do not exceed, the requirements and implementation timetables for (i) any coke oven batteries for which the EPA has promulgated standards under § 112(d) of the Clean Air Act, and (ii) facilities subject to review under § 112(k) of the Clean Air Act and that receive scrap metal from persons subject to § 46.2-635 of the Code of Virginia.
- § 10.1-1328 F—This section is a state-specific rule that prohibits electric generating facilities in nonattainment areas from meeting mercury compliance obligations by purchasing credits from other facilities. An exception applies when the facility owner can demonstrate compliance using allowances at another of its facilities within 200 kilometers of the Virginia border.

These rules and provisions have been incorporated into the emissions estimates and the future-year emission inventories. The future-year emissions estimates also reflect the implementation timing and effects of the CAIR and CAMR emission reduction provisions (using the best available information at the time the work was conducted).

For quality assurance purposes, preparation of the future-year emissions included an analysis of expected emissions reductions, future-year trends for all source categories, and a comparison of Virginia emissions with neighboring states, regions, and national sources affecting Virginia.

As for the base-year, SMOKE was used to process the mercury emissions for each future year and to merge the criteria pollutant and mercury emissions into a model-ready emissions inventory for CMAQ.

EMISSIONS SUMMARIES

Table 3-2 summarizes the criteria pollutant emissions by state and by source category for the base and future year scenarios. The tables include totals for Virginia and the surrounding states of Kentucky, Maryland, North Carolina, Pennsylvania, Tennessee, Washington, D.C., and West Virginia. The sectors include area sources (sources that do no have elevated or well-defined stacks such waste incinerators, medical waste incinerators, gold mines etc.), point sources (sources with elevated, well defined stacks or plumes such as power plants, steel mills, etc.), on-road mobile sources, and non-road mobile sources (such as construction equipment, farm equipment, etc.).

Table 3-2a. 2001 Criteria Pollutant Emissions Totals (tons/yr) by Source Category for the Commonwealth of Virginia and Selected Surrounding States.

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO_2 (tpy)	PM_{10} (tpy)	PM_{25} (tpy)	NH_3 (tpy)
Kentucky	Area	80,863	166,716	247,445	58,064	308,441	251,438	45,107
Kentucky	Point	284,354	117,482	110,445	580,121	74,939	52,708	618
Kentucky	Onroad	140,239	81,926	1,078,638	4,558	3,884	2,922	4,625
Kentucky	Nonroad	91,843	34,166	291,250	12,119	5,655	5,178	37
Kentucky	*Total*	*597,298*	*400,290*	*1,727,779*	*654,862*	*392,919*	*312,246*	*50,387*
Maryland	Area	18,922	109,517	135,388	41,889	136,820	108,108	16,863
Maryland	Point	100,586	33,779	126,434	293,667	30,567	23,138	470
Maryland	Onroad	140,278	80,157	1,113,751	3,598	3,836	2,805	5,265
Maryland	Nonroad	45,474	45,349	460,610	5,165	4,032	3,701	42
Maryland	*Total*	*305,260*	*268,801*	*1,836,182*	*344,318*	*175,256*	*137,752*	*22,640*
North Carolina	Area	36,074	390,264	785,754	34,693	387,396	294,325	46,787
North Carolina	Point	212,450	122,904	84,210	525,481	60,277	38,811	1,917
North Carolina	Onroad	266,950	177,024	2,178,291	10,236	7,538	5,660	9,196
North Carolina	Nonroad	78,211	70,921	734,017	7,891	6,900	6,324	87
North Carolina	*Total*	*593,686*	*761,113*	*3,782,271*	*578,301*	*462,110*	*345,120*	*57,987*

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO_2 (tpy)	PM_{10} (tpy)	PM_{25} (tpy)	NH_3 (tpy)
Pennsylvania	Area	56,932	341,963	300,048	99,081	473,707	421,835	34,378
Pennsylvania	Point	328,499	134,489	129,342	1,093,503	109,222	79,557	1,519
Pennsylvania	Onroad	302,656	181,634	2,614,202	9,946	8,207	6,116	10,368
Pennsylvania	Nonroad	126,257	87,784	955,139	13,959	8,993	8,243	101
Pennsylvania	*Total*	*814,343*	*745,870*	*3,998,732*	*1,216,490*	*600,129*	*515,751*	*46,367*
Tennessee	Area	27,268	244,652	202,999	42,729	318,413	270,359	40,426
Tennessee	Point	243,510	154,351	133,451	457,127	80,975	57,406	2,415
Tennessee	Onroad	199,670	129,223	1,654,713	7,457	5,497	4,119	6,799
Tennessee	Nonroad	91,499	49,447	452,304	10,624	6,199	5,677	57
Tennessee	*Total*	*561,946*	*577,672*	*2,443,468*	*517,937*	*411,084*	*337,561*	*49,696*
Washington DC	Area	2,341	10,890	2,440	6,197	7,960	7,376	982
Washington DC	Point	969	412	158	1,715	525	201	14
Washington DC	Onroad	8,814	6,187	73,920	219	234	164	386
Washington DC	Nonroad	2,700	1,295	15,475	325	239	220	3
Washington DC	*Total*	*14,824*	*18,783*	*91,992*	*8,456*	*8,958*	*7,961*	*1,384*
West Virginia	Area	15,071	73,430	119,094	13,577	153,602	136,022	7,868
West Virginia	Point	259,566	74,274	120,816	562,935	61,965	45,436	533
West Virginia	Onroad	63,790	36,615	509,776	2,190	1,771	1,349	1,956
West Virginia	Nonroad	56,267	15,531	120,691	7,466	2,884	2,642	13
West Virginia	*Total*	*394,693*	*199,849*	*870,378*	*586,168*	*220,221*	*185,449*	*10,370*
Virginia	Area	49,038	226,091	242,778	15,667	306,474	237,512	28,410
Virginia	Point	161,377	78,184	78,531	298,851	39,759	26,477	845
Virginia	Onroad	215,356	127,508	1,738,543	6,409	5,804	4,309	7,423
Virginia	Nonroad	91,845	57,828	598,852	9,280	6,497	5,937	61
Virginia	*Total*	*517,617*	*489,611*	*2,658,704*	*330,207*	*358,533*	*274,235*	*36,739*

Data Source: EPA 2001 Tier 3 criteria emissions summary

Table 3-2b. 2010 Criteria Pollutant Emissions Totals (tons/yr) by Source Category, for the Commonwealth of Virginia and Selected Surrounding States.

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
Kentucky	Area	82,996	115,489	181,661	55,375	137,123	43,770	53,612
Kentucky	Point	141,084	68,696	126,928	412,980	52,452	40,009	636
Kentucky	Onroad	83,213	44,449	664,670	536	2,766	1,746	5,757
Kentucky	Nonroad	75,948	27,166	309,567	10,075	5,129	4,924	27
Kentucky	*Total*	*383,240*	*255,799*	*1,282,827*	*478,967*	*197,470*	*90,450*	*60,031*
Maryland	Area	21,720	66,161	122,762	51,438	67,799	30,644	25,852
Maryland	Point	35,079	7,165	136,717	96,451	15,029	10,914	447
Maryland	Onroad	89,989	42,727	660,593	580	2,788	1,713	6,348
Maryland	Nonroad	37,759	28,348	468,771	2,506	3,409	3,238	29
Maryland	*Total*	*184,545*	*144,400*	*1,388,843*	*150,975*	*89,025*	*46,509*	*32,677*
North Carolina	Area	30,937	298,148	755,017	33,288	156,422	70,272	174,184
North Carolina	Point	114,612	69,863	98,222	337,188	49,727	37,982	2,208
North Carolina	Onroad	150,713	94,532	1,229,513	1,018	5,148	3,226	10,998
North Carolina	Nonroad	58,590	50,980	785,545	1,639	5,790	5,509	56
North Carolina	*Total*	*354,852*	*513,524*	*2,868,298*	*373,133*	*217,086*	*116,989*	*187,446*
Pennsylvania	Area	62,115	244,661	263,780	104,895	180,074	69,608	77,644
Pennsylvania	Point	191,761	41,294	134,998	365,698	63,226	50,403	1,402
Pennsylvania	Onroad	193,428	95,632	1,494,397	1,160	5,793	3,612	12,580
Pennsylvania	Nonroad	100,897	66,418	1,023,691	7,860	8,019	7,656	65
Pennsylvania	*Total*	*548,201*	*448,006*	*2,916,865*	*479,613*	*257,112*	*131,279*	*91,692*
Tennessee	Area	30,251	204,378	167,511	44,891	140,596	46,253	43,973
Tennessee	Point	105,744	95,554	153,220	315,452	57,675	47,621	2,673
Tennessee	Onroad	110,406	66,297	924,624	738	3,708	2,316	8,020
Tennessee	Nonroad	72,462	38,041	490,821	6,566	5,448	5,210	38
Tennessee	*Total*	*318,863*	*404,270*	*1,736,176*	*367,647*	*207,427*	*101,400*	*54,705*
Washington DC	Area	2,880	10,059	2,257	7,101	3,376	1,473	1,054
Washington DC	Point	563	5	139	875	262	144	11
Washington DC	Onroad	5,834	3,207	43,633	41	178	105	457
Washington DC	Nonroad	2,060	800	15,342	24	174	167	2
Washington DC	*Total*	*11,336*	*14,071*	*61,371*	*8,042*	*3,990*	*1,889*	*1,525*

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
West Virginia	Area	16,531	52,655	111,783	14,020	31,642	17,442	11,239
West Virginia	Point	107,084	17,877	140,526	267,319	46,041	35,580	535
West Virginia	Onroad	25,446	14,280	229,499	165	877	544	1,936
West Virginia	Nonroad	48,100	14,830	139,182	7,060	2,821	2,712	10
West Virginia	*Total*	*197,162*	*99,643*	*620,989*	*288,564*	*81,380*	*56,279*	*13,720*
Virginia	Area	51,055	152,710	226,435	18,280	99,538	43,065	47,036
Virginia	Point	116,452	46,965	89,346	223,803	29,280	23,840	725
Virginia	Onroad	117,831	68,430	1,014,190	803	3,499	2,038	9,229
Virginia	Nonroad	71,890	37,973	572,677	3,661	5,424	5,176	43
Virginia	*Total*	*357,228*	*306,077*	*1,902,648*	*246,547*	*137,740*	*74,119*	*57,034*

Data Source: SMOKE input files for EPA 2010 Clear Skies

Table 3-2c. 2015 Criteria Pollutant Emissions Totals (tons/yr) by Source Category for the Commonwealth of Virginia and Selected Surrounding States.

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
Kentucky	Area	86,737	118,613	178,135	57,037	140,843	44,206	54,466
Kentucky	Point	119,509	76,259	136,994	309,021	53,360	40,343	677
Kentucky	Onroad	51,705	33,987	587,044	594	2,335	1,279	6,293
Kentucky	Nonroad	70,723	22,742	320,697	11,310	4,723	4,536	29
Kentucky	*Total*	*328,673*	*251,602*	*1,222,870*	*377,962*	*201,261*	*90,364*	*61,466*
Maryland	Area	22,630	68,291	118,312	54,886	70,262	30,836	27,493
Maryland	Point	36,612	7,991	161,990	84,609	14,339	9,833	516
Maryland	Onroad	73,128	35,380	625,121	662	2,495	1,341	7,140
Maryland	Nonroad	33,804	25,893	498,732	2,652	3,078	2,917	32
Maryland	*Total*	*166,174*	*137,555*	*1,404,155*	*142,810*	*90,174*	*44,927*	*35,182*
North Carolina	Area	31,658	312,232	749,577	34,395	161,045	71,037	184,705
North Carolina	Point	109,442	81,892	110,228	207,069	49,737	36,966	2,482
North Carolina	Onroad	93,967	72,588	1,086,449	1,140	4,427	2,413	12,140
North Carolina	Nonroad	47,408	43,984	815,102	1,374	4,815	4,569	61
North Carolina	*Total*	*282,474*	*510,696*	*2,761,356*	*243,977*	*220,024*	*114,984*	*199,388*
Pennsylvania	Area	63,134	255,255	250,978	105,197	184,330	69,349	78,772
Pennsylvania	Point	185,948	46,770	149,289	265,251	57,667	44,017	1,536
Pennsylvania	Onroad	153,638	78,421	1,403,706	1,294	4,990	2,710	13,832
Pennsylvania	Nonroad	89,284	57,293	1,069,881	8,480	7,054	6,727	71
Pennsylvania	*Total*	*492,005*	*437,739*	*2,873,854*	*380,222*	*254,041*	*122,802*	*94,211*
Tennessee	Area	31,754	219,627	164,797	46,727	145,615	47,163	44,435
Tennessee	Point	101,939	111,197	173,664	298,076	64,647	53,321	2,958
Tennessee	Onroad	69,026	50,812	817,379	826	3,200	1,740	8,845
Tennessee	Nonroad	64,785	32,126	508,528	7,157	4,800	4,587	42
Tennessee	*Total*	*267,504*	*413,762*	*1,664,369*	*352,785*	*218,261*	*106,811*	*56,279*
Washington DC	Area	3,079	10,689	2,150	7,450	3,586	1,540	1,133
Washington DC	Point	600	7	205	904	272	154	12
Washington DC	Onroad	4,925	2,664	41,975	47	167	88	517
Washington DC	Nonroad	1,548	706	15,872	4	130	126	2
Washington DC	*Total*	*10,152*	*14,065*	*60,202*	*8,405*	*4,156*	*1,907*	*1,664*

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
West Virginia	Area	17,278	53,639	109,396	14,834	31,981	17,303	11,573
West Virginia	Point	88,160	19,978	156,249	178,345	42,924	31,832	600
West Virginia	Onroad	15,185	10,240	196,680	175	725	394	2,011
West Virginia	Nonroad	46,281	12,086	146,386	8,014	2,702	2,600	11
West Virginia	*Total*	*166,903*	*95,943*	*608,710*	*201,367*	*78,332*	*52,128*	*14,195*
Virginia	Area	53,166	156,772	222,764	18,598	102,437	43,372	48,435
Virginia	Point	121,479	55,055	99,165	183,246	30,440	24,461	793
Virginia	Onroad	100,587	56,674	975,905	898	3,223	1,670	10,161
Virginia	Nonroad	64,211	33,983	602,616	3,732	4,787	4,560	47
Virginia	*Total*	*339,442*	*302,484*	*1,900,450*	*206,474*	*140,887*	*74,063*	*59,437*

Data Source: SMOKE input files for EPA 2015 Clear Skies

Table 3-2d. 2020 Criteria Pollutant Emissions Totals (tons/yr) by Source Category for the Commonwealth of Virginia and Selected Surrounding States.

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
Kentucky	Area	91,929	117,064	175,225	58,588	138,317	43,793	55,439
Kentucky	Point	112,256	84,578	149,195	272,636	52,185	38,451	726
Kentucky	Onroad	36,425	28,950	572,119	653	2,273	1,146	6,819
Kentucky	Nonroad	68,163	20,642	338,836	13,621	4,537	4,359	32
Kentucky	*Total*	*308,773*	*251,234*	*1,235,375*	*345,499*	*197,312*	*87,748*	*63,016*
Maryland	Area	23,703	69,174	114,208	56,995	66,608	30,393	28,702
Maryland	Point	41,377	8,980	189,610	71,464	18,652	13,607	585
Maryland	Onroad	67,957	32,189	639,970	745	2,518	1,255	7,917
Maryland	Nonroad	31,434	25,361	534,327	3,180	2,838	2,682	35
Maryland	*Total*	*164,471*	*135,705*	*1,478,114*	*132,383*	*90,616*	*47,938*	*37,238*
North Carolina	Area	32,749	313,241	744,973	35,223	153,549	70,098	191,673
North Carolina	Point	118,220	93,256	122,923	177,489	61,778	47,911	2,775
North Carolina	Onroad	65,948	61,657	1,062,447	1,263	4,358	2,191	13,256
North Carolina	Nonroad	40,447	41,299	866,518	1,616	4,057	3,834	66
North Carolina	*Total*	*257,364*	*509,453*	*2,796,861*	*215,592*	*223,742*	*124,034*	*207,769*
Pennsylvania	Area	63,868	262,341	238,780	103,800	176,760	67,356	79,494
Pennsylvania	Point	196,733	52,510	162,991	249,522	59,811	45,465	1,702
Pennsylvania	Onroad	140,686	71,937	1,427,330	1,429	4,908	2,463	15,054
Pennsylvania	Nonroad	83,360	53,304	1,139,122	10,181	6,387	6,082	78
Pennsylvania	*Total*	*484,646*	*440,092*	*2,968,223*	*364,932*	*247,865*	*121,366*	*96,328*
Tennessee	Area	33,135	226,549	162,220	48,399	140,943	46,600	45,461
Tennessee	Point	108,714	127,886	197,795	208,450	66,544	53,876	3,273
Tennessee	Onroad	48,696	43,211	799,580	915	3,155	1,585	9,652
Tennessee	Nonroad	60,367	29,464	538,760	8,600	4,362	4,165	46
Tennessee	*Total*	*250,911*	*427,111*	*1,698,355*	*266,363*	*215,004*	*106,225*	*58,431*
Washington DC	Area	3,330	11,344	2,073	7,771	3,529	1,587	1,279
Washington DC	Point	743	15	288	1,164	524	396	14
Washington DC	Onroad	4,718	2,435	43,448	53	173	85	576
Washington DC	Nonroad	1,170	684	16,776	4	90	86	2
Washington DC	*Total*	*9,961*	*14,478*	*62,585*	*8,992*	*4,317*	*2,154*	*1,871*

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
West Virginia	Area	18,515	54,453	107,414	15,421	32,162	17,227	11,895
West Virginia	Point	93,866	22,567	174,325	175,279	46,449	34,842	682
West Virginia	Onroad	10,450	8,489	187,203	185	689	346	2,086
West Virginia	Nonroad	46,111	10,606	154,623	9,664	2,717	2,617	13
West Virginia	*Total*	*168,941*	*96,114*	*623,565*	*200,548*	*82,016*	*55,032*	*14,676*
Virginia	Area	55,793	160,118	219,532	18,464	100,396	43,151	49,754
Virginia	Point	126,542	62,519	107,744	163,561	38,406	31,722	871
Virginia	Onroad	97,572	52,436	1,009,305	995	3,279	1,602	11,076
Virginia	Nonroad	59,359	32,773	643,226	4,464	4,305	4,092	52
Virginia	*Total*	*339,266*	*307,846*	*1,979,807*	*187,484*	*146,386*	*80,567*	*61,753*

Data Source: SMOKE input files for EPA 2020 Clear Skies

Table 3-3 summarizes the mercury emissions by state and source category for the base and future-year scenarios. The tables include totals for Virginia and the surrounding states of Kentucky, Maryland, North Carolina, Pennsylvania, Tennessee, Washington, D.C., and West Virginia. Point-source, non-point source, and total emissions are provided. The non-point source category includes such sources as residential/industrial fuel combustion, fluorescent lamp breakage, health services, agricultural production, waste disposal, landfills, and other combustion sources.

For 2002 base-year mercury emissions, the State of Pennsylvania has the highest totals, followed by West Virginia and North Carolina. In EPA's estimates (in their Clear Skies modeling analysis) for the future years, mercury emissions drop significantly for some states, reflecting expected reductions due to CAIR controls and the original CAMR control provisions.

Table 3-3a. 2002 Mercury Emissions Totals (tpy) for Virginia and Surrounding States.

State	Point				Non-Point				Total			
	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)
Kentucky	1.39	0.90	0.15	2.45	0.04	0.03	0.02	0.09	1.44	0.93	0.17	2.54
Maryland	0.47	0.80	0.15	1.42	0.08	0.05	0.03	0.17	0.55	0.85	0.19	1.59
North Carolina	1.17	1.29	0.24	2.69	0.08	0.05	0.03	0.15	1.24	1.34	0.27	2.85
Pennsylvania	3.25	3.30	0.62	7.18	0.19	0.11	0.08	0.38	3.44	3.42	0.69	7.55
Tennessee	1.73	0.87	0.18	2.77	0.03	0.02	0.01	0.05	1.76	0.88	0.19	2.83
Washington DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01
West Virginia	2.03	1.92	0.37	4.32	0.05	0.03	0.02	0.09	2.08	1.95	0.39	4.42
Virginia	0.63	0.39	0.17	1.18	0.09	0.06	0.04	0.19	0.72	0.44	0.20	1.37

Notes: Point Source: Emissions for Virginia are based on VDEQ 2002 data and the emissions for other states are based on the EPA 2002 NEI Version 3.

Non-Point Source: Emissions are based on 2002 NEI Version 3

Table 3-3b. 2010 Mercury Emissions Totals (tpy) for Virginia and Surrounding States.

State	Point				Non-Point				Total			
	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)
Kentucky	1.07	0.49	0.19	1.74	0.05	0.01	0.00	0.06	1.12	0.49	0.19	1.81
Maryland	0.55	0.39	0.20	1.14	0.08	0.02	0.01	0.11	0.63	0.41	0.21	1.25
North Carolina	1.11	0.50	0.18	1.79	0.09	0.02	0.01	0.12	1.21	0.51	0.19	1.91
Pennsylvania	1.93	0.98	0.39	3.29	0.22	0.08	0.05	0.34	2.15	1.05	0.43	3.64
Tennessee	1.02	0.36	0.13	1.50	0.07	0.01	0.00	0.08	1.09	0.36	0.13	1.59
Washington DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
West Virginia	1.02	0.26	0.05	1.33	0.03	0.00	0.00	0.03	1.05	0.26	0.05	1.36
Virginia	0.39	0.26	0.11	0.76	0.11	0.02	0.01	0.14	0.50	0.28	0.12	0.90

Notes: Point Source: Emissions for Virginia are based on VDEQ 2010 estimates and the emissions for other states are based on the EPA 2010 Clear Skies estimates

Non-Point Source: Emissions based on the EPA 2010 Clear Skies estimates

Table 3-3c. 2015 Mercury Emissions Totals (tpy) for Virginia and Surrounding States.

State	Point				Non-Point				Total			
	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)
Kentucky	0.84	0.44	0.19	1.47	0.06	0.01	0.00	0.07	0.90	0.45	0.20	1.54
Maryland	0.57	0.37	0.18	1.12	0.08	0.02	0.01	0.11	0.65	0.39	0.20	1.24
North Carolina	0.94	0.36	0.12	1.43	0.10	0.01	0.01	0.12	1.04	0.38	0.13	1.56
Pennsylvania	2.06	0.82	0.38	3.27	0.22	0.07	0.05	0.35	2.29	0.90	0.43	3.61
Tennessee	1.08	0.33	0.15	1.57	0.08	0.01	0.00	0.09	1.16	0.34	0.16	1.66
Washington DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
West Virginia	1.07	0.10	0.02	1.19	0.03	0.00	0.00	0.03	1.09	0.11	0.02	1.22
Virginia	0.36	0.26	0.10	0.72	0.11	0.02	0.01	0.15	0.48	0.28	0.12	0.87

Notes: Point Source: Emissions for Virginia are based on VDEQ 2015 estimates and the emissions for other states are based on the EPA 2015 Clear Skies estimates

Non-Point Source: Emissions based on the EPA 2015 Clear Skies estimates

Table 3-3d. 2018/2020 Mercury Emissions Totals (tpy) for Virginia and Surrounding States.

State	Point				Non-Point				Total			
	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)
Kentucky	0.90	0.41	0.21	1.52	0.06	0.01	0.00	0.07	0.96	0.42	0.21	1.59
Maryland	0.62	0.40	0.19	1.21	0.09	0.02	0.01	0.12	0.71	0.42	0.20	1.32
North Carolina	0.89	0.39	0.14	1.42	0.11	0.01	0.01	0.13	0.99	0.41	0.15	1.55
Pennsylvania	2.06	0.83	0.41	3.30	0.23	0.07	0.05	0.35	2.29	0.90	0.46	3.65
Tennessee	1.06	0.21	0.10	1.37	0.09	0.01	0.01	0.10	1.15	0.22	0.11	1.47
Washington DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01
West Virginia	1.10	0.11	0.02	1.23	0.03	0.00	0.00	0.04	1.13	0.11	0.03	1.26
Virginia	0.36	0.24	0.10	0.70	0.12	0.02	0.01	0.15	0.48	0.26	0.12	0.85

Notes: Point Source: Emissions for Virginia are based on VDEQ 2018 estimates and the emissions for other states are based on the EPA 2020 Clear Skies estimates

Non-Point Source: Emissions based on the EPA 2020 Clear Skies estimates

Meteorological Inputs

As noted earlier, existing meteorological input files were used for this study. These were prepared by EPA for use in CMAQ modeling for the selected modeling domain using the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Fifth Generation Mesoscale Model (MM5) (EPA, 2005a). The MM5 outputs were postprocessed by EPA for input to CMAQ using the Meteorology-Chemistry Interface Processor (MCIP) program. The meteorological input preparation methodology and some information on MM5 model performance are provided by McNally (2003). The 2001 MM5-derived meteorological fields are available for both 36- and 12-km resolution. The 36-km meteorological fields were used directly, since the VDEQ 36-km domain is the same as that used by EPA. The 12-km meteorological fields for the VDEQ subdomain were extracted from a larger 12-km domain used by EPA.

The 2002 meteorological inputs used for sensitivity testing were also prepared by EPA (using MM5 and MCIP), for both 36- and 12-km resolution (Dolwick et al., 2007).

Initial and Boundary Conditions and Other Geophysical Data

For this study, existing initial condition, boundary condition, land-use and photolysis rate input files prepared by EPA for use in CMAQ modeling for the selected modeling domain and simulation period (EPA, 2005a) were used. For mercury, the boundary conditions were extracted from the output of a global model—the Chemical Transport Model (CTM) (Shia et al., 1999; Seigneur et al., 2001). This set of boundary conditions was selected based on a comparison of three sets of boundary conditions available for use in this study. Boundary values from three global models (the CTM, Geos-Chem, and GRAHM models) were compared (Myers et al., 2006) and the CTM values were found to be in the middle of the range of the three models.

3.2.4. Model Performance Evaluation

The evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species. The non-mercury species include ozone, fine particulate matter ($PM_{2.5}$), and related species. For mercury, simulated total wet deposition was compared with actual and "estimated" data for the MDN monitoring sites. The simulated and observed values of concentration and/or deposition for each site and the average over all sites were compared for 1) the full domain, 2) the 12-km inner grid of the modeling domain, and 3) Virginia (mercury only).

A variety of statistical measures were used to quantify model performance. These include:

- Mean observed concentration or deposition = $\sum O_i / N$
- Mean simulated concentration or deposition = $\sum S_i / N$
- Ratio of means = $(\sum S_i / N)/(\sum O_i / N)$
- Mean bias = $\sum (S_i - O_i) / N$
- Mean fractional bias (expressed as percent) = $200 \cdot (\sum (S_i - O_i)/ (S_i + O_i)) /N$
- Mean error = $\sum |S_i - O_i| /N$
- Mean fractional error (expressed as percent) = $200 \cdot (\sum |S_i - O_i|/ (S_i + O_i)) /N$
- Coefficient of determination (R^2) =
  $(\sum S_i O_i - \sum S_i \sum O_i/N)^2 /[(\sum O_i^2 - (\sum O_i)^2/N) \cdot (\sum S_i^2 - (\sum S_i)^2/N)]$

Where S is the simulated value, O is the observed value, and N is the number of simulation-observation pairs used in the calculation. The subscript i is an index and is used here to indicate that each sum is from i =1 to N. Statistical measures were calculated on a monthly, seasonal and annual basis, based on data availability.

Plots and graphics were also used to assess the reasonableness of the results. Spatial plots of the simulated and observed values were used to qualitatively assess the ability of the model to emulate the spatial deposition patterns. Monthly time-series plots comparing these same values at the monitoring sites were used to determine whether the timing and magnitude of the simulated values matches the observations. Scatter plots were used to graphically compare the simulated and observed deposition values.

As part of the performance evaluation, potential weaknesses in the model input fields were identified and some limited sensitivity analysis was conducted to examine the effects of these weaknesses or uncertainties. This focused on the mercury boundary conditions and the meteorological representativeness of the simulation period. In addition, PPTM was also used as a probing tool and examined the PPTM results to verify that the contributions from selected emission sources are commensurate with the locations and emissions of the sources as well as the prescribed meteorological conditions.

Model performance is summarized in Section 5.

3.2.5. Base- and Future-year Modeling and Analysis

CMAQ version 4.6 with PPTM was applied for the 2001/2002 base year and three future years: 2010, 2015, and 2018.

Several CMAQ/PPTM simulations were conducted using the baseline 2001/2002 emissions inventory. These simulations were designed to assess the contributions of various source sectors to mercury deposition to water bodies in Virginia.

The first scenario examined and quantified the contributions from all mercury air emissions sources in 1) Virginia, 2) surrounding states (defined here as the remainder of the 12-km grid), 3) all other U.S. states (outside of the 12-km grid), 4) Canada and Mexico, 5) global emissions sources, and 6) natural emissions. Tags were assigned to each of the six regions/categories listed above. An initial/boundary condition tag was used to represent the global impact on deposition. In this tag, the boundary conditions are those for the outer, 36-km domain. Natural emissions include those from soils, rocks, volcanoes, and the oceans. This set of tags provides estimates of Virginia, regional, national, and global impacts on deposition for any location (grid cell or group of grid cells) within the state or the modeling domain.

The second scenario quantified the contributions from Electric Generating Unit (EGU) and non-EGU facilities in Virginia and the surrounding states. The tags were assigned to 1) all of Virginia's EGU sources and separately, 2) all of the non-EGU sources in the state, 3) all EGU sources in the surrounding states (remainder of the 12-km grid), and 4) all non-EGU sources in the surrounding states (remainder of the 12-km grid). The results allow us to quantify and compare the contributions from the EGU and non-EGU source sectors to mercury deposition for any location (grid cell or group of grid cells) within the state or the modeling domain.

CMAQ was then applied for 2010, 2015 and 2018, using emissions projected to these years. For 2010 and 2015, PPTM was not employed. For 2018, the same CMAQ/PPTM scenarios that were done for the baseline were also done for the future year.

For each future year, the simulated change in mercury deposition, overall and from each tagged or modeled source or source category, was examined. The PPTM results were used to attribute the future-year reductions in mercury deposition for 2018 for each area of interest to the specific tagged sources or source categories.

Graphical and tabular summaries of the results were prepared. Plots of the CMAQ results were prepared for each CMAQ modeling domain and for each of the major water basins in the Commonwealth of Virginia. Tabular summaries of the overall and PPTM results were also assembled. Analysis of the results focused on the effectiveness of the various measures and emissions changes in reducing future-year mercury deposition both statewide and within the key areas of interest. Given the uncertainties associated with mercury deposition modeling, analysis of the results emphasizes the relative changes in deposition associated with the emissions changes for each source and source category.

The CMAQ modeling results are presented in Section 5.

4. Source-Specific Mercury Deposition Modeling Methodology

The EPA Gaussian model AERMOD (EPA, 2004) was used to examine mercury deposition at the local scale for selected areas and sources. The methodology for the application of AERMOD is presented in this section of the report.

4.1. Selection and Overview of AERMOD

The selection of AERMOD for the Virginia mercury study was based on the technical formulation and capabilities of the model as well as its extensive use for other source-specific model applications.

AERMOD is a steady-state Gaussian dispersion model designed to simulate the local-scale dispersion of pollutants from low-level or elevated sources in simple or complex terrain. It is an EPA "preferred" model (40 CFR Part 51, Appendix W, *Guideline on Air Quality Models*). Recent versions of AERMOD (EPA, 2006a) include algorithms for simulating deposition of gaseous and particulate pollutants. In this study, AERMOD (version 07026) was applied for selected point sources in the Virginia emissions inventory and was used to screen the mercury emissions sources and to determine whether they have the potential to impact areas outside the vicinity of the source. AERMOD was also used to simulate the effects of local emission changes for selected areas and sources.

The dispersion algorithms are based on the fundamental concepts of planetary boundary layer meteorology. The airflow and stability characteristics (e.g., convective versus stable) as well as the vertical structure of the boundary layer are accounted for in simulating dispersion. Numerous features and options accommodate a variety of source types, pollutants, and land-use and topographical features.

Wet and dry deposition can be estimated using AERMOD. The wet deposition algorithms use a washout ratio that is dependent on precipitation rate and the properties of the pollutant being simulated. Dry deposition is based on aerodynamic resistance calculations, and the deposition velocities are calculated based on surface type and local meteorological conditions. The ability to simulate mercury deposition is a relatively new feature of AERMOD and has not been widely tested.

Additional detail regarding the selection of the AERMOD model is provided in the modeling protocol document (Appendix A).

4.2. AERMOD Application Procedures for the Virginia Mercury Deposition Modeling Study

The application of AERMOD, including the simulation period, sources and receptor areas, input preparation, performance evaluation, and base-case and future-year modeling, is discussed in this section. AERMOD was applied separately for each selected source and for elemental, reactive gaseous, and particulate-bound mercury.

4.2.1. Simulation Period

The simulation period for the application of AERMOD is calendar year 2001.

4.2.2. AERMOD Spatial Configuration

Selection of Sources for Application of AERMOD

AERMOD was applied for the 15 sources in Virginia with the greatest mercury emissions based on the VDEQ 2002 emissions inventory data. The sources reflect several different types of facilities and a variety of species distributions, stack parameters, locations relative to sensitive watershed areas, and designated potentials for future control. The top 15 sources and their emissions rates are listed in Table 4-1.

Table 4-1. AERMOD Facilities and Emissions Rates for Elemental (HG0), Reactive Gaseous (HG2), Particulate (HGP), and Total Mercury. Electric Generating Units (EGUs) are also Identified.

Facility Name	Rank	HG0 (lbs/yr)	HG2 (lbs/yr)	HGP (lbs/yr)	Total (lbs/yr)	EGU?
Dominion—Chesterfield Power Station	1	179.42	107.65	71.77	358.83	EGU
Chaparral Steel	2	233.84	29.23	29.23	292.30	non-EGU
Dominion—Bremo	3	83.86	50.32	33.55	167.73	EGU
American Electric Power- Clinch River	4	38.21	121.00	0.00	159.21	EGU
Dominion - Chesapeake Energy Center	5	78.69	47.22	31.48	157.38	EGU
Potomac River Generating Station	6	11.83	106.43	0.00	118.26	EGU
Dominion - Yorktown Power Station	7	53.82	32.29	21.53	107.64	EGU
Jewel Coke Company LLP	8	84.50	10.56	10.56	105.62	non-EGU
Dominion-Possum Point Power Station	9	50.09	30.06	20.04	100.19	EGU
Stone Container Enterprises (Smurfit)	10	38.88	23.33	15.55	77.76	non-EGU
Stone Container Corporation -Hopewell	11	34.84	20.91	13.94	69.69	non-EGU
American Electric Power (Glen Lyn)	12	26.06	39.08	0.00	65.14	EGU
Intermet Foundry Archer Creek	13	32.50	19.50	13.00	65.01	non-EGU
RES dba Steel Dynamics	14	48.64	6.08	6.08	60.80	non-EGU
Spruance Genco LLC	15	27.75	16.65	11.10	55.50	EGU

For most facilities, the speciation is based on EPA default speciation profiles. For the two American Electric Power (AEP) facilities and the Potomac River Generating Station, the speciation is based on (limited) stack testing. Use of the alternative speciation results in no HGP emissions for these facilities.

Specification of Receptor Grids

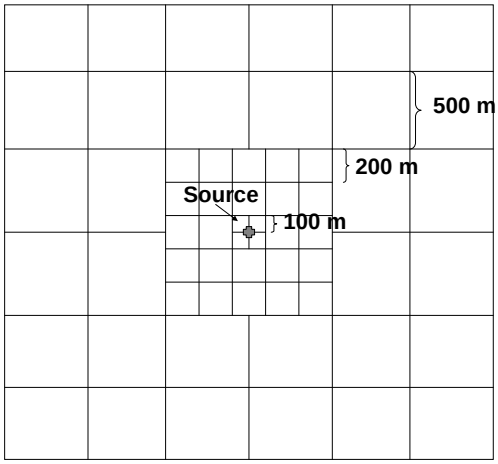
The receptor area for each source was defined following EPA guidance and consists of a 10 by 10 grid with grid cells of 100 x 100 meters (m) near the source that increase to 200 x 200 m and then to 500 x 500 m. The receptor area covers a 3000 x 3000 m (3 x 3 km) area surrounding the source. Note that while the location of the maximum deposition varied within each receptor area, the specified 3-km square receptor area appeared to capture the maximum deposition in all cases.

In the AERMOD input file, this receptor configuration is defined as follows:

GRIDCART 3KMVAR XPNTS -1500. -1000. -500. -300. -100. 100. 300. 500. 1000. 1500.

GRIDCART 3KMVAR YPNTS -1500. -1000. -500. -300. -100. 100. 300. 500. 1000. 1500.

Where GRIDCART refers to a Cartesian grid and the location of each grid point in the west-east (x) and south-north (y) directions (XPNTS and YPNTS, respectively) are given in meters. The source is at location (0,0). This basic grid configuration is depicted below.



4.2.3. Input Preparation

AERMOD requires several input files:

The simulation control file specifies which options and features of AERMOD are to be applied, and contains information about the emissions sources (location, emissions rate, stack parameters, etc.) as well as the receptor locations (essentially the gridded geographical area over which the estimated concentrations and deposition amounts are calculated). This file also specifies several deposition-related parameters. Separate simulation control files were prepared for elemental, reactive gaseous, and particulate-bound mercury.

Two meteorological input files provide detailed information about 1) the characteristics of the boundary layer (wind, temperature, stability parameters) and 2) the vertical structure of temperature and wind near the source location. For deposition analyses, the boundary layer meteorological file includes information about pressure, relative humidity, cloud cover and precipitation.

Emissions Inputs

Source-specific emissions estimates for input to AERMOD for both the baseline year and each future year are the same as those used for the CMAQ modeling and are based on the 2002 emissions data for Virginia. Stack parameter, exit velocity, and stack diameter information for use by AERMOD was also extracted from the CMAQ emissions inventory. The emissions rates were converted to g/s for use by AERMOD. Separate simulation control files were prepared for elemental, reactive gaseous, and particulate emissions.

Deposition Parameters

There are four parameters that AERMOD uses to calculate wet deposition of elemental and reactive gaseous mercury. These are 1) diffusivity in air, 2) diffusivity in water, 3) cuticular resistance, and 4) Henry's Law coefficient. These were set in accordance with EPA guidance

and are based on Wesely et al. (2002). Where possible, information from CMAQ was used to adjust the AERMOD values. These are summarized in Table 4-2.

Table 4-2. AERMOD Gaseous Wet Deposition Parameter Specifications for the Virginia Mercury Study.

Form of Mercury	Diffusivity in Air ($cm^2\ s^{-1}$)	Diffusivity in Water ($cm^2\ s^{-1}$)	Cuticular Resistance ($s\ cm^{-1}$)	Henry's Law Coefficient ($Pa\ m^3\ mol^{-1}$)
Elemental	7.23×10^{-2}	6.30×10^{-6}	1.0×10^{5}	150
Reactive gaseous	6.0×10^{-2}	3.256×10^{-4}	1.0×10^{5}	6.0×10^{-6}

AERMOD relies on several other parameters to calculate dry deposition of mercury, including seasonal definitions, deposition land-use category, reactivity factor, and fractional maximum leaf area index. For this application, each month was assigned to a season as follows:

- **Seasonal Category 1** *(midsummer with lush vegetation):* May–August
- **Seasonal Category 2** (autumn with un-harvested cropland): September, October
- **Seasonal Category 3** *(late autumn or winter with no snow):* January, February, November, December
- **Seasonal Category 5** *(transitional spring):* March, April.

The land-use category for dry deposition was set to Category 4 (forest). Following EPA guidance, the reactivity factor was set to 0 for HG0 and to 1 for HG2, reflecting the higher reactivity for HG2. The fraction of maximum leaf area index was set to 0.5.

For particle-bound mercury, Method 2 of AERMOD was applied. This method is applicable when particle size distribution is not well known or when particles represent a small portion of the mass. Method 2 requires the specification of the fine mass fraction and the mean particle diameter. For this study, a fine mass fraction of 0.8 and a mean particle diameter of 0.4 microns were used, based on Wesely et al. (2002).

Meteorological and Land-Use Inputs

Corresponding meteorological inputs for AERMOD for 2001 were developed using observed data. For each source included in the AERMOD analysis, meteorological inputs were prepared using available surface and upper-air meteorological data from nearby, geographically representative monitoring sites. The meteorological monitoring sites were paired with the source locations based on proximity, and similarities in geographical and land-use characteristics. Table 4-3 lists the AERMOD sources along with the matched surface and upper-air meteorological monitoring sites. The elevation of each location is given in the table. The distance between the facility and each of the paired meteorological monitoring sites is also listed.

Table 4-3. AERMOD Facilities and Paired Meteorological Monitoring Sites. Locations are in Virginia, Except Where Noted.

Facility Name	Facility Elevation (m)	Met Site Type	WBAN or CASTNet #	WBAN or CASTNet Name	Met Site Elevation (m)	Distance (km)
Dominion—Chesterfield Power Station	10.1	SFC	13740	Richmond	50	16.0
		UPR	93734	Sterling (Washington Dulles)	85	177.9
Chaparral Steel	50.3	SFC	13740	Richmond	50	38.7
		UPR	93734	Sterling (Washington Dulles)	85	199.9
Dominion—Bremo	67.1	SFC	93736	Charlottesville	190	49.2
		UPR	93734	Sterling (Washington Dulles)	85	158.0
American Electric Power—Clinch River	452.5	SFC	13877	Bristol-Johnson City-Kingsport, TN	465	53.4
		UPR	53829	Roanoke/Blacksburg	648	161.4
Dominion—Chesapeake Energy Center	4.0	SFC	13737	Norfolk	7	17.8
		UPR	93739	Wallops Island	13	147.8
Potomac River Generating Station	10.4	SFC	13743	Washington, DC	3	5.2
		UPR	93734	Sterling (Washington Dulles)	85	41.1
Dominion—Yorktown Power Station	4.0	SFC	93741	Newport News	13	9.7
		UPR	93739	Wallops Island	13	117.3
Jewel Coke Company LLP	365.9	SFC	13877	Bristol-Johnson City-Kingsport, TN	457	89.5
		UPR	53829	Roanoke/Blacksburg	648	144.6
Dominion-Possum Point Power Station	11.0	SFC	13773	Quantico	4	5.2
		UPR	93734	Sterling (Washington Dulles)	85	41.1
Stone Container Enterprises (Smurfit)	3.0	SFC	13740	Richmond	50	45.3
		UPR	93734	Sterling (Washington Dulles)	85	170.5
Stone Container Corporation—Hopewell	14.3	SFC	13740	Richmond	50	24.6
		UPR	93734	Sterling (Washington Dulles)	85	187.9
American Electric Power (Glen Lyn)	464.5	SFC	VPI120	Horton Station	920	27.4
		UPR	53829	Roanoke/Blacksburg	648	44.4
Intermet Foundry Archer Creek	167.6	SFC	13733	Lynchburg	287	16.2
		UPR	53829	Roanoke/Blacksburg	648	122.0
RES dba Steel Dynamics	301.8	SFC	13741	Roanoke	350	5.7
		UPR	53829	Roanoke/Blacksburg	648	37.3
Spruance Genco LLC	16.5	SFC	13740	Richmond	50	12.2
		UPR	93734	Sterling (Washington Dulles)	85	169.8

The meteorological inputs for AERMOD were generated using the AERMOD Meteorological Processor (AERMET) program (version 06341) (EPA, 1998 and 2006c). For each location/site pair, one needs to specify the roughness length, albedo and Bowen ratio based on the land-use characteristics of the area in which the surface meteorological monitoring site is located. This was accomplished by first assessing the land-use for each 100 by 100 m grid cell in a 3-km area surrounding the site. The land-use was plotted and divided into sectors of similar land use based on visual inspection. For each sector the fractional land use was calculated. Each land-use value was assigned a value of roughness length, albedo and Bowen ratio based on tables provided in EPA (2007c). Then a weighted value for each parameter was calculated for each sector based on the fractional land use.

The remaining steps included extraction of hourly surface and twice-daily upper-air data from the National Weather Service (NWS) database, quality assurance of the data, merging of the surface and upper-air data, and application of AERMET to calculate the planetary boundary layer parameters required by AERMOD. In applying AERMET, the methods and reference levels for standard NWS data were employed (EPA, 1998).

The meteorological inputs are contained in two files. The first file includes surface wind, temperature, pressure, relative humidity, and stability information as well as cloud cover and precipitation values. The second file contains information on the vertical structure of temperature and wind near the source location.

It is difficult to review the AERMET-derived meteorological files from a physical meteorological perspective. AERMET and AERMOD, however, both provide report files that contain error and warning messages that can be used to identify problems with data completeness or questionable values in the observed data or calculated parameters. Each of the report files was carefully reviewed. On average less than 8 percent of the hourly data values were reported as missing, and about 20 percent of the hourly wind speeds were reported as calm.

4.2.4. Model Performance Evaluation

The first step in evaluating AERMOD performance was to check the results for reasonableness. The annual deposition output from AERMOD was plotted for each facility and corresponding receptor area. Plots of wet, dry, and total deposition were reviewed to confirm that the magnitude and spatial distribution was reasonable. The deposition of HG0, HG2 and HGP was compared to the speciation of the emissions and checks were made to ensure that these were consistent. Three key findings emerged from this review: 1) dry deposition is greater than wet deposition for all facilities, 2) maximum wet deposition tends to occur in the receptor cells closest to the facility, and 3) maximum dry deposition within the 3-km receptor area tends to occur further away from the facility location. As noted earlier, the 3-km square receptor area appeared to capture the maximum deposition in all cases.

The finding related to wet deposition is consistent with wash out of the emissions near the facility when precipitation is occurring. The finding related to dry deposition is consistent with expected plume behavior under a variety of meteorological conditions and transport of the emissions to a downwind location before deposition occurs.

To further explore the reasonableness of the AERMOD results, several sensitivity tests were conducted in which selected AERMOD input parameters were varied. According to Wesely et al. (2002), the deposition parameters for the three forms of mercury are not at all well established. Thus, possible uncertainties in the values for air diffusivity, water diffusivity, and particle size distribution were explored by making small changes to these parameters. In addition, the effects of using homogeneous versus more detailed surface characteristics and the sensitivity of the model to changes in the emissions rates and stack parameter information were examined. The sensitivity results for AERMOD are presented in Section 6 of this report.

It was not possible to evaluate the AERMOD results using observed data. However, the AERMOD results were compared with the CMAQ results, in terms of the overall deposition amount and the relative deposition of HG0, HG2 and HGP and wet versus dry deposition. This comparison is also presented in Section 6.

4.2.5. Base- and Future-year Modeling and Analysis

AERMOD was applied for the base simulation period using 2002 emissions and for 2010, 2015 and 2018 using projected emissions for those years. Total emissions for the base and future years are summarized in Table 4-4.

Table 4-4. AERMOD Emissions Rates for Total Mercury (lbs/yr) for 2002, 2010, 2015 and 2018 for the Top 15 Emitting Facilities for the Base Year.

Facility Name	Rank	2002 Total Hg (lbs/yr)	2010 Total Hg (lbs/yr)	2015 Total Hg (lbs/yr)	2018 Total Hg (lbs/yr)
Dominion—Chesterfield Power Station	1	358.83	183.15	151.47	159.39
Chaparral Steel	2	292.30	100.50	50.50	50.50
Dominion—Bremo	3	167.73	172.74	189.88	200.38
American Electric Power- Clinch River	4	159.21	80.00	81.00	81.00
Dominion—Chesapeake Energy Center	5	157.38	81.05	89.09	94.01
Potomac River Generating Station	6	118.26	72.37	72.37	29.77
Dominion—Yorktown Power Station	7	107.64	105.85	73.46	31.19
Jewel Coke Company LLP	8	105.62	106.91	106.91	106.91
Dominion-Possum Point Power Station	9	100.19	1.99	1.49	1.25
Stone Container Enterprises (Smurfit)	10	77.76	80.57	82.36	83.41
Stone Container Corporation -Hopewell	11	69.69	9.66	9.79	9.87
American Electric Power (Glen Lyn)	12	65.14	67.09	73.74	77.82
Intermet Foundry Archer Creek	13	65.01	21.77	12.87	13.89
RES dba Steel Dynamics	14	60.80	21.57	12.65	13.65
Spruance Genco LLC	15	55.50	25.95	28.53	30.11

There are both increases and decreases in the emissions between the base and future years, depending on the facility and the year. Compared to the base year, overall total mercury emissions for these fifteen facilities are 42 percent lower for 2010, 47 percent lower for 2015, and 50 percent lower for 2018. Additional detailed summaries of the AERMOD emissions are provided in Section 6 of this report.

Tabular and graphical summaries of the AERMOD results for the base and future years were prepared and analyzed. The results are presented in Section 6.

In this study, AERMOD was intended to be used primarily as a screening tool - to identify facilities that may have large local impacts on mercury deposition that may not be resolved by CMAQ due to the grid resolution and other factors. To complete this goal, the reductions simulated by AERMOD for each future year were compared in a relative sense (e.g., using percent change) with those simulated by CMAQ and used to quantify the possible uncertainty in the CMAQ results that are attributable to the effects of grid resolution. The combined CMAQ/AERMOD results are presented in Section 7 of this report.

5. CMAQ Modeling Results

The CMAQ modeling results are presented in this section of the report. The base-year modeling exercises included the initial simulation for the 2001/2002 base year, a meteorological sensitivity simulation, an update to the emissions inventory, and an evaluation of model performance. The CMAQ/PPTM feature was used to assess baseline contributions from tagged sources and source regions to mercury deposition.

The future-year modeling exercise included the application of CMAQ for 2010 and 2015, and the application of CMAQ/PPTM for 2018. For 2018, PPTM was applied for the same sources and source regions that were tagged and examined for base-year simulation. All future-year modeling results were assessed relative to the base year results, with emphasis on the relative, rather than absolute, changes in mercury deposition.

The spatial plots of mercury deposition presented in this section use a variety of different scales in order to display the spatial patterns of deposition and deposition differences. Note that the color scheme is not tied to specific ranges of deposition, but is used instead to highlight the patterns of deposition corresponding to each individual plot. For example, in a given a plot of total annual mercury deposition from all sources the scale may range from 0 to 64 grams per square kilometer (g km^{-2}) and the color red may be used to designate deposition values greater than 56 g km^{-2}, in another plot of mercury deposition from selected sources the scale may range from 0 to 20 g km^{-2} and the color red may be used to designate deposition values greater than 17.5 g km^{-2}, and in another a plot of mercury deposition from natural sources the scale may range from 0 to 2 g km^{-2} and the color red may be used to designate deposition values greater than 1.8 g km^{-2}. The spatial plots are intended to display the spatial patterns. For detailed comparisons of the deposition amounts the reader should refer to the pie charts, bar charts and tables that are also presented in this section.

In addition to the results presented in this section, a full of set CMAQ-derived, gridded output files of mercury deposition for each simulation year have been prepared and provided to VDEQ for use in water quality analysis.

5.1. Base-year Modeling

The results of the meteorological sensitivity simulation, the evaluation of model performance, and the CMAQ/PPTM baseline contribution analysis are presented in this section of the report.

5.1.1. Meteorological Sensitivity Simulation

While 2001 was selected as the annual simulation period, sensitivity testing was conducted using 2002 meteorological inputs. CMAQ-ready meteorological inputs for 2002 were obtained from EPA. These alternate meteorological inputs were prepared using the same tools and methods used for 2001, namely MM5 and MCIP (as discussed in Section 4). In particular, assessing the sensitivity of the model to the meteorological inputs (and thus potentially the use of a different base year for the modeling analysis) was of interest.

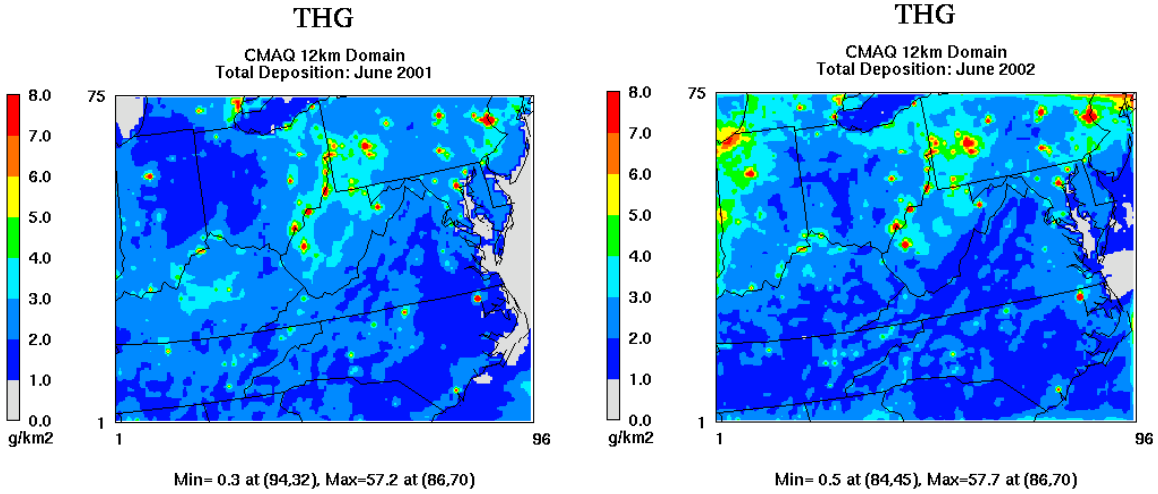
It is widely understood that changes in the meteorological conditions input to a simulation have the potential to affect simulated mercury deposition in a variety of complex ways. Wet deposition is directly related to the location, amount and timing of rainfall and other forms of precipitation. Dry deposition is affected by atmospheric stability and wind speed. The sources contributing to both wet and dry deposition are determined in part by the source-receptor relationships defined by wind speed and wind direction. Thus changes in any of these parameters have the potential

to affect deposition. This study did not include a detailed assessment of the differences between the meteorological inputs and their effects on simulation deposition. Instead, the assessment focused on whether use of a different simulation period (and its associated meteorological conditions) would produce very different CMAQ results.

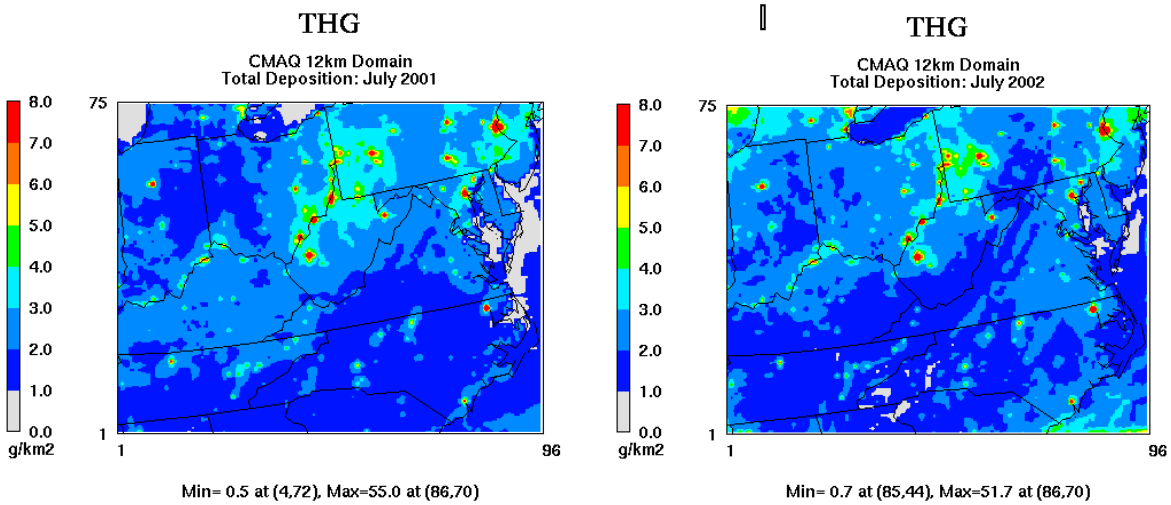
For Virginia, both precipitation and wet deposition tend to be highest during the summer months. The data presented in Section 2 indicate that wet deposition tends to be greatest for the third quarter of the year. Thus the sensitivity simulations focused on July, August and September. The CMAQ base year simulation for July, August, and September was rerun using the complete set of meteorological inputs for these months for 2002. The monthly deposition totals are compared in Figure 5-1, which displays total deposition for each of the three months for 2001 and 2002.

Figure 5-1. Monthly CMAQ-Simulated Total Mercury Deposition (g km^{-1}) for June, July, August 2001 and 2002.

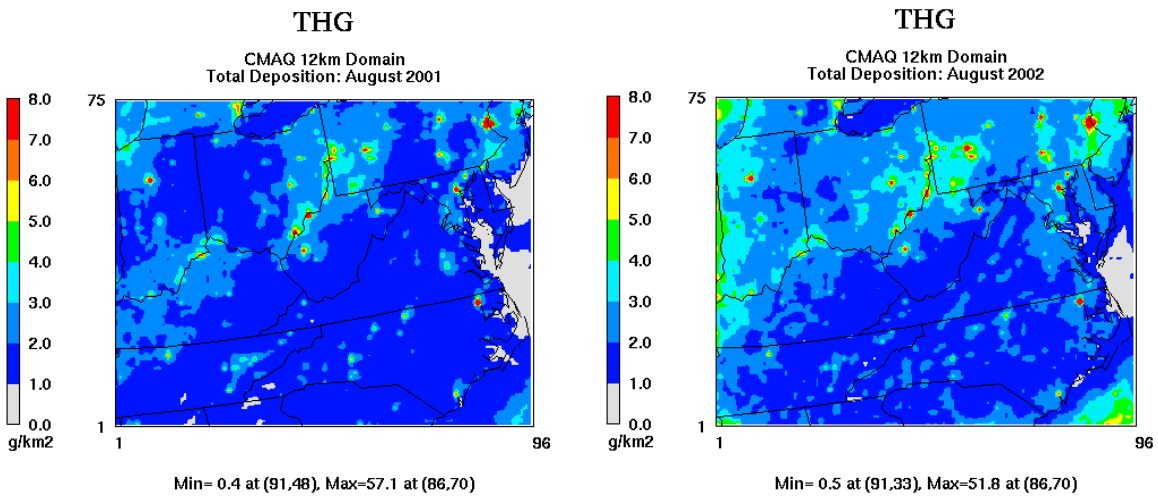
(a) June 2001 (left) and June 2002 (right)



(b) July 2001 (left) and July 2002 (right)



(c) August 2001 (left) and August 2002 (right)



When comparing the simulated deposition within the 12-km domain, there are similarities in the deposition patterns that are related to the distribution of emissions sources. Overall deposition amounts for 2002 are greater for June, less for July, and greater for August compared to those for 2001. A similar comparison of the wet and dry deposition amounts (not shown) indicates that the differences in total deposition are due to differences in both wet and dry deposition, but that some of the larger differences are for wet deposition.

Wet deposition is, of course, correlated with rainfall. So it is important to examine how the rainfall compares between the two years. The reliability of the deposition results also depends on how well the observed rainfall is represented by the meteorological inputs. Thus another important factor to consider in assessing the quality of the results for the two different years is the ability of MM5 to simulate the observed rainfall amounts for each year. Table 5-1 summarizes and compares the observed and simulated rainfall amounts for three locations in Virginia (Shenandoah National Park, Charlottesville, and Norfolk) for each of the three months and each year. These sites were selected to represent different geographical areas in the state (namely the mountains, mid-section and coastal regions). In addition to total rainfall amount, the number of days with measurable precipitation is also given.

Table 5-1a. Observed and Simulated Monthly Rainfall Amount (in) and Number of Rain Days for June, July, and August 2001 and 2002: Shenandoah National Park.

Month	2001				2002			
	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days
June	5.44	9.78	15	17	3.47	7.79	9	15
July	2.82	4.79	5	14	3.21	9.51	10	19
August	6.63	7.39	17	16	3.48	8.51	13	21
Total	14.89	21.96	37	47	10.16	25.81	32	55

Table 5-1b. Observed and Simulated Monthly Rainfall Amount (in) and Number of Rain Days for June, July, and August 2001 and 2002: Charlottesville.

Month	2001				2002			
	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days
June	5.12	4.51	17	12	3.18	3.80	11	10
July	2.04	2.29	10	8	4.55	5.18	14	12
August	2.68	2.44	15	9	2.16	2.46	9	9
Total	9.84	9.24	42	29	9.89	11.44	34	31

Table 5-1c. Observed and Simulated Monthly Rainfall Amount (in) and Number of Rain Days for June, July, and August 2001 and 2002: Norfolk.

Month	2001				2002			
	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days
June	6.96	3.02	12	8	4.29	5.02	10	9
July	2.43	1.81	11	6	3.10	6.22	11	15
August	5.97	9.12	14	11	2.77	6.67	11	13
Total	15.36	13.95	37	25	10.16	17.91	32	37

The observed values for the two years show that 2001 was characterized by a greater amount of precipitation than 2002 for Shenandoah and Norfolk and about the same amount as for 2002 for Charlottesville. The number of days with measurable precipitation is greater for 2001 for all three areas. The distribution of rain throughout the summer months is different for the two years.

For Shenandoah (Table 5-1a), the MM5-derived rainfall amounts are higher than observed for both 2001 and 2002. The overestimation is much greater for 2002. The average rainfall bias for this site is 2.4 in for 2001 and 5.2 in for 2002.

For Charlottesville (Table 5-1b), the MM5-derived rainfall amounts are slightly lower than observed for 2001 and slightly higher than observed for 2002. The average bias for this site is -0.2 in for 2001 and 0.5 in for 2002.

For Norfolk (Table 5-1c), the MM5-derived rainfall amounts are slightly lower than observed for 2001 and higher than observed for 2002. The average bias for this site is -0.5 in for 2001 and 2.6 in for 2002.

Figure 5-2 provides a visual comparison of the simulated and observed rainfall amount by month for each year and each site.

Figure 5-2a. Observed and Simulated Monthly Rainfall Amount (in) for June, July, and August 2001 and 2002: Shenandoah National Park.

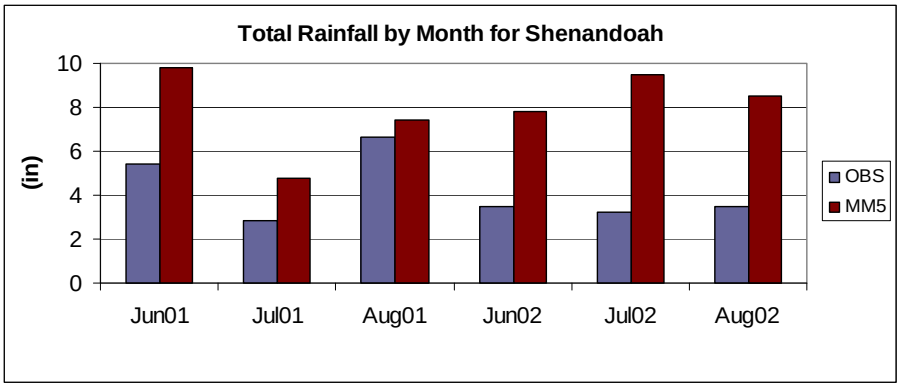


Figure 5-2b. Observed and Simulated Monthly Rainfall Amount (in) for June, July, and August 2001 and 2002: Charlottesville.

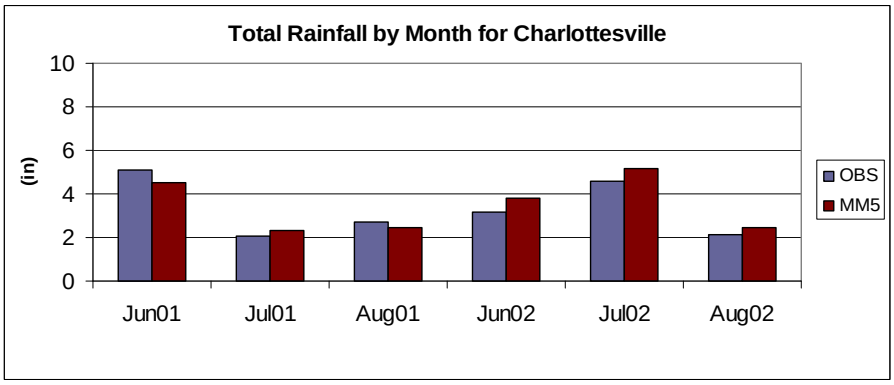
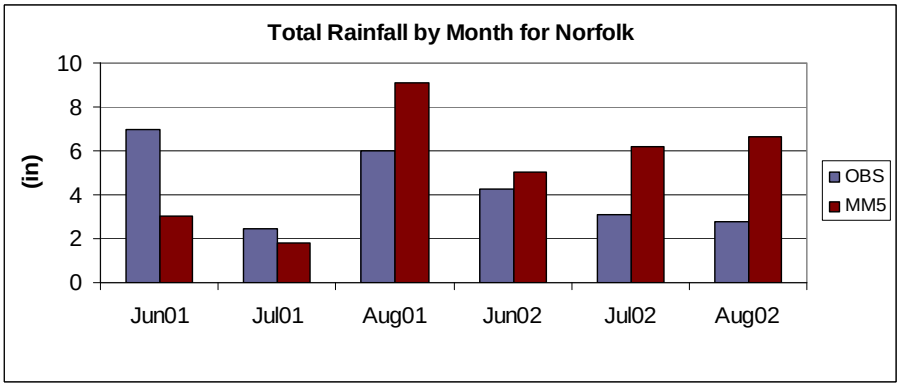


Figure 5-2c. Observed and Simulated Monthly Rainfall Amount (in) for June, July, and August 2001 and 2002: Norfolk.



In summary, this comparison with observed precipitation data indicates that the MM5 model does a better job of simulating the observed precipitation amounts for the selected sites for 2001 for the subset simulation period. However, model performance does vary by month. The overall better representation of summertime precipitation amounts by MM5 provides some additional confirmation that 2001 is a more suitable simulation period than 2002 (for the critical summer months). Note that the selection of the simulation period was discussed in more detail in Section 3. The results of the sensitivity simulation indicate that the model is sensitive to rainfall and possibly other of the meteorological conditions. One conclusion from this analysis is that the ability of CMAQ to simulate deposition is dependent on the ability of the meteorological inputs to represent key meteorological conditions, such as rainfall.

5.1.2. Model Performance Evaluation

The CMAQ model is a multi-pollutant model and certain of the non-mercury species, especially ozone and other oxidants, may influence the simulation of mercury. In addition, examining model performance for a variety different species and for both air concentrations and deposition may aid the overall evaluation of the model results and specifically the identification of biases or deficiencies for certain regions, time periods and/or meteorological (or other) conditions. Thus, the evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species.

The simulated and observed values of concentration and deposition for each monitoring site and the average over all sites within 1) the full domain, 2) the 12-km inner grid of the modeling domain, and 3) Virginia were compared. The emphasis of the model performance evaluation was mercury deposition for Virginia and the 12-km grid. Following EPA guidance (EPA, 2006b), the evaluation of model performance examined 1) whether the CMAQ model is able to replicate observed (and estimated) mercury deposition data, and 2) whether the response of the model to changes in mercury emissions is reasonable.

Model Evaluation Datasets

NON-MERCURY SPECIES CONCENTRATIONS AND DEPOSITION DATA

Model performance for ozone was evaluated against observations available from the EPA Air Quality System (AQS) network. For the national-scale modeling domain, the number of sites ranges from approximately 500 to several thousand, depending on the time of year. The sites are primarily located in urban areas. The daily average simulated ozone concentration for each monitor for each day of the annual simulation period was compared to the corresponding observed concentration.

Measurements of $PM_{2.5}$ were obtained from the AQS network, which includes several thousand sites, and the Interagency Monitoring of Protected Visual Environments (IMPROVE) network, which samples approximately 150 Class I national parks and wilderness areas throughout the U.S. For $PM_{2.5}$ and its component species, daily, monthly and annual average values were compared.

Observed wet deposition amounts of sulfate, nitrate, and ammonia from the National Acid Deposition Program (NADP) were used to assess the model's ability to simulate the deposition for each of these species. The NADP network includes more than 200, typically rural, sites. Monthly average values were compared.

MERCURY DEPOSITION DATA

For mercury, the CMAQ wet deposition values were compared to data from the Mercury Deposition Network (MDN), as available from the National Acid Deposition Program (NADP). There are a total of 53 MDN monitors with complete data for 2001 in the full modeling domain.

Emphasis was given to the evaluation of model performance for the 12-km grid. There are a total of 9 MDN monitors with complete data for 2001 in the 12-km modeling domain, and these include several sites in Pennsylvania and North Carolina. Sites at the Allegheny Portage Railroad National Historic Site, Pennsylvania; Arendtsville, Pennsylvania; and Pettigrew State Park, North Carolina all have data for 2001 and are likely most representative, based on proximity and/or similar geographical features, to the areas of interest in Virginia. In particular, Pettigrew State Park, near the Albemarle Sound, may be representative of coastal Virginia.

Mercury wet deposition data for Virginia are available for three MDN monitoring sites, Shenandoah National Park (beginning in October 2002), Culpeper (beginning in November 2002) and Harcum (beginning in December 2004). The Culpeper site is located in north-central Virginia and the Harcum site is located in coastal Virginia. Although there are no actual data for these sites for the 2001 simulation period, the data for 2003-2005 for sites in Virginia and throughout region were used to estimate deposition for 2001 at the Virginia monitoring sites. The methodology used to estimate deposition is discussed in the next section. The estimated deposition values were used in the evaluation of CMAQ model performance.

ESTIMATED MERCURY DEPOSITION "DATA"

The results from the Classification and Regression Tree (CART) analysis (which was conducted to support the development of the conceptual model) were used to estimate deposition for 2001 for the Virginia monitoring sites. CART is a statistical analysis tool developed by Brieman, et al. (1984) and enhanced by Steinberg, et al. (1997) and Salford Systems (2007). Specifically, each seven-day period in 2001 was classified according to the observed meteorological conditions and determined the corresponding CART-based classification group. The daily average mercury deposition for the grouping (the daily average for all other periods in the classification group) was assigned to the 2001 weekly period (multiplying by 7 to get the weekly deposition amount). This was done for each period for the entire year of 2001 and then the weekly mercury deposition values were used to estimate seasonal and annual deposition amounts. The key assumption here is that by matching the meteorological conditions for 2001 on a weekly basis to those for later years, observed mercury deposition for the later years can be used to estimate deposition for 2001. Applying this assumption on a weekly basis accounted for the variable effects of meteorology throughout the year.

As a second approach to estimating the data, each of the Virginia sites was paired with a nearby site with a longer period of record. Various ratios of the observed data were used to estimate wet deposition for the Virginia sites for 2001. The ratios were based on year-to-year differences in wet deposition at the longer-term sites and, alternatively, site-to-site differences in deposition between the paired sites for each year with available data at both sites. The Culpeper site was paired with Arendtsville, PA; the Shenandoah site was paired with the Allegheny Portage Railroad National Historic Site, PA; and Harcum was paired with Pettigrew State Park, NC. Refer to Figure 2-1 for a map showing the locations of these sites.

The results of both the CART and ratio methods are presented in Table 5-2.

Table 5-2a. Observed and Estimated Annual Mercury Wet Deposition (g km^{-2}) for Selected MDN Sites in Virginia: Culpeper.

Year	Culpeper (VA08)			
	Observed	Estimated Based on Year-to-Year Ratio	Estimated Based on Site-to-Site Ratio	Estimated Using CART Analysis
2001		6.85	6.78	5.88
2003	12.73			
2004	7.78			
2005	8.81			

Table 5-2b. Observed and Estimated Annual Mercury Wet Deposition (g km^{-2}) for Selected MDN Sites in Virginia: Shenandoah.

Year	Shenandoah (VA28)			
	Observed	Estimated Based on Year-to-Year Ratio	Estimated Based on Site-to-Site Ratio	Estimated Using CART Analysis
2001		11.53	10.99	8.18
2003	11.87			
2004	9.73			
2005	7.07			

Table 5-2c. Observed and Estimated Annual Mercury Wet Deposition (g km^{-2}) for Selected MDN Sites in Virginia: Harcum.

Year	Harcum (VA98)			
	Observed	Estimated Based on Year-to-Year Ratio	Estimated Based on Site-to-Site Ratio	Estimated Using CART Analysis
2001		4.50	4.50	7.05
2003				
2004				
2005	8.15			

The more detailed CART-based estimation technique gives a result that is different from one obtained from ratios of the observed data. The differences among the estimates highlight that there is uncertainty in the estimated data. Because the CART-based estimation technique relies only on data for the Virginia sites and accounts for year-to-year difference in meteorology at these sites, the CART-based estimates were used in calculating statistical performance evaluation. Nevertheless, the other values may provide perspective to the reader in reviewing the statistical results.

Statistical Performance Metrics

A variety of statistical measures were used to quantify model performance. These were listed and described in Section 3. Statistical measures were calculated on a monthly, seasonal and annual basis, based on data availability.

Currently, EPA modeling guidance does not provide benchmarks for the evaluation of CMAQ model performance for any species. For ozone modeling, early EPA modeling guidance (EPA, 1991) suggested ranges for the normalized bias (within ±15 percent) and normalized gross error (less than or equal to 35 percent). Although originally developed for urban-scale ozone modeling, these ranges have continued to be referenced for regional-scale modeling. More recently, model performance criteria based on a mean fractional bias of within ±15 percent and a mean fractional error of less than 35 percent have been applied or recommended (e.g., Boylan et al., 2005). Compared to the normalized bias and error, the fractional bias and error are better suited for regional modeling since the measures can be meaningfully calculated for a broader range of concentrations. For $PM_{2.5}$, typical and recommended ranges for mean fractional bias and error are considerably wider. Boylan and Russell (2006) recommend the following criteria for acceptable model performance: mean fractional bias within ±60 percent and mean fractional error less than 75 percent, with corresponding goals of ±30 and 50 percent, respectively. These values are based on the results of selected modeling studies. There are currently no such criteria for deposition, including for mercury deposition (Bullock et al., 2008), so we have also adopted these same values for deposition. In the remainder of this section, the qualitative assessments of model performance are referenced to these criteria.

Results

OZONE

Model performance for ozone is summarized in Table 5-3. Table 5-3a presents the statistical performance measures for the 36-km domain, and Table 5-3b presents this same information for the 12-km subdomain. Statistical measures for ozone are summarized for each month of the typical ozone season (April through October). Daily average ozone values were used to calculate the statistical measures. Only days with daily averaged observed values greater than 40 ppb were used in the calculations.

Table 5-3a. Summary of CMAQ Model Performance for Ozone for the 2001 Simulation Period: 36-km Domain.

Metric Descriptor	Units	Metric ID	Apr	May	Jun	Jul	Aug	Sep	Oct
No. of obs/sim pairs		N	26515	29982	27067	27928	28759	23521	17608
Mean observed	ppb	OBS	55.8	62.1	66.2	64.5	66.2	59.2	54.9
Mean simulated	ppb	SIM	64.5	70.1	73.3	67.2	69.5	60.8	54.6
Ratio of means		RATIO	1.2	1.1	1.1	1.0	1.0	1.0	1.0
Mean bias	ppb	MB	8.7	8.0	7.1	2.8	3.2	1.6	-0.3
Mean fractional bias	%	MFB	14.2	12.6	10.8	4.5	5.4	3.2	-0.1
Mean error	ppb	ME	10.8	11.8	12.7	11.5	12.3	9.7	8.1
Mean fractional error	%	MFE	18.0	17.9	18.5	17.2	18.0	16.0	14.6
Correlation		R	0.559	0.602	0.625	0.527	0.525	0.528	0.513
Correlation coefficient		R2	0.312	0.362	0.391	0.278	0.276	0.279	0.263

Table 5-3b. Summary of CMAQ Model Performance for Ozone for the 2001 Simulation Period: VDEQ 12-km Subdomain.

Metric Descriptor	Units	Metric ID	Apr	May	Jun	Jul	Aug	Sep	Oct
No. of obs/sim pairs		N	9033	9535	9247	9453	9966	7426	4914
Mean observed	ppb	OBS	56.6	63.9	68.8	65.1	67.3	58.6	54.8
Mean simulated	ppb	SIM	63.1	68.1	73.1	66.9	69.5	56.7	51.2
Ratio of means		RATIO	1.1	1.1	1.1	1.0	1.0	1.0	0.9
Mean bias	ppb	MB	6.5	4.2	4.3	1.8	2.2	-1.9	-3.6
Mean fractional bias	%	MFB	11.0	7.5	7.2	3.1	4.1	-2.9	-6.4
Mean error	ppb	ME	9.1	8.7	10.3	9.6	10.1	8.5	7.7
Mean fractional error	%	MFE	15.4	13.7	15.0	14.6	14.8	14.8	14.6
Correlation		R	0.558	0.738	0.729	0.619	0.613	0.546	0.587
Correlation coefficient		R2	0.311	0.545	0.531	0.383	0.376	0.298	0.345

For the 36-km grid (Table 5-3a), the ratio of mean simulated to mean observed ozone is close to one for each month. The mean fractional bias is within 15 percent and is positive for all months, with the exception of October. Note that a positive value indicates an overestimation of ozone. The mean fractional error is within 20 percent. These values are indicative of reasonable model performance for ozone on the national scale.

For the 12-km grid (Table 5-3b), the ratio of mean simulated to mean observed ozone is also close to one for all months. The mean fractional bias is within 10 percent and the mean fractional error is within 15 percent for all months, with the exception of April (and they are only slightly higher than these thresholds for April). The bias changes from positive to negative during the course of the ozone season, which indicates that CMAQ overestimates ozone early in the ozone

season and underestimates ozone later in the season. The errors are generally consistent throughout the seven-month period, but highest for the summer months (when ozone is also at its highest). Compared to the ranges provided earlier, the bias and error values indicate good model performance for ozone, on average, for the region encompassed by the 12-km grid.

PM2.5 (AQS)

Model performance for total $PM_{2.5}$ (based on AQS data) is summarized in Table 5-4. Table 5-4a presents the statistical performance measures for the 36-km domain, and Table 5-4b presents this same information for the 12-km subdomain. Statistical measures for total $PM_{2.5}$ are summarized for each month and for the entire annual simulation period. Daily (24-hour average) $PM_{2.5}$ values were used to calculate the statistical measures. For most sites, data are available on a daily basis. Only observed $PM_{2.5}$ values greater than 0.10 μgm^{-3} were used in calculating the statistical measures.

Table 5-4a. Summary of CMAQ Model Performance for PM2.5 for the AQS Sites for the 2001 Simulation Period: 36-km Domain.

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	1125	1119	1130	1130	1135	1145	1141	1147	1154	1150	1151	1150	1217
Mean observed	μgm^{-3}	OBS	15.9	12.5	11.9	11.2	11.6	13.4	13.1	14.6	10.8	10.7	13.6	10.7	12.5
Mean simulated	μgm^{-3}	SIM	15.0	12.5	12.3	10.5	9.2	10.1	9.9	11.2	10.1	10.7	12.9	10.6	11.3
Ratio of means		RATIO	0.9	1.0	1.0	0.9	0.8	0.8	0.8	0.8	0.9	1.0	1.0	1.0	0.9
Mean bias	μgm^{-3}	MB	-0.9	0.0	0.4	-0.7	-2.4	-3.3	-3.2	-3.4	-0.6	0.1	-0.7	0.0	-1.2
Mean fractional bias	%	MFB	-11.2	-6.7	-2.1	-12.6	-27.0	-32.3	-29.1	-28.6	-8.0	-3.8	-9.7	-5.8	-16.1
Mean error	μgm^{-3}	ME	5.9	4.3	3.4	3.4	3.5	4.3	4.4	4.5	2.6	3.2	4.9	4.5	3.2
Mean fractional error	%	MFE	39.8	36.2	30.8	33.0	36.0	39.5	39.3	37.9	26.0	30.2	37.8	41.9	29.5
Correlation		R	0.308	0.322	0.526	0.508	0.602	0.730	0.619	0.712	0.536	0.461	0.238	0.196	0.599
Correlation coefficient		R2	0.095	0.104	0.277	0.258	0.362	0.533	0.383	0.507	0.287	0.213	0.057	0.038	0.359

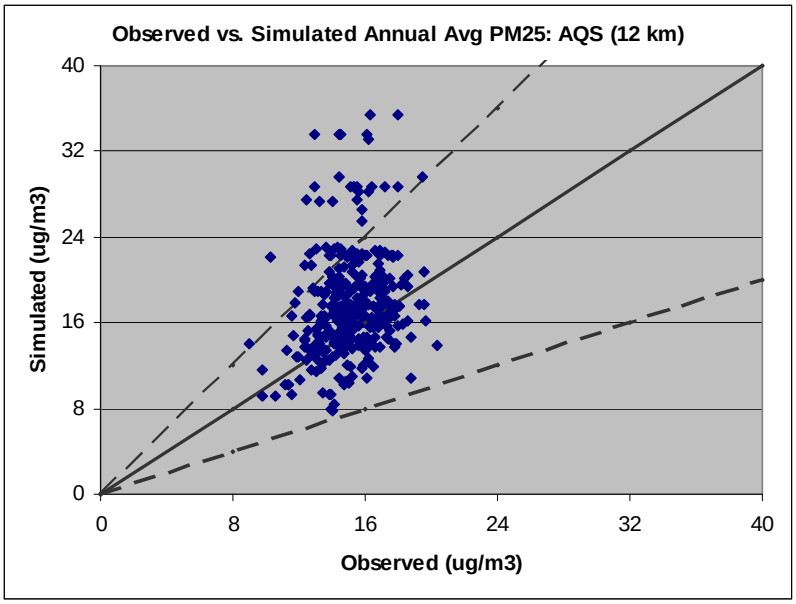
Table 5-4b. Summary of CMAQ Model Performance for PM2.5 for the AQS Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	339	335	339	336	337	338	337	337	340	343	346	344	358
Mean observed	μgm^{-3}	OBS	17.8	13.9	12.8	13.3	15.3	18.9	16.7	21.2	13.2	12.1	15.0	11.3	15.1
Mean simulated	μgm^{-3}	SIM	25.3	19.1	16.8	16.1	14.7	16.8	16.1	20.1	16.0	18.0	21.6	18.1	18.5
Ratio of means		RATIO	1.4	1.4	1.3	1.2	1.0	0.9	1.0	1.0	1.2	1.5	1.4	1.6	1.2
Mean bias	μgm^{-3}	MB	7.5	5.2	3.9	2.8	-0.6	-2.1	-0.7	-1.0	2.8	5.9	6.6	6.7	3.4
Mean fractional bias	%	MFB	28.9	25.9	23.2	15.8	-7.0	-14.4	-6.0	-6.1	17.7	33.6	32.6	38.5	11.4
Mean error	μgm^{-3}	ME	8.1	5.9	4.4	3.9	4.1	4.3	4.4	4.4	3.5	6.3	8.1	7.1	4.6
Mean fractional error	%	MFE	33.7	31.7	27.6	23.7	26.3	23.3	25.9	21.3	23.0	36.9	40.4	42.2	20.9
Correlation		R	0.480	0.252	0.522	0.147	-0.113	0.219	0.182	0.222	0.155	0.330	-0.022	0.452	0.225
Correlation coefficient		R2	0.230	0.064	0.272	0.022	0.013	0.048	0.033	0.049	0.024	0.109	0.000	0.204	0.050

For the 36-km grid (Table 5-4a), the ratio of mean simulated to mean observed $PM_{2.5}$ ranges form 0.8 to 1. The mean fractional bias is within 35 percent and is negative for all months, indicating that $PM_{2.5}$ concentrations are underestimated. The underestimation is most pronounced during the summer months. On an annual basis, the mean fractional bias is -16.1 percent. The mean fractional error is within about 40 percent for all months, and is 29.5 percent for the annual period. Based on the ranges provided earlier, these values are indicative of reasonable model performance for $PM_{2.5}$ on the national scale.

For the 12-km grid (Table 5-4b), the ratio of mean simulated to mean observed $PM_{2.5}$ ranges from 0.9 to 1.6 and is 1.2 for the year. The mean fractional bias is within 35 percent, with the exception of December. The bias is positive for January through April and September through December, and negative for the remaining (summer) months. Thus there is a mix of over- and underestimation, which results in an annual bias of 11.4 percent. The mean fractional error is within about 40 percent for all months, and is 20.9 percent for the annual period. These values are indicative of reasonable model performance for $PM_{2.5}$ on the regional scale. Figure 5-3 compares simulated and observed annual average $PM_{2.5}$ for all AQS sites within the 12-km subdomain. Each point in the scatter diagram represents a different AQS site. The dashed lines designate agreement within 50 percent of the observed value.

Figure 5-3. Scatter Diagram Comparing Simulated and Observed Annual Average PM2.5 Concentrations for the AQS Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.



PM2.5 (IMPROVE)

Model performance for total and speciated $PM_{2.5}$ (based on IMPROVE data) is summarized in Table 5-5. Table 5-5a presents the statistical performance measures for total $PM_{2.5}$ for the 36-km domain, and Table 5-5b presents the performance metrics for $PM_{2.5}$ and several component species for the 12-km subdomain. Statistical measures for total $PM_{2.5}$ are summarized for each month and for the entire annual simulation period. Daily (24-hour average) species values were used to calculate the statistical measures. For the IMPROVE sites, the measurements are taken every three days. The statistical measures are calculated using monthly and annual average species concentrations, a cut-off value of 0.01 μgm^{-3} was assigned for each species to avoid using very low concentrations in the calculations.

Table 5-5a. Summary of CMAQ Model Performance for PM2.5 for the IMPROVE Sites for the 2001 Simulation Period: 36-km Domain.

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	104	103	113	120	125	126	128	129	131	133	132	133	135
Mean observed	μgm^{-3}	OBS	3.9	3.8	4.5	6.2	6.8	7.4	7.3	8.4	6.0	5.4	5.3	3.5	5.8
Mean simulated	μgm^{-3}	SIM	4.8	4.5	5.2	5.2	4.8	5.4	5.6	6.5	5.8	5.7	5.9	4.5	5.6
Ratio of means		RATIO	1.2	1.2	1.2	0.8	0.7	0.7	0.8	0.8	1.0	1.1	1.1	1.3	1.0
Mean bias	μgm^{-3}	MB	0.9	0.7	0.7	-1.0	-2.0	-2.0	-1.7	-1.9	-0.3	0.3	0.6	1.0	-0.3
Mean fractional bias	%	MFB	18.2	12.7	11.0	-29.3	-41.4	-30.2	-22.2	-25.1	-7.9	-0.9	2.2	19.0	-9.2
Mean error	μgm^{-3}	ME	1.7	1.5	1.5	2.3	2.2	2.6	2.6	3.1	1.8	1.7	2.0	1.8	1.4
Mean fractional error	%	MFE	39.9	36.4	32.5	45.0	44.7	39.7	39.0	42.7	30.1	27.9	35.0	42.4	27.4
Correlation		R	0.839	0.823	0.851	0.683	0.832	0.797	0.717	0.725	0.660	0.770	0.781	0.731	0.9
Correlation coefficient		R2	0.704	0.677	0.724	0.466	0.692	0.635	0.514	0.526	0.436	0.593	0.610	0.534	0.731

Table 5-5b. Summary of CMAQ Model Performance for PM2.5 for the IMPROVE Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.

PM2.5

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	7.7	7.8	8.2	10.4	12.8	15.5	12.5	19.8	10.7	8.5	9.9	6.6	11.4
Mean simulated	μgm^{-3}	SIM	12.8	11.5	11.5	11.8	11.0	13.0	12.1	16.4	12.9	12.3	14.9	10.6	12.8
Ratio of means		RATIO	1.7	1.5	1.4	1.1	0.9	0.8	1.0	0.8	1.2	1.5	1.5	1.6	1.1
Mean bias	μgm^{-3}	MB	5.1	3.7	3.4	1.4	-1.8	-2.5	-0.4	-3.4	2.2	3.8	4.9	4.0	1.4
Mean fractional bias	%	MFB	37.6	28.8	27.2	7.8	-19.6	-20.1	-3.1	-25.2	14.6	27.6	28.3	34.8	8.0
Mean error	μgm^{-3}	ME	5.1	3.7	3.4	2.3	2.2	2.7	4.2	5.0	2.6	3.9	5.6	4.0	1.9
Mean fractional error	%	MFE	37.6	28.9	27.2	17.0	21.8	21.7	35.3	33.1	17.7	28.1	34.1	34.8	13.3
Correlation		R	0.910	0.849	0.824	0.379	0.765	0.726	0.427	0.324	0.314	0.726	0.342	0.893	0.812
Correlation coefficient		R2	0.828	0.721	0.679	0.144	0.585	0.528	0.183	0.105	0.099	0.527	0.117	0.798	0.659

Sulfate (SO4)

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	2.5	2.7	3.0	3.7	5.1	6.9	6.1	10.1	4.8	2.8	3.1	2.1	4.6
Mean simulated	µgm-3	SIM	2.5	2.6	2.7	4.1	5.1	6.7	6.4	9.7	6.4	3.8	3.9	2.4	4.7
Ratio of means		RATIO	1.0	1.0	0.9	1.1	1.0	1.0	1.1	1.0	1.3	1.4	1.3	1.1	1.0
Mean bias	μgm^{-3}	MB	0.0	-0.1	-0.3	0.4	0.0	-0.2	0.3	-0.4	1.6	1.0	0.8	0.3	0.1
Mean fractional bias	%	MFB	2.3	-3.6	-9.9	8.6	-1.5	-2.7	5.1	-3.9	23.4	26.5	20.3	10.9	2.5
Mean error	μgm^{-3}	ME	0.4	0.3	0.4	0.6	0.4	0.7	0.8	1.9	1.6	1.0	0.8	0.4	0.3
Mean fractional error	%	MFE	18.6	11.4	15.7	14.2	7.7	10.4	12.0	18.6	23.5	26.5	20.3	16.6	6.0
Correlation		R	0.838	0.850	0.800	0.192	0.682	0.739	0.789	0.608	0.093	0.569	0.530	0.666	0.800
Correlation coefficient		R2	0.702	0.722	0.640	0.037	0.466	0.546	0.622	0.369	0.009	0.324	0.281	0.443	0.641

Nitrate (NO3)

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	1.7	1.2	1.6	1.0	0.7	0.4	0.3	0.4	0.4	0.5	1.1	1.3	0.8
Mean simulated	μgm^{-3}	SIM	2.1	1.9	2.7	1.5	0.5	0.5	0.4	0.4	0.5	1.5	2.4	1.3	1.4
Ratio of means		RATIO	1.2	1.6	1.7	1.5	0.7	1.3	1.1	1.1	1.4	3.0	2.1	0.9	1.7
Mean bias	μgm^{-3}	MB	0.4	0.7	1.1	0.5	-0.2	0.1	0.0	0.1	0.2	1.0	1.3	-0.1	0.6
Mean fractional bias	%	MFB	8.8	34.1	39.1	15.2	-207.1	-134.2	-160.3	-405.7	-50.6	58.1	43.7	-26.0	28.4
Mean error	μgm^{-3}	ME	0.5	0.8	1.1	0.5	0.2	0.3	0.2	0.3	0.3	1.0	1.3	0.4	0.6
Mean fractional error	%	MFE	32.7	38.7	43.7	31.3	211.3	169.6	185.6	439.9	83.4	59.8	48.4	40.9	34.0
Correlation		R	0.934	0.894	0.903	0.697	0.936	0.847	0.590	0.696	0.762	0.875	0.697	0.833	0.894
Correlation coefficient		R2	0.873	0.799	0.816	0.486	0.877	0.717	0.348	0.485	0.581	0.766	0.486	0.694	0.799

Organic Carbon (OC)

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	1.6	1.6	1.3	1.5	1.8	1.9	1.8	2.2	1.5	1.9	2.7	1.2	1.8
Mean simulated	μgm^{-3}	SIM	2.6	2.4	1.8	2.1	1.7	1.6	1.5	1.5	1.8	2.3	2.9	2.2	2.0
Ratio of means		RATIO	1.7	1.6	1.4	1.4	0.9	0.8	0.8	0.7	1.1	1.2	1.1	1.8	1.1
Mean bias	μgm^{-3}	MB	1.0	0.9	0.5	0.6	-0.2	-0.4	-0.4	-0.7	0.2	0.4	0.2	1.0	0.2
Mean fractional bias	%	MFB	31.7	28.4	20.3	22.8	-13.9	-31.6	-31.3	-54.8	6.1	12.7	3.8	37.6	7.1
Mean error	μgm^{-3}	ME	1.2	1.0	0.7	0.7	0.3	0.5	0.5	0.8	0.4	0.5	1.3	1.1	0.4
Mean fractional error	%	MFE	43.3	36.2	35.3	28.2	20.1	37.8	36.7	59.3	20.8	18.2	42.0	44.6	18.5
Correlation		R	0.808	0.583	0.396	0.427	0.720	0.783	0.538	0.334	0.418	0.594	0.221	0.742	0.657
Correlation coefficient		R2	0.653	0.340	0.156	0.182	0.518	0.613	0.289	0.111	0.174	0.353	0.049	0.550	0.432

Elemental Carbon (EC)

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.4	0.4	0.5	0.3	0.4
Mean simulated	μgm^{-3}	SIM	0.6	0.5	0.4	0.4	0.3	0.4	0.3	0.4	0.4	0.5	0.6	0.5	0.4
Ratio of means		RATIO	1.4	1.2	1.2	1.1	0.8	0.8	0.8	0.7	0.8	1.1	1.1	1.5	1.0
Mean bias	μgm^{-3}	MB	0.2	0.1	0.1	0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.1	0.2	0.0
Mean fractional bias	%	MFB	13.4	-3.9	2.1	0.9	-48.4	-35.7	-41.0	-59.9	-40.4	-4.3	-4.5	15.4	-12.7
Mean error	μgm^{-3}	ME	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.3	0.2	0.1
Mean fractional error	%	MFE	33.1	34.0	25.4	22.7	53.6	40.5	49.4	64.3	47.0	22.7	41.8	25.1	26.9
Correlation		R	0.950	0.688	0.765	0.856	0.755	0.910	0.793	0.786	0.609	0.823	0.358	0.611	0.855
Correlation coefficient		R2	0.902	0.473	0.585	0.732	0.570	0.829	0.629	0.618	0.371	0.677	0.128	0.373	0.731

For the 36-km grid (Table 5-5a), the ratio of mean simulated to mean observed $PM_{2.5}$ ranges form 0.7 to 1.3. The mean fractional bias is within 30 percent for all months with the exception of May. It is positive during the cooler months (January through March, November and December) and negative (and somewhat larger) for the remaining (typically warmer) months. On an annual basis, the mean fractional bias is -9.2 percent. The mean fractional error is within 45 percent for all months, and is 27.4 percent for the annual period (based on annual average $PM_{2.5}$ concentrations). Overall $PM_{2.5}$ is less well simulated for the more rural IMPROVE sites, compared to the AQS sites.

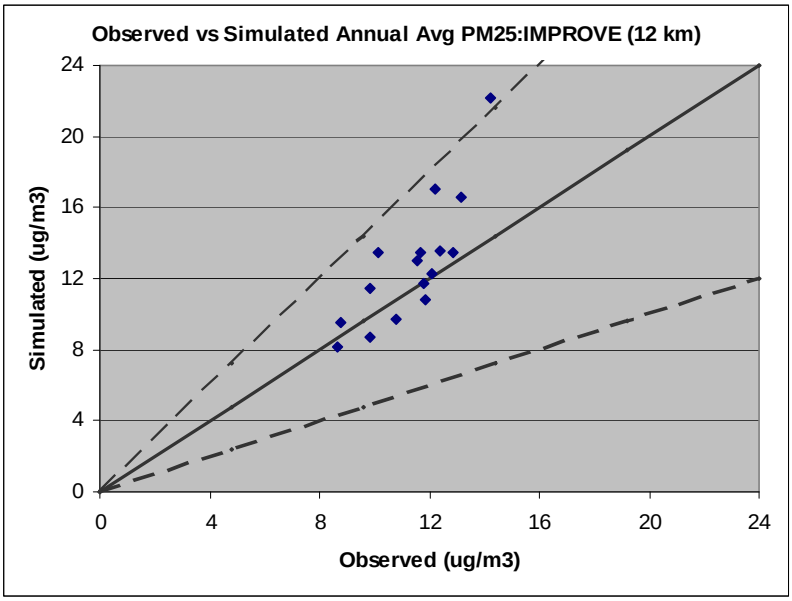
For the 12-km grid (Table 5-5b), the ratio of mean simulated to mean observed $PM_{2.5}$ ranges from 0.8 to 1.7 and is 1.1 for the year. The mean fractional bias is within about 35 percent. The bias is positive for January through April and September through December, and negative for the remaining (summer) months. Thus there is a mix of over- and underestimation, which results in an annual bias of 8 percent. The mean fractional error is also within about 35 percent for all months,

and is 13 percent for the annual period. Based on the ranges provided earlier, these values are indicative of reasonable model performance for $PM_{2.5}$ at the more rural sites within the 12-km domain. The statistical measures for the IMPROVE sites indicate better performance for the higher resolution grid, compared to the full 36-km domain. Considering the component species, model performance for sulfate is similar to that for overall $PM_{2.5}$ (since sulfate is a predominant species). Agreement between the simulated and observed values is less good for OC and EC, especially during the summer months, when both of these components are underestimated. Nitrate is not well represented by CMAQ at the IMPROVE sites, but is present in very small amounts for sites in the region encompassed by the 12-km grid (so small differences in concentration can result in large errors). On an annual average basis, nitrate is overestimated.

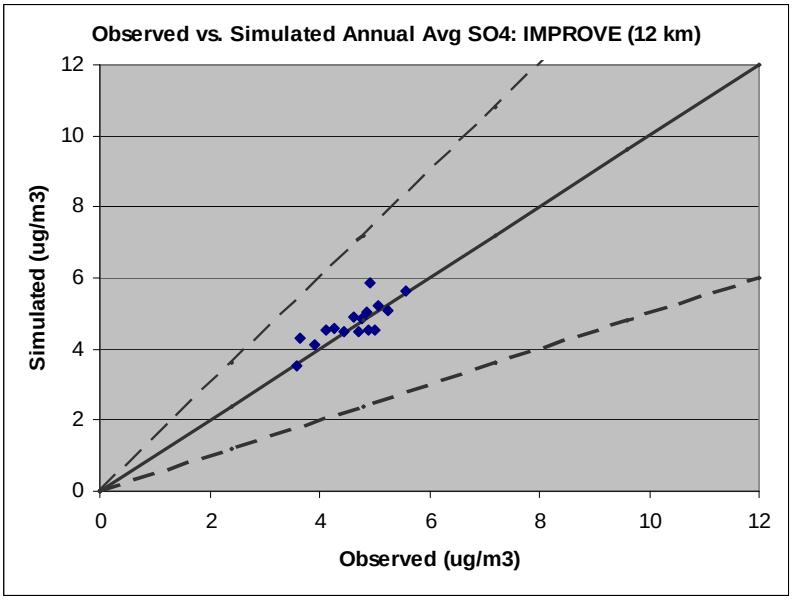
Figure 5-4 compares simulated and observed annual average $PM_{2.5}$ and its component species for all IMPROVE sites within the 12-km subdomain. Each point in the scatter diagram represents a different IMPROVE site. The dashed lines designate agreement within 50 percent of the observed value.

Figure 5-4. Scatter Diagram Comparing Simulated and Observed Annual Average PM2.5 Concentrations for the 2001 Simulation Period: VDEQ 12-km Subdomain.

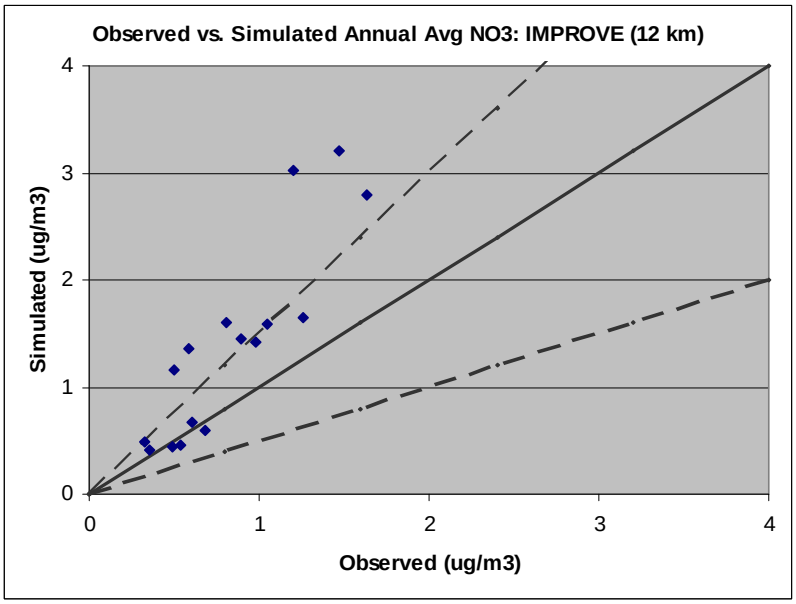
Total PM2.5



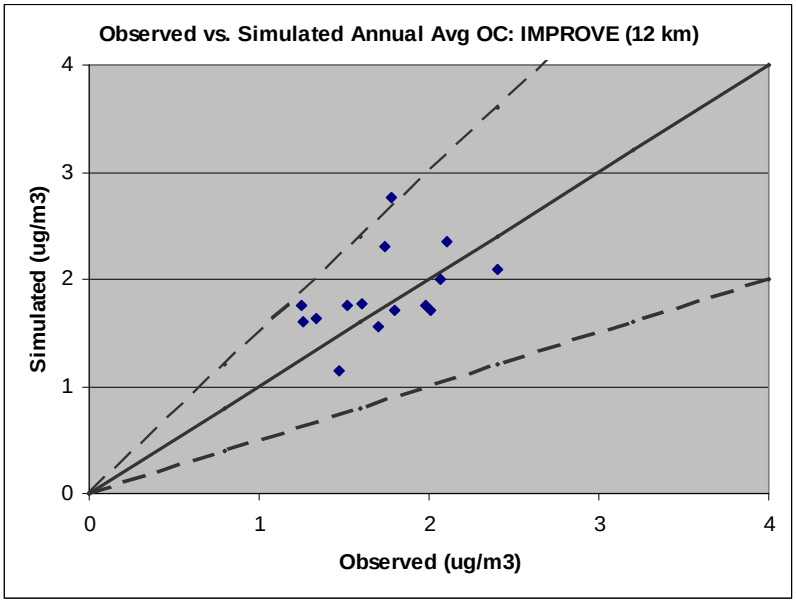
Sulfate (SO4)



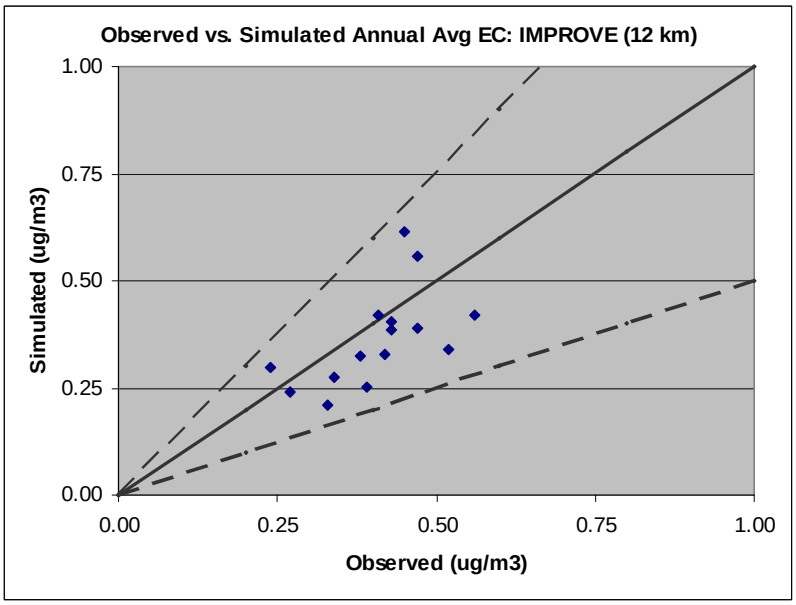
Nitrate (NO3)



Organic Carbon (OC)



Elemental Carbon (EC)



ACID DEPOSITION

Model performance for sulfate, nitrate and ammonium deposition is summarized in Table 5-6. Table 5-6a presents the statistical performance measures for the 36-km domain, and Table 5-6b presents this same information for the 12-km subdomain. These statistics were calculated using data from the NADP monitoring sites. Statistical measures for each species are summarized for each season and for the annual simulation period. Weekly values were used to calculate the statistical measures.

Table 5-6a. Summary of CMAQ Model Performance for Acid Deposition for the NADP Sites for the 2001 Simulation Period: 36-km Domain.

Sulfate Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	199	217	207	214	152
Mean observed	g km^{-2}	OBS	1.7	2.4	3.4	1.7	10.8
Mean simulated	g km^{-2}	SIM	2.0	2.7	4.4	2.2	13.1
Ratio of means		RATIO	1.2	1.1	1.3	1.2	1.2
Mean bias	g km^{-2}	MB	0.3	0.3	1.0	0.4	2.3
Mean fractional bias	%	MFB	11.1	7.8	18.4	15.1	11.2
Mean error	g km^{-2}	ME	5.9	4.3	3.4	3.4	3.2
Mean fractional error	%	MFE	39.8	36.2	30.8	33.0	29.5
Correlation		R	0.308	0.322	0.526	0.508	0.599
Correlation coefficient		R2	0.095	0.104	0.277	0.258	0.359

Nitrate Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	219	218	212	220	152
Mean observed	g km^{-2}	OBS	1.5	2.2	2.8	1.4	9.2
Mean simulated	g km^{-2}	SIM	1.7	1.8	2.0	1.4	8.1
Ratio of means		RATIO	1.2	0.8	0.7	1.0	0.9
Mean bias	g km^{-2}	MB	0.3	-0.4	-0.8	0.0	-1.1
Mean fractional bias	%	MFB	6.8	-16.6	-31.5	-0.1	-19.6
Mean error	g km^{-2}	ME	0.7	0.7	1.1	0.5	2.3
Mean fractional error	%	MFE	46.8	40.8	48.9	41.5	32.1
Correlation		R	0.705	0.736	0.703	0.776	0.755
Correlation coefficient		R2	0.497	0.542	0.494	0.602	0.570

Ammonium Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	167	201	201	184	152
Mean observed	g km^{-2}	OBS	0.3	0.7	0.7	0.4	2.2
Mean Simulated	g km^{-2}	SIM	0.3	0.5	0.8	0.4	2.1
Ratio of means		RATIO	0.8	0.8	1.1	0.9	1.0
Mean bias	g km^{-2}	MB	-0.1	-0.1	0.1	0.0	-0.1
Mean fractional bias	%	MFB	-24.9	-18.5	7.1	-6.0	-6.0
Mean error	g km^{-2}	ME	0.1	0.3	0.3	0.2	0.6
Mean fractional error	%	MFE	48.8	42.4	41.1	42.6	31.7
Correlation		R	0.461	0.673	0.566	0.685	0.708
Correlation coefficient		R2	0.213	0.453	0.320	0.469	0.501

Table 5-6b. Summary of CMAQ Model Performance for Acid Deposition for the NADP Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.

Sulfate Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	44	44	44	44	44
Mean observed	g km^{-2}	OBS	2.7	4.2	6.5	2.6	16.0
Mean simulated	g km^{-2}	SIM	3.6	5.5	8.0	3.2	20.3
Ratio of means		RATIO	1.3	1.3	1.2	1.3	1.3
Mean bias	g km^{-2}	MB	0.9	1.3	1.5	0.7	4.3
Mean fractional bias	%	MFB	24.5	19.9	11.9	15.1	18.0
Mean error	g km^{-2}	ME	1.1	1.7	2.5	1.0	5.2
Mean fractional error	%	MFE	29.4	29.8	31.3	29.9	24.4
Correlation		R	0.540	0.507	0.418	0.823	0.643
Correlation coefficient		R2	0.292	0.257	0.175	0.678	0.413

Nitrate Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	44	44	44	44	44
Mean observed	g km^{-2}	OBS	2.1	3.4	4.0	1.7	11.1
Mean simulated	g km^{-2}	SIM	2.9	2.9	2.6	1.7	10.1
Ratio of means		RATIO	1.4	0.9	0.7	1.0	0.9
Mean bias	g km^{-2}	MB	0.8	-0.5	-1.3	0.0	-1.0
Mean fractional bias	%	MFB	25.7	-19.8	-65.9	-6.3	-13.5
Mean error	g km^{-2}	ME	0.8	0.9	1.5	0.4	1.7
Mean fractional error	%	MFE	27.3	32.6	72.3	31.0	19.1
Correlation		R	0.648	0.586	0.323	0.860	0.761
Correlation coefficient		R2	0.420	0.343	0.104	0.740	0.578

Ammonium Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	44	44	44	44	44
Mean observed	g km^{-2}	OBS	0.3	0.8	0.9	0.4	2.5
Mean simulated	g km^{-2}	SIM	0.3	0.8	1.1	0.4	2.6
Ratio of means		RATIO	1.0	1.0	1.2	0.9	1.1
Mean bias	g km^{-2}	MB	0.0	0.0	0.2	0.0	0.2
Mean fractional bias	%	MFB	-9.8	-5.2	9.2	-6.2	1.8
Mean error	g km^{-2}	ME	0.1	0.2	0.4	0.1	0.5
Mean fractional error	%	MFE	40.0	30.5	29.5	33.5	20.1
Correlation		R	0.246	0.434	0.481	0.779	0.606
Correlation coefficient		R2	0.060	0.188	0.231	0.607	0.367

The statistical measures indicate good agreement with observed deposition data for both the 36-km and 12-km domains.

MERCURY

Model performance for mercury wet deposition (based on MDN data) is summarized in Table 5-7. Table 5-7a presents the statistical performance measures for the 36-km domain, and Table 5-7b presents the statistical information for the 12-km subdomain. The measures for mercury are summarized for each season and for the entire annual simulation period. Approximately weekly values were used to calculate the statistical measures. The measurement periods vary in length throughout the year and are different for each site. Thus, in order to calculate the statistics, the simulation days were matched to the observation periods for each site. Then monthly, seasonal, and annual deposition amounts were calculated.

Table 5-7a. Summary of CMAQ Model Performance for Mercury Wet Deposition for the MDN Sites for the 2001 Simulation Period: 36-km Domain.

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	52	52	52	52	52
Mean Observed	g km^{-2}	OBS	1.3	2.4	3.7	2.0	9.3
Mean Simulated	g km^{-2}	SIM	1.9	2.6	2.8	2.1	9.4
Ratio of means		RATIO	1.4	1.1	0.8	1.1	1.0
Mean bias	g km^{-2}	MB	0.6	0.2	-0.9	0.2	0.1
Mean fractional bias	%	MFB	21.3	-1.1	-33.8	7.4	-4.2
Mean error	g km^{-2}	ME	0.8	0.9	1.5	0.7	2.7
Mean fractional error	%	MFE	40.9	34.7	53.9	33.9	28.9
Correlation		R	0.666	0.453	0.598	0.718	0.627
Correlation coefficient		R2	0.444	0.205	0.357	0.516	0.393

Table 5-7b. Summary of CMAQ Model Performance for Mercury Wet Deposition for the MDN Sites for the 2001 Simulation Period: 12-km Domain.

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	13	13	13	13	13
Mean Observed	g km^{-2}	OBS	1.4	2.7	3.4	1.5	9.0
Mean Simulated	g km^{-2}	SIM	1.9	2.7	2.4	1.4	8.3
Ratio of means		RATIO	1.4	1.0	0.7	0.9	0.9
Mean bias	g km^{-2}	MB	0.5	0.0	-1.0	-0.1	-0.7
Mean fractional bias	%	MFB	24.5	-9.7	-58.4	-23.2	-13.7
Mean error	g km^{-2}	ME	0.5	0.9	1.3	0.5	1.7
Mean fractional error	%	MFE	25.8	35.6	65.0	49.6	21.8
Correlation		R	0.845	-0.241	0.251	0.815	0.610
Correlation coefficient		R2	0.714	0.058	0.063	0.664	0.372

For the 36-km grid (Table 5-7a), the ratio of mean simulated to mean observed mercury wet deposition ranges from 0.8 (for the summer months) to 1.4 (for the winter months). The mean fractional bias also indicates that mercury deposition is overestimated (on average) during the winter (by 21.3 percent) and underestimated during the summer months (by 33.4 percent). On an annual basis, the mean fractional bias is -4.2 percent. The mean fractional error is 28.9 percent for the annual period, but larger than this for all of the individual seasonal periods.

For the 12-km grid (Table 5-7b), the ratio of mean simulated to mean observed mercury wet deposition ranges from 0.7 (for the summer months) to 1.4 (for the winter months). The mean fractional bias indicates that mercury deposition is overestimated (on average) during the winter months, but underestimated during the remaining three seasonal periods. On an annual basis,

the mean fractional bias is -13.7 percent. The mean fractional error is 21.8 percent for the annual period, but larger than this for all of the individual seasonal periods.

The simulated and observed mercury wet deposition values are graphically compared in Figures 5-5 and 5-6. Figure 5-5 compares simulated and observed wet deposition totals, by season and for the year, averaged over all sites for the 36- and 12-km domains. Figure 5-6 focuses on the annual deposition totals for each site, and each point in the scatter diagram represents a different MDN site. The dashed lines designate agreement within 50 percent of the observed value.

Figure 5-5a. Comparison of Simulated and Observed Mercury Wet Deposition Averaged over all MDN Sites for Each Season and the Full 2001 Simulation Period: VDEQ 36-km Subdomain.

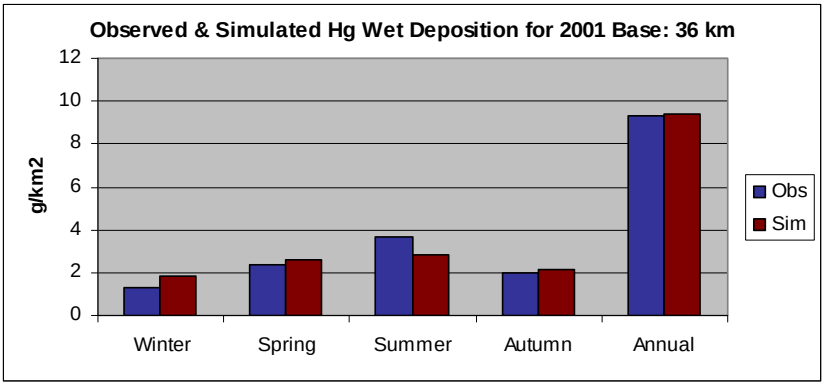


Figure 5-5b. Comparison of Simulated and Observed Mercury Wet Deposition Averaged over all MDN Sites for Each Season and the Full 2001 Simulation Period: VDEQ 12-km Subdomain.

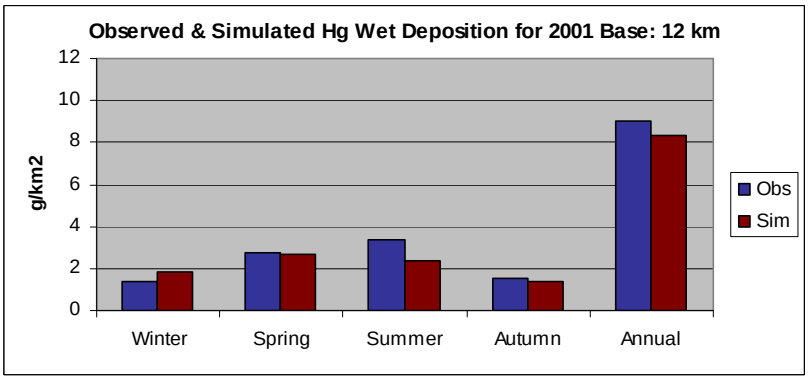


Figure 5-6a. Scatter Diagram Comparing Simulated and Observed Annual Mercury Wet Deposition Totals for the MDN Sites for the 2001 Simulation Period: VDEQ 36-km Subdomain.

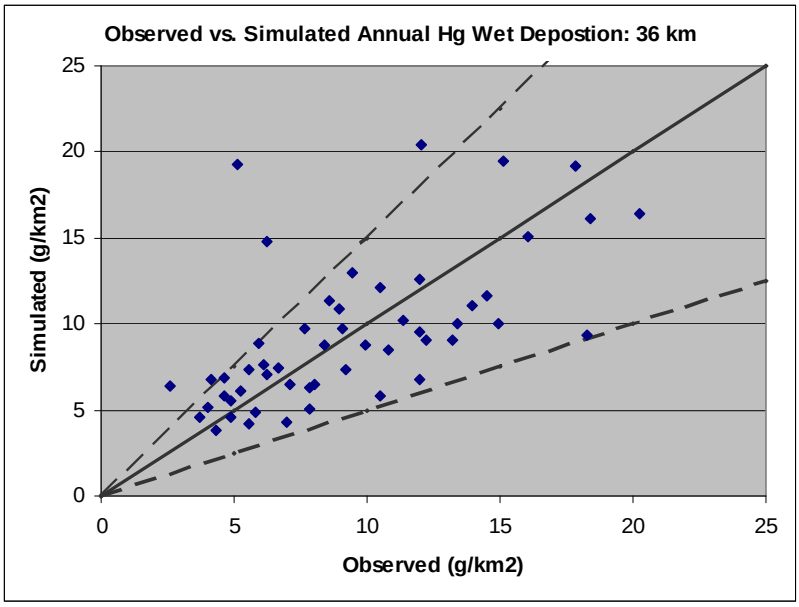
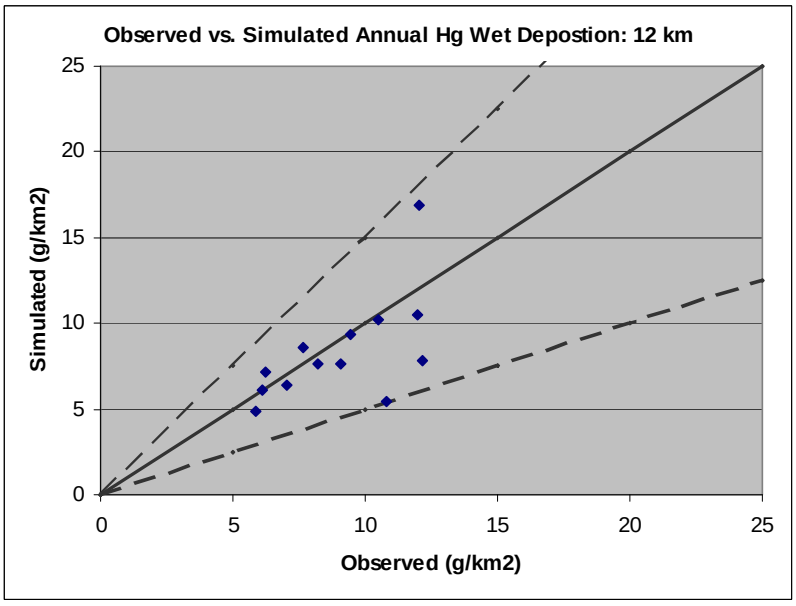


Figure 5-6b. Scatter Diagram Comparing Simulated and Observed Annual Mercury Wet Deposition Totals for the MDN Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.



Finally, 5-7 compares simulated and observed mercury wet deposition totals, by season and for the year, for the Virginia sites only. The simulated values are compared with the estimated data for 2001, as discussed earlier in this section.

Figure 5-7a. Comparison of Simulated and Estimated Mercury Wet Deposition Averaged over all MDN Sites in Virginia for Each Season and the Full 2001 Simulation Period.

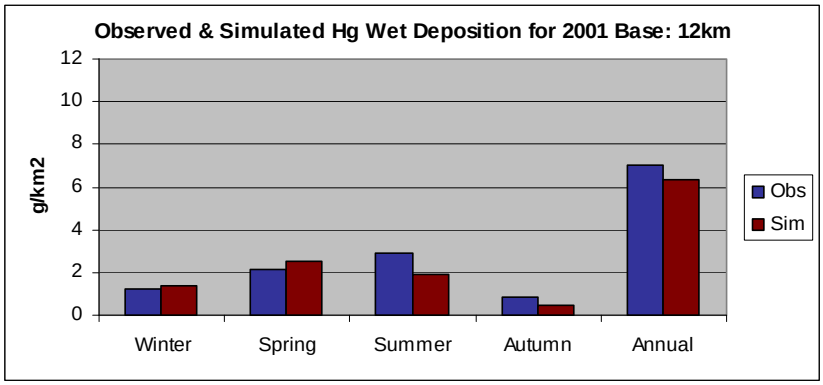
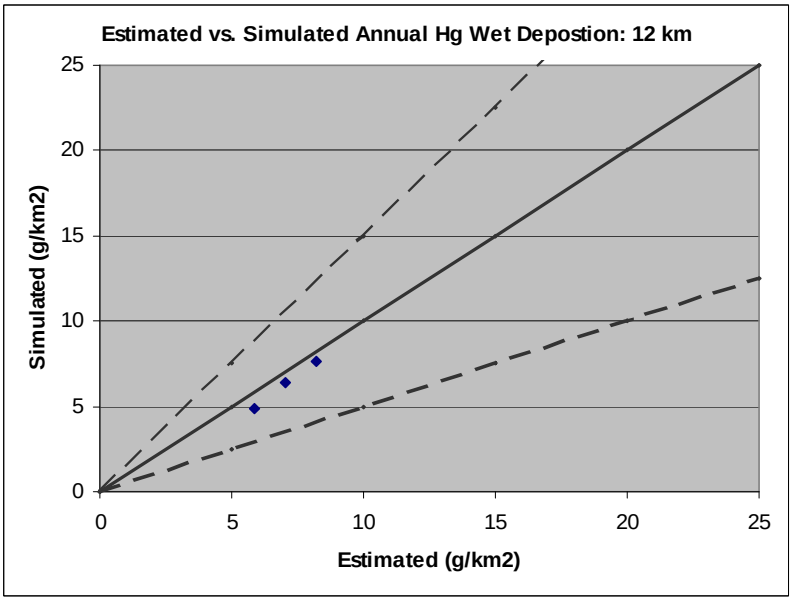


Figure 5-7b. Scatter Diagram Comparing Simulated and Estimated Annual Mercury Wet Deposition Totals for the Virginia MDN Sites for the 2001 Simulation Period.



Overall model performance for mercury wet deposition appears reasonable, especially when considering the annual deposition. Differences between the simulated and observed values are attributable to a number of different factors including the numerical approximations and physical parameterizations used in the CMAQ model, imperfect representation of the meteorological conditions (in particular the timing and amount of rainfall), uncertainties in the emission inventory and boundary condition estimates, and even uncertainties in the measurements. Nevertheless, the simulated annual deposition amounts on average are within 10 percent of the observed values for both the 36- and 12-km domains.

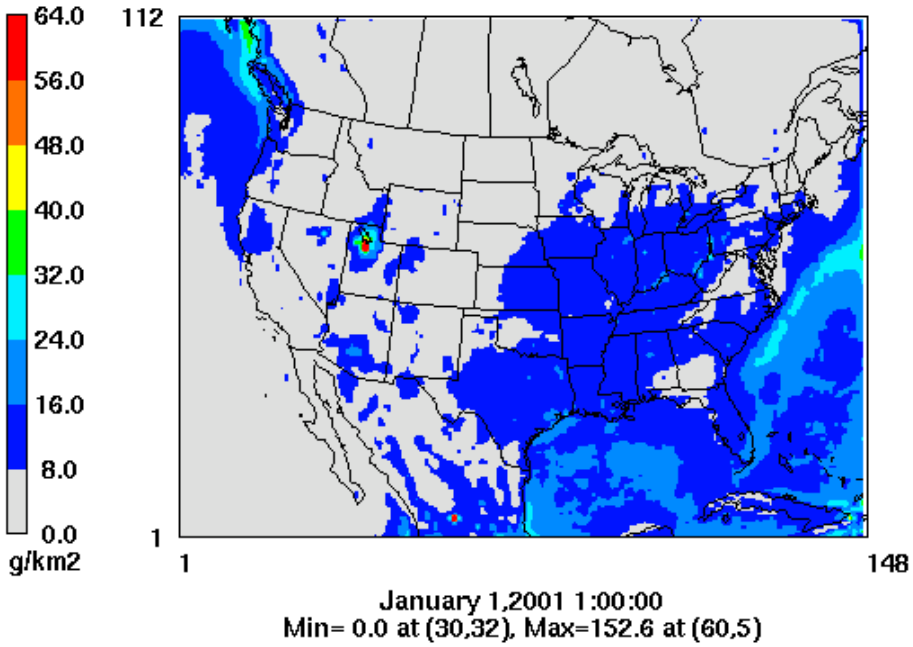
Earlier in this section, it was noted that the simulated deposition amounts are sensitive to rainfall and other meteorological factors. In the remainder of this section, the contributions of the emissions and the boundary conditions to the simulated deposition amounts are examined.

5.1.3. Base Year Mercury Deposition Results

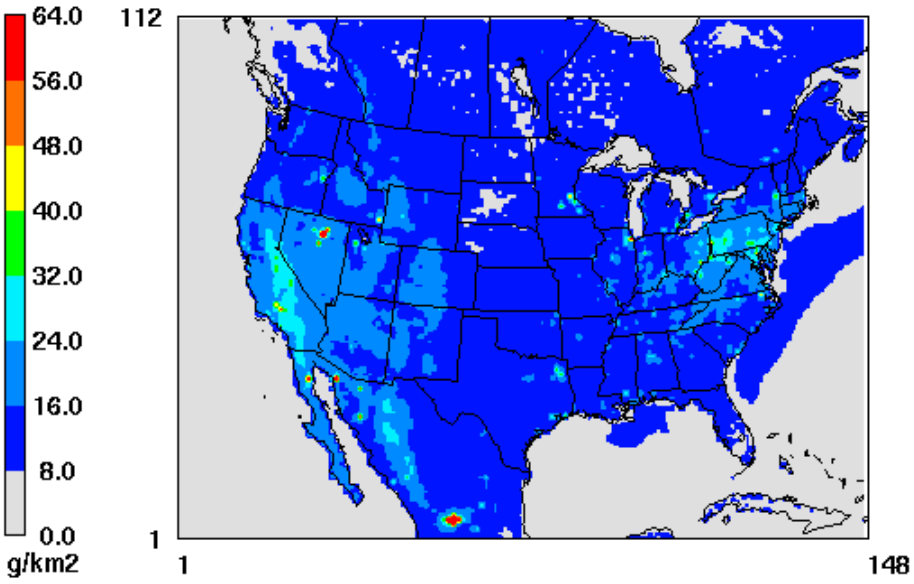
Figures 5-8 and 5-9 display the CMAQ-derived, base-year, annual mercury deposition results for the 36-km (outer) domain. Figure 5-8 displays wet, dry and annual total mercury deposition. Wet deposition (Figure 5-8a) is generally greater in the eastern U.S. compared to the western U.S. and this is consistent with higher annual precipitation amounts in this part of the domain. Dry deposition (Figure 5-8b) is distributed throughout the domain. The dry deposition pattern reflects the distribution of emissions and is characterized by relatively high values over the mid-Atlantic states, in northern Nevada, and over the central valley of California. Alternatively, Figure 5-9 displays total mercury deposition for the elemental (HG0), reactive gaseous (HG2), and particle-bound (HGP) phases. Most of the deposition is in the form of reactive gaseous mercury, with some contribution from particles.

Figure 5-8. CMAQ Simulated Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 36-km Modeling Domain: Wet, Dry and Total Deposition.

(a) Wet Mercury Deposition

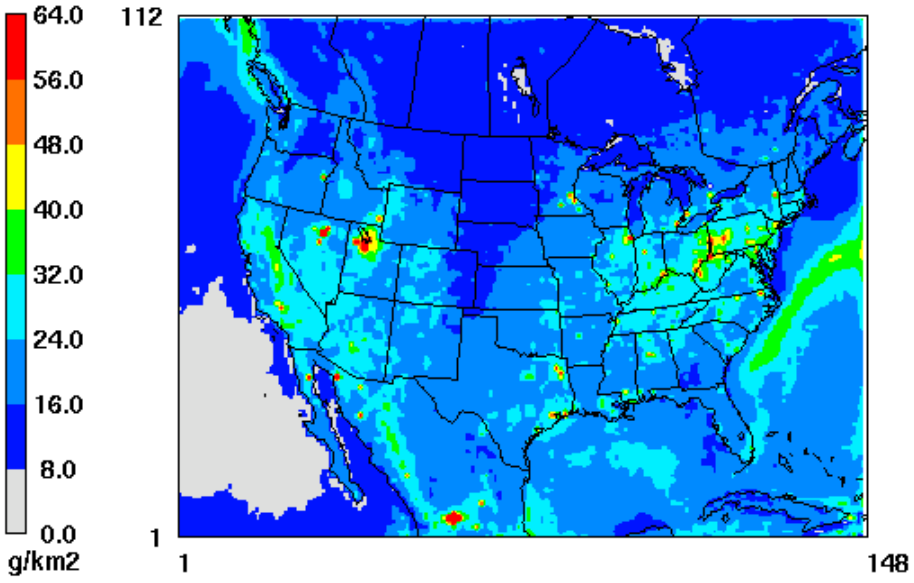


(b) Dry Mercury Deposition



January 1,2001 1:00:00
Min= 1.3 at (24,93), Max=587.6 at (60,5)

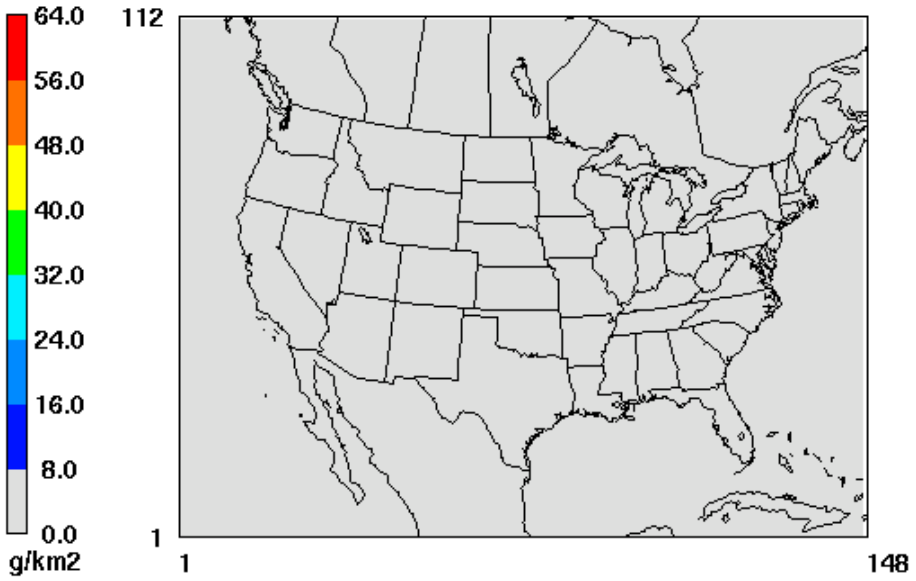
(c) Total Mercury Deposition



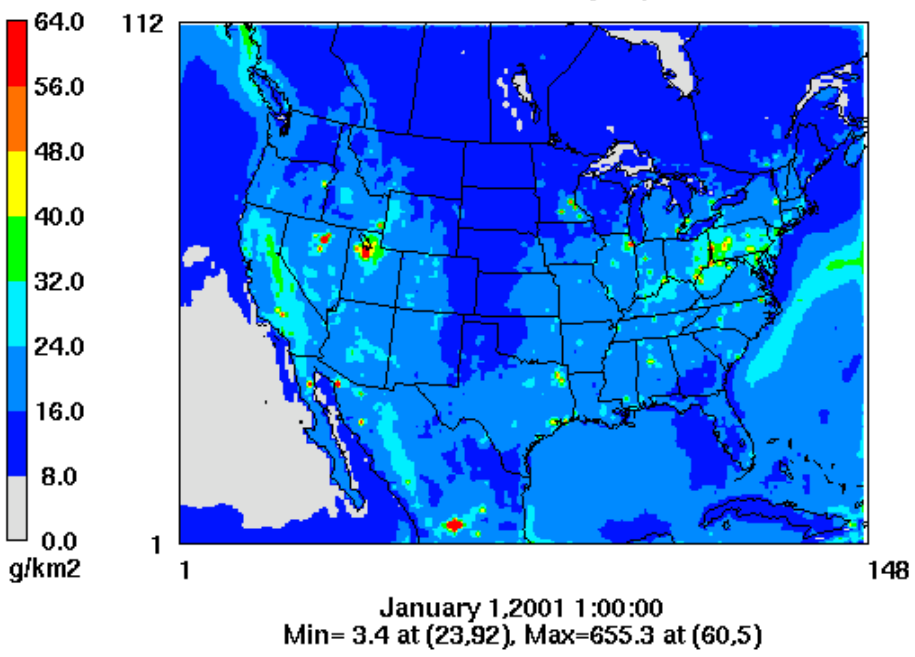
January 1,2001 1:00:00
Min= 4.0 at (23,92), Max=740.2 at (60,5)

Figure 5-9. CMAQ Simulated Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 36-km Modeling Domain: Elemental, Reactive Gaseous, and Particulate Phases.

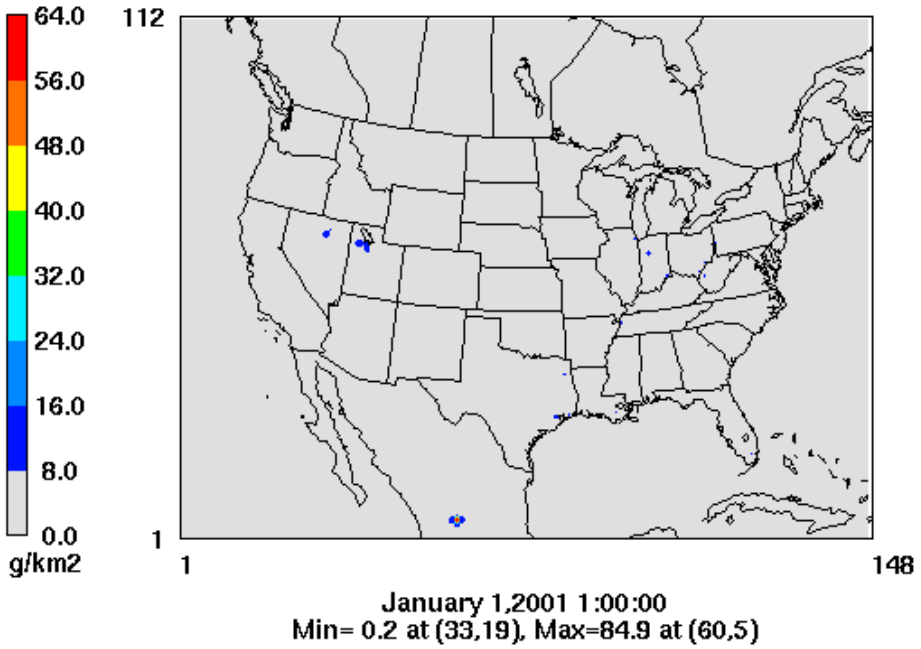
(a) Elemental Mercury Deposition (Wet Only)



(b) Reactive Gaseous Mercury Deposition



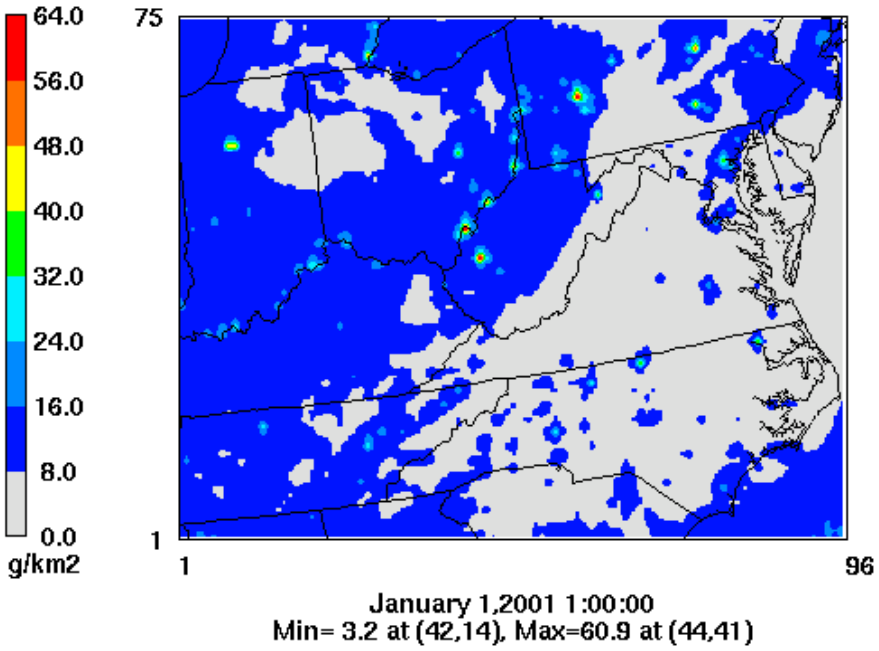
(c) Particulate Mercury Deposition



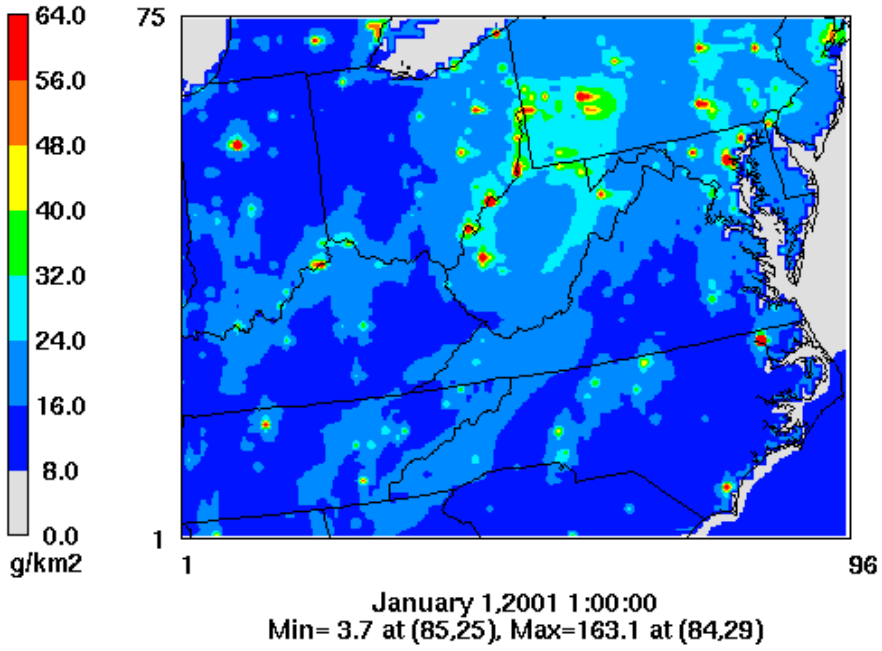
Figures 5-10 and 5-11 display the CMAQ-derived, base-year, annual mercury deposition results for the 12-km domain. Figure 5-10 displays wet, dry and annual total mercury deposition. Most of the wet deposition (Figure 5-10a) occurs to the west and south of Virginia. Figure 5-10b shows that dry deposition is greater than wet deposition over Virginia. The highest dry deposition amounts within the subdomain are over Pennsylvania, West Virginia, and southeastern Ohio. Total deposition (Figure 5-10c) reflects a similar spatial pattern. The locations of the relative maximum values of mercury deposition within Virginia can be correlated with several of the emissions sources located within the Commonwealth. Alternatively, Figure 5-11 displays total mercury deposition for the elemental (HG0), reactive gaseous (HG2), and particle-bound (HGP) phases. Most of the deposition is in the form of reactive gaseous mercury, with some (mostly local) contribution from particles. This local contribution is further examined using the AERMOD model in Section 6.

Figure 5-10. CMAQ Simulated Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 12-km Modeling Domain: Wet, Dry and Total Deposition.

(a) Wet Mercury Deposition



(b) Dry Mercury Deposition



(c) Total Mercury Deposition

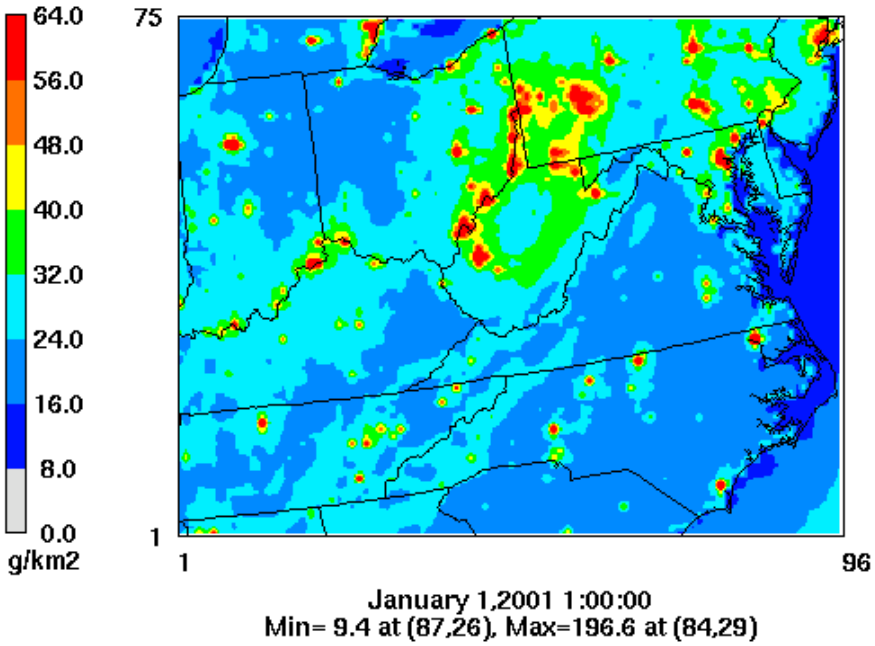
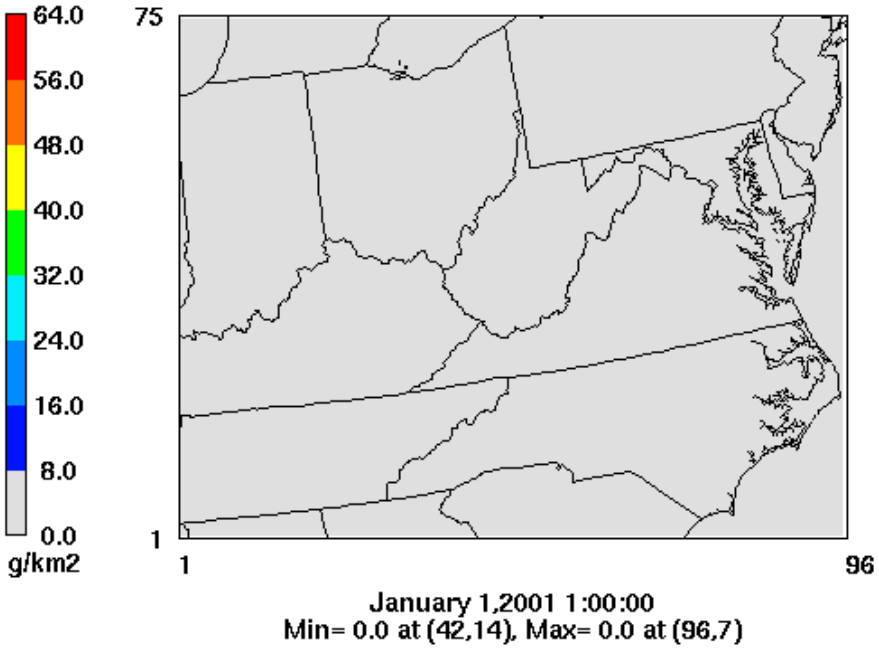
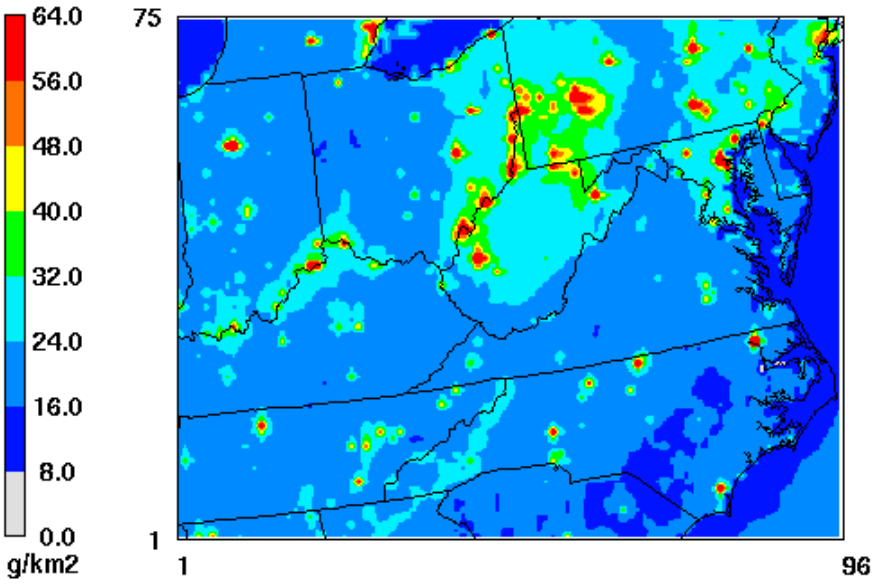


Figure 5-11. CMAQ Simulated Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 12-km Modeling Domain: Elemental, Reactive Gaseous, and Particulate Phases.

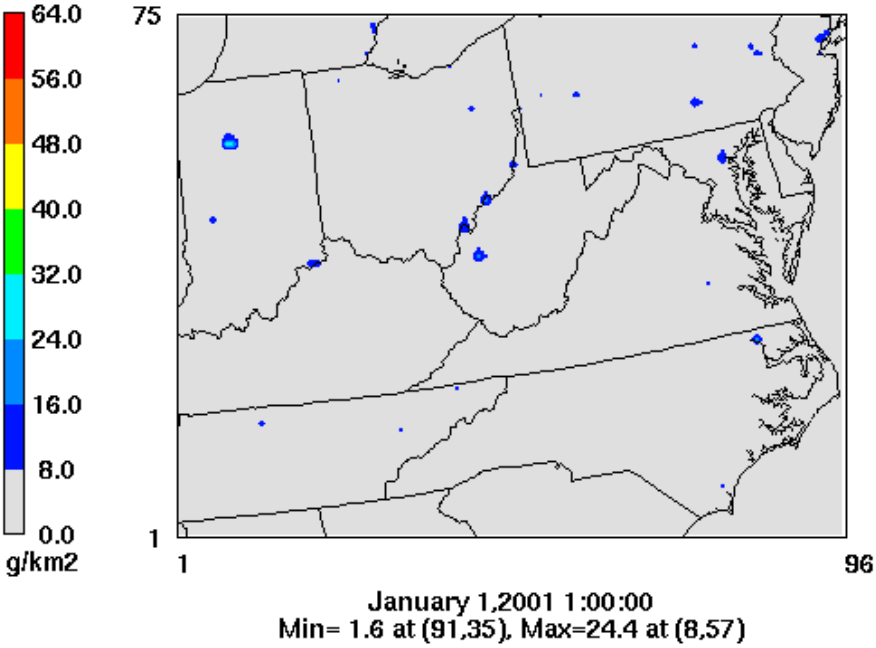
(a) Elemental Mercury Deposition (Wet Only)



(b) Reactive Gaseous Mercury Deposition



(c) Particulate Mercury Deposition



5.1.4. Baseline Contribution Analysis for Virginia

CMAQ/PPTM simulations were conducted using the baseline 2001/2002 emissions inventory to assess the contributions of selected source sectors to simulated mercury deposition.

The first scenario examined the contributions from mercury air emissions sources in 1) Virginia, 2) the remainder of the 12-km modeling domain, 3) all other U.S. states (outside of the 12-km domain), 4) Canada and Mexico, 5) global emissions sources, and 6) natural emissions. Tags were assigned to each of the six regions/categories listed above. An initial/boundary condition tag was used to represent the global impact on deposition. This scenario was run for both the 36- and 12-km domains and the specific tags were defined as follows:

- All anthropogenic emissions sources in Virginia
- All anthropogenic emissions sources in the remainder of the 12-km grid
- All anthropogenic emissions sources in the U.S., excluding those in the 12-km grid
- All anthropogenic emissions sources in Canada & Mexico
- IC/BCs (initial and boundary conditions)
- Natural emissions.

For the 12-km simulation, the tags incorporated information from the 36-km PPTM simulation. This was done to track the contributions from sources outside of the 12-km domain as well as the possible recirculation of emissions from sources within the 12-km domain. Information from the tags for the 36-km simulation was incorporated into the tags for the 12-km simulation as additional species in the IC/BC tags for the subdomain.

The second scenario quantified the contributions from Electric Generating Unit (EGU) and non-EGU facilities in Virginia and the surrounding states. The tags included 1) all of Virginia's EGU sources, 2) all of the non-EGU sources in the state, 3) all EGU sources in the surrounding states (remainder of the 12-km grid), and 4) all non-EGU sources in the surrounding states. The results allow us to quantify and compare the contributions from the EGU and non-EGU source sectors to mercury deposition for any location (grid cell or group of grid cells) within the state or the modeling domain. The specific tags for this scenario were defined as follows:

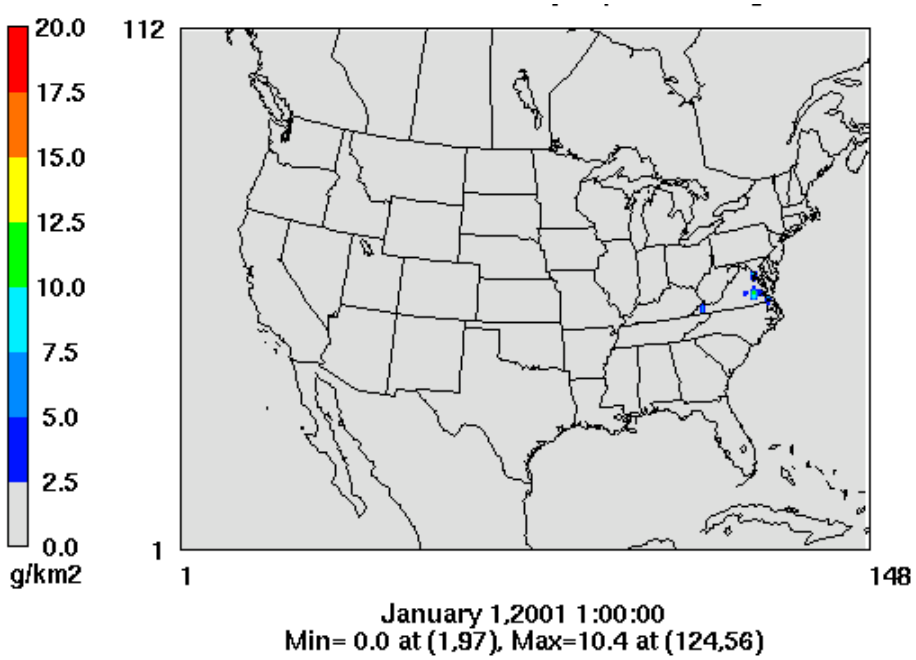
- All EGU sources in Virginia
- All non-EGU sources in Virginia
- All EGU sources in the remainder of the 12-km grid
- All non-EGU sources in the remainder of the 12-km grid.

Selected plots of the PPTM results are shown in Figures 5-12 through 5-14. For the 36-km domain, the contribution to annual total (wet plus dry) mercury deposition from each of the six tags is displayed in Figure 5-12. Note that the scales may differ among the plots.

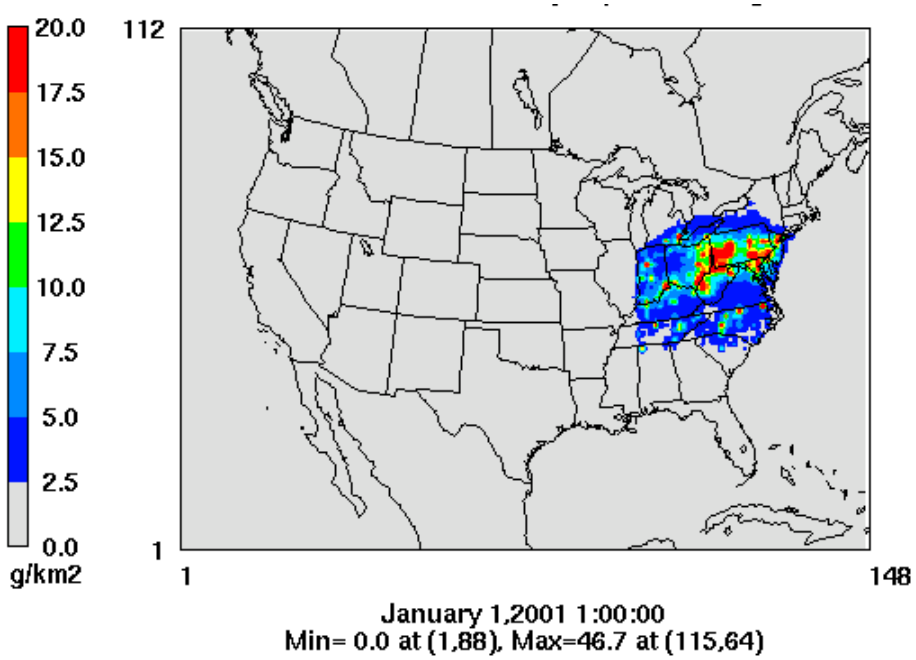
As noted earlier, the spatial plots of mercury deposition use a variety of different scales in order to display the spatial patterns of depositions. Note that the color scheme is not tied to specific ranges of deposition, but is used instead to highlight the patterns of deposition corresponding to each individual plot. The spatial plots are intended to display the spatial patterns. For detailed comparisons of the deposition amounts the reader should refer to the pie charts, bar charts and tables that are also presented in this section.

Figure 5-12. CMAQ/PPTM Simulated Contribution to Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 36-km Modeling Domain.

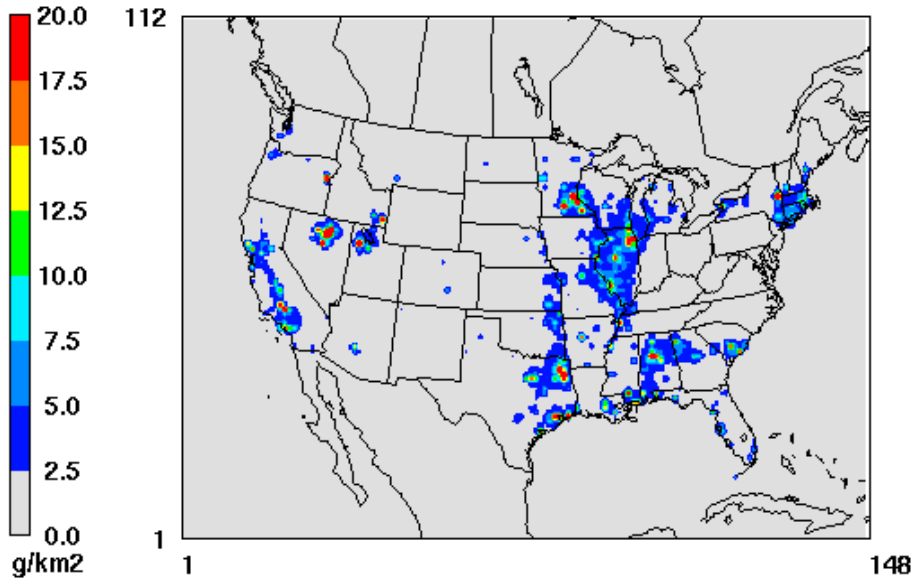
(a) Contribution from Sources in Virginia



(b) Contribution from Sources in the Remainder of the 12-km Domain

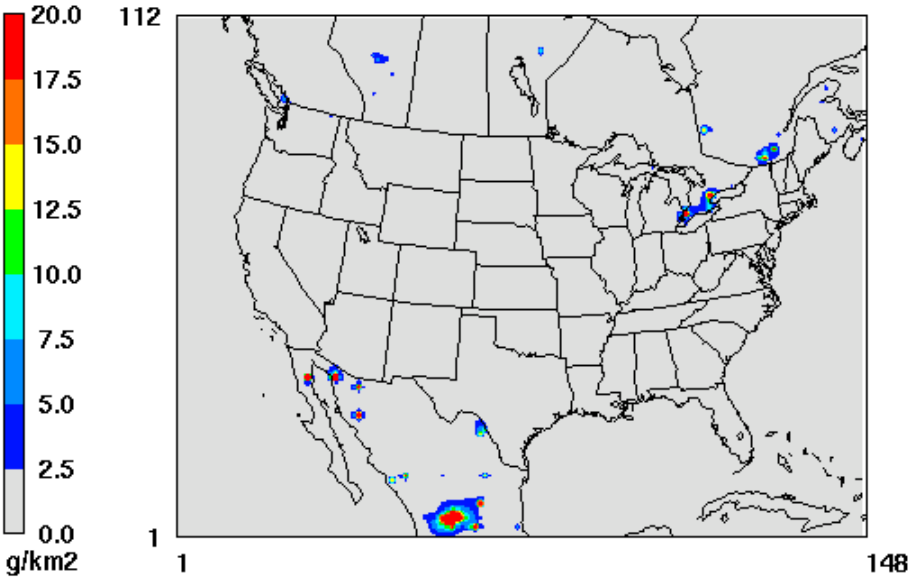


(c) Contribution from Sources in the Remainder of the U.S.



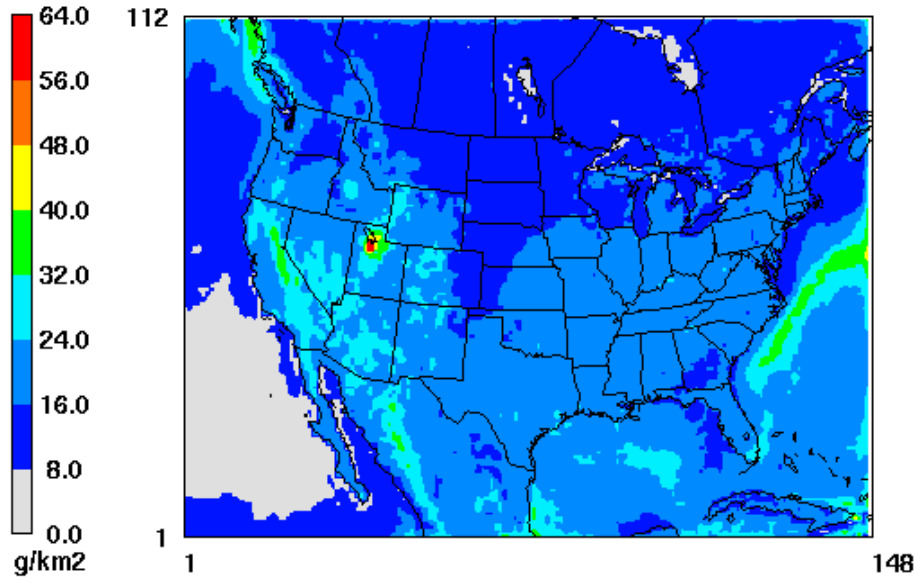
January 1,2001 1:00:00
Min= 0.0 at (1,83), Max=101.7 at (32,66)

(d) Contribution from Sources in Canada and Mexico

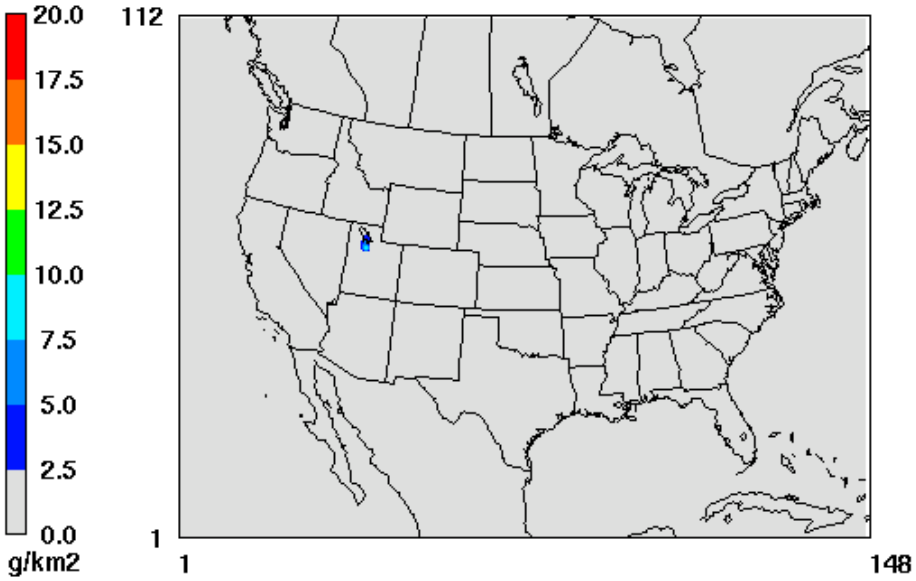


January 1,2001 1:00:00
Min= 0.0 at (1,91), Max=715.5 at (60,5)

(e) Contribution from 36-km Domain IC/BCs



(f) Contribution from Natural Emissions Sources

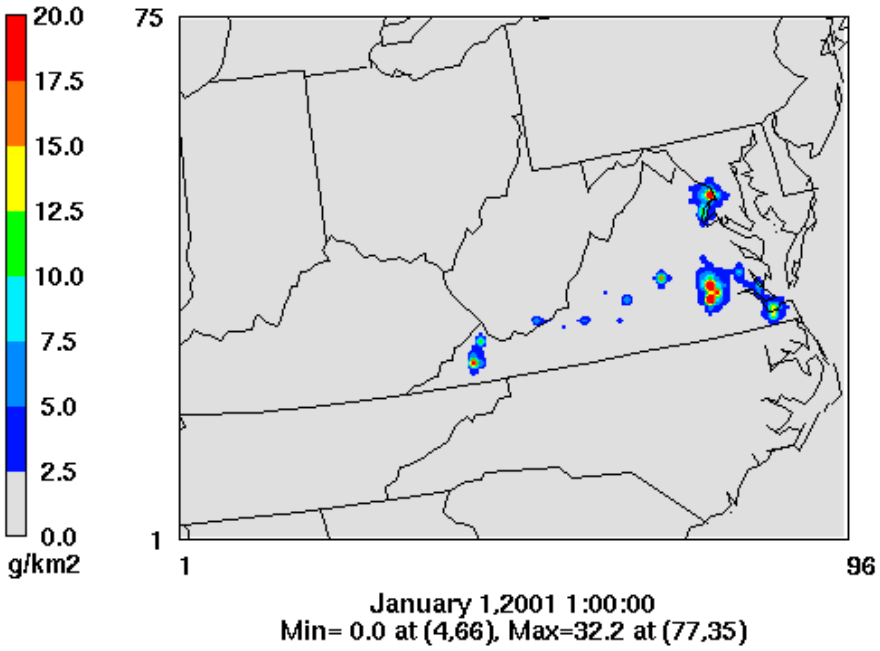


Figures 5-12a through d indicate that anthropogenic mercury emissions sources in the U.S., Canada and Mexico have primarily local to regional impacts during this annual simulation period. Note that these emissions may also contribute to the global background. Figure 5-12e suggests that global background concentrations (represented here by the boundary conditions) contribute significantly to mercury deposition throughout the domain, including in Virginia. Figure 5-12f suggests that contributions from natural emissions are small.

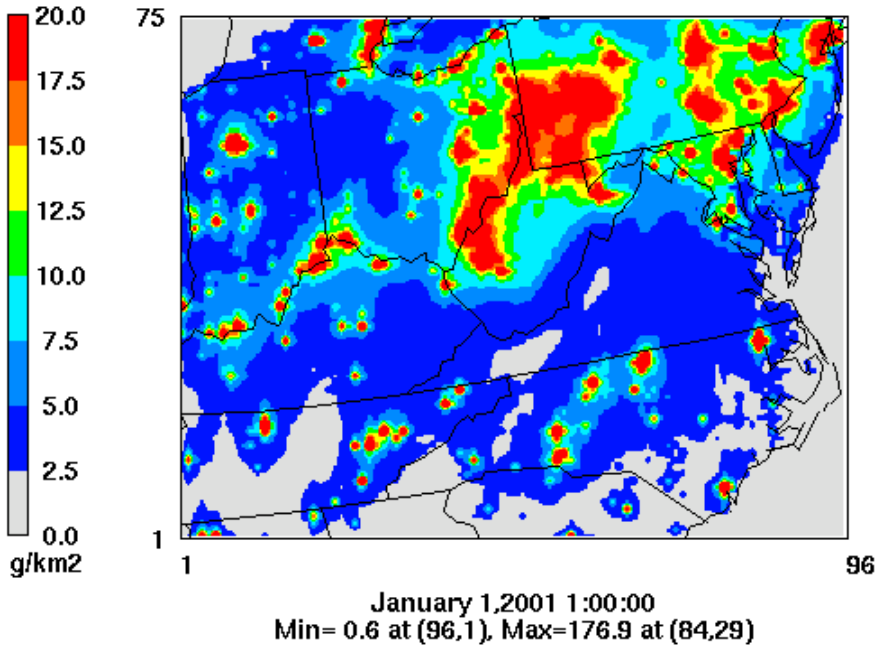
Figure 5-13 focuses on the 12-km domain and displays the contribution to annual total (wet and dry) mercury deposition from these same six tags, as simulated using the higher resolution grid. Note that the scale varies among the plots for each tag.

Figure 5-13. CMAQ/PPTM Simulated Contribution to Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 12-km Modeling Domain.

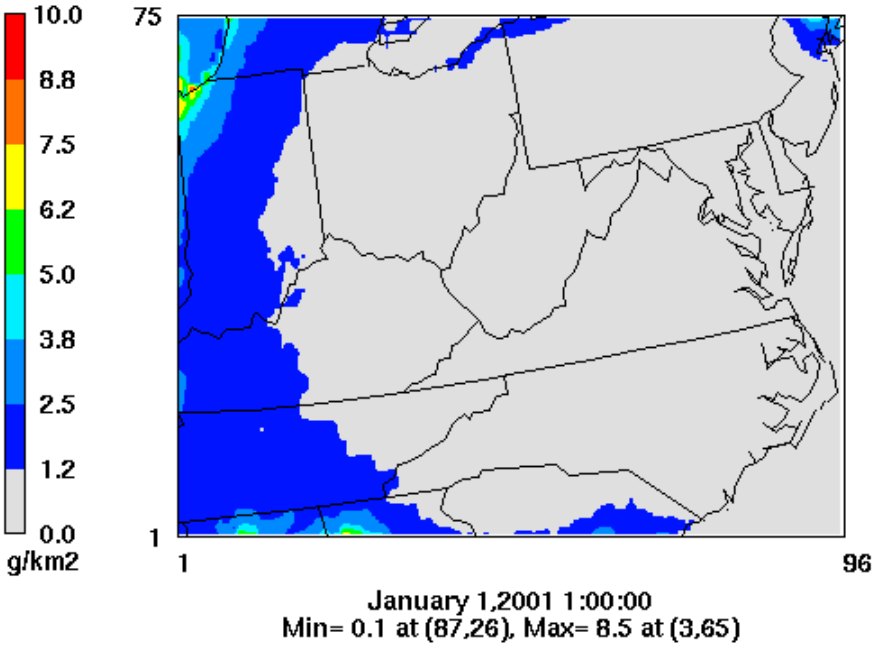
(a) Contribution from Sources in Virginia



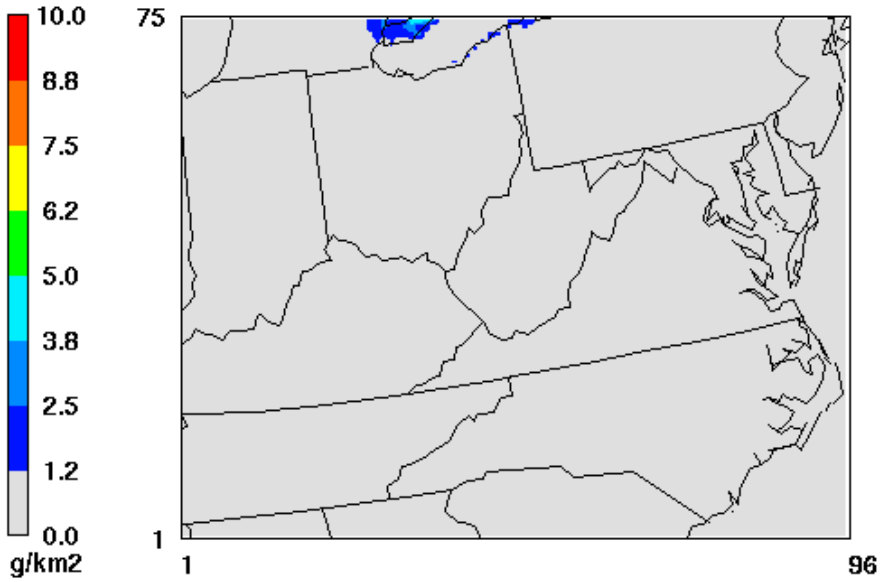
(b) Contribution from Sources in the Remainder of the 12-km Domain



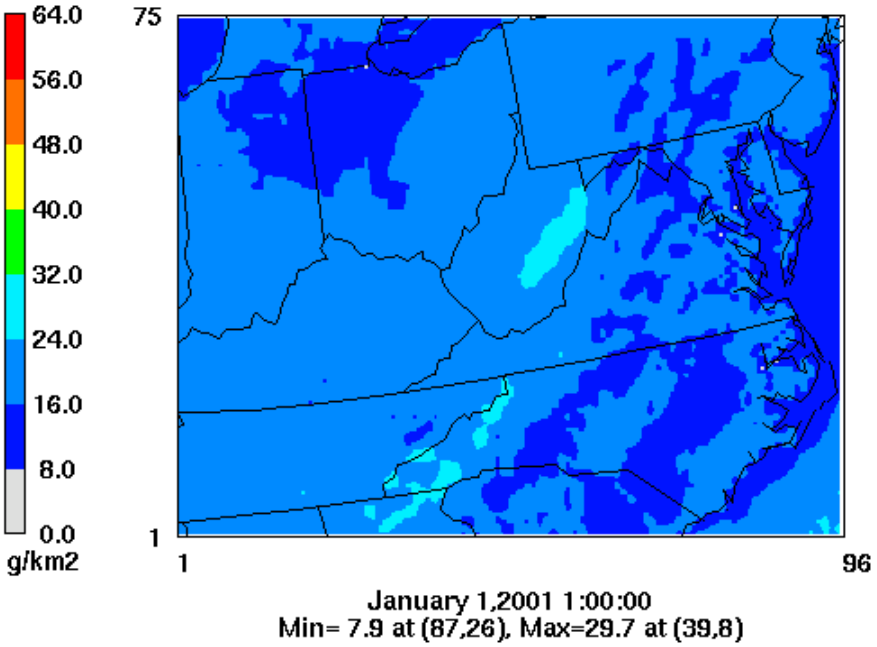
(c) Contribution from Sources in the Remainder of the U.S.



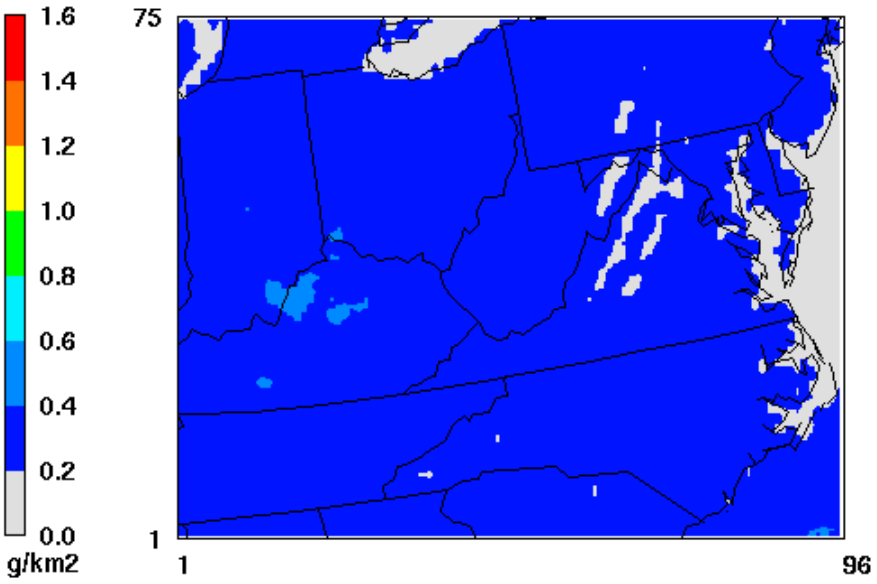
(d) Contribution from Sources in Canada and Mexico



(e) Contribution from 36-km Domain IC/BCs



(f) Contribution from Natural Emissions Sources

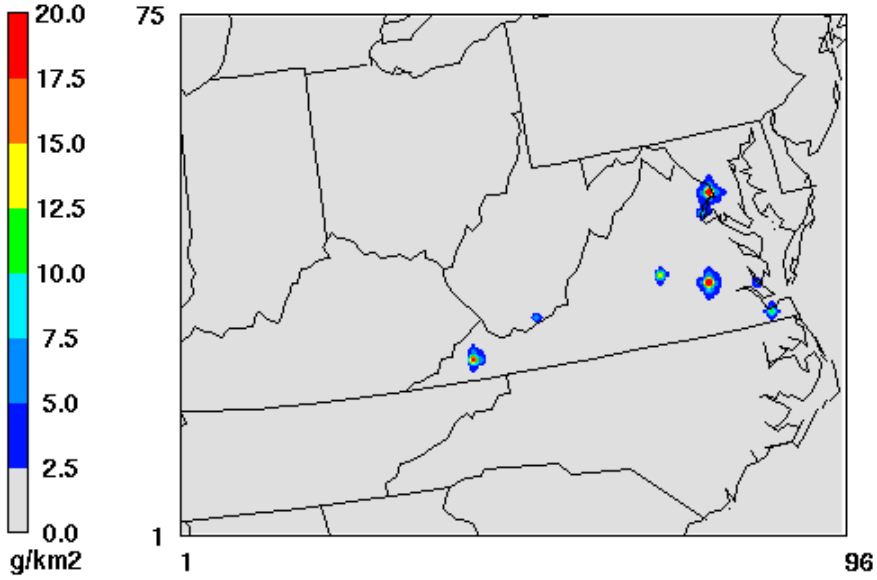


The PPTM results indicate that global background (Figure 5-13e) and emissions from sources in the surrounding states (Figure 5-13b) contribute to mercury deposition in Virginia. The transported mercury is distributed relatively evenly throughout the Commonwealth. Emissions from sources in Virginia (Figure 5-13a) also contribute to mercury deposition and the greatest impacts from the in-state sources are simulated near the source locations.

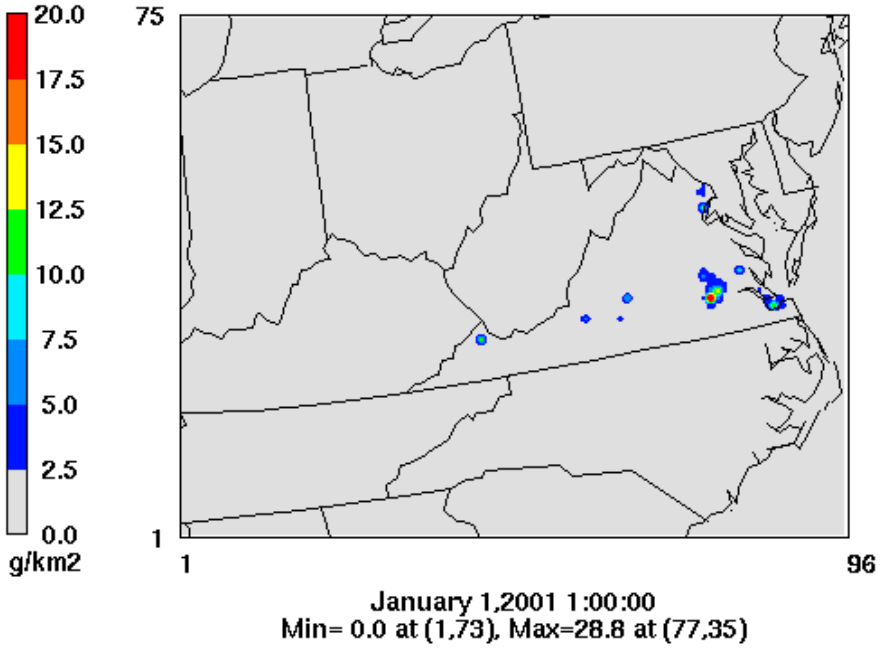
Figure 5-14 further parses the contributions from sources in Virginia and the remainder of the 12-km domain into EGU and non-EGU contributions.

Figure 5-14. CMAQ/PPTM Simulated Contribution to Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 12-km Modeling Domain.

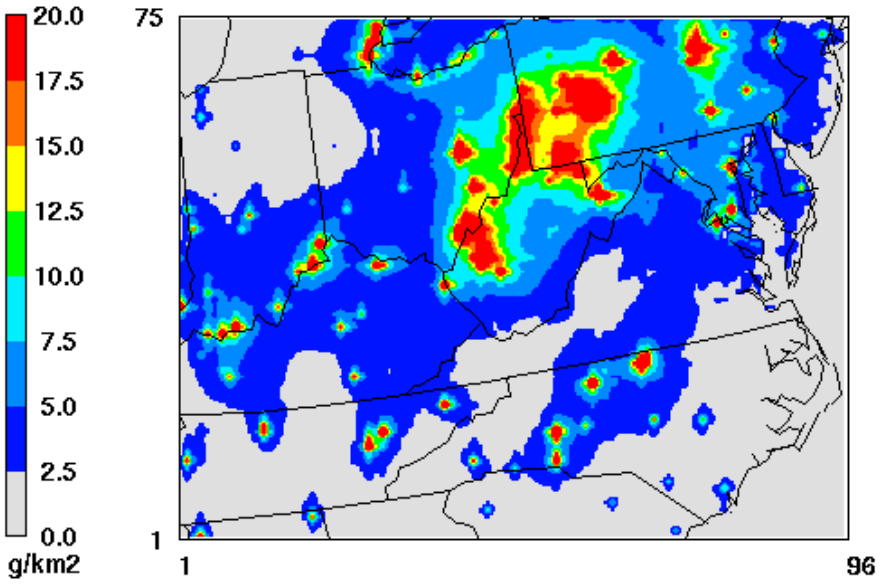
(a) Contribution from EGU Sources in Virginia



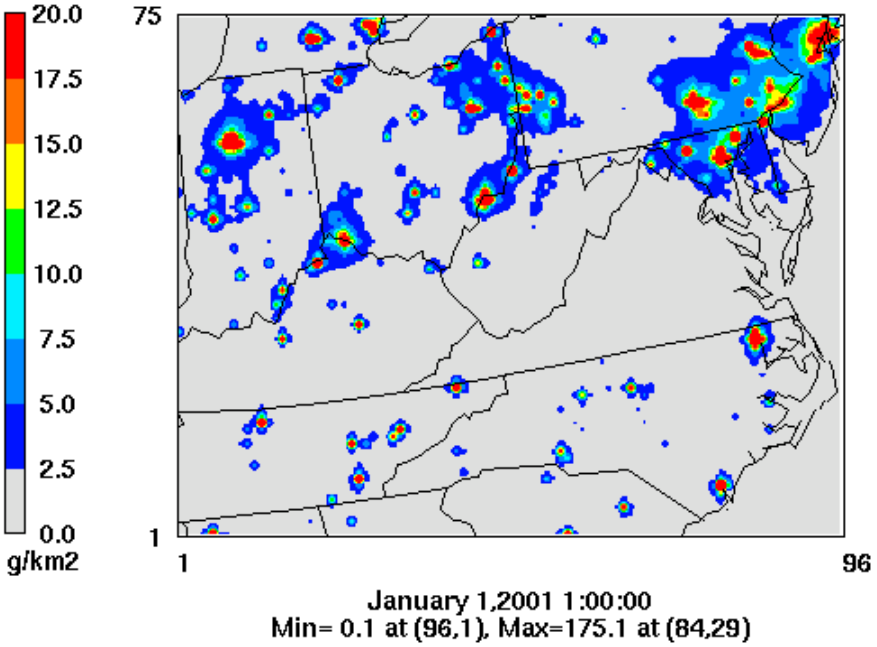
(b) Contribution from Non-EGU Sources in Virginia



(c) Contribution from EGU Sources in the Remainder of the 12-km Domain



(d) Contribution from Non-EGU Sources in the Remainder of the 12-km Domain



Within Virginia, neither source category is dominant. For a given area, the dominant in-state source of simulated mercury deposition is determined based on location relative to EGU and non-EGU sources. There are a greater number of emissions sources within the surrounding states. The deposition patterns for these sources indicate that, overall, EGU sources tend to impact a larger area compared to most non-EGU sources. This is likely due, in part, to greater stack heights and exit velocities for the EGU sources. The EGU sources in the surrounding states contribute more to mercury deposition in Virginia than the non-EGU sources in the surrounding states.

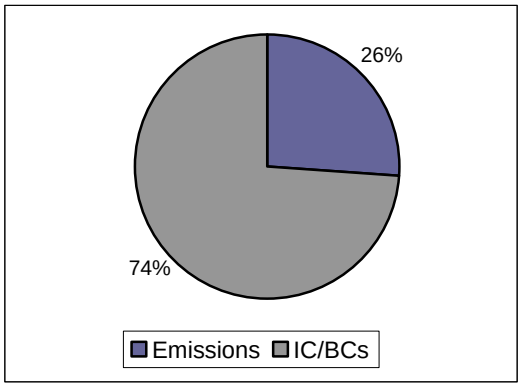
In addition to the spatial contribution patterns, PPTM also provides information on the contributions of the tagged source regions and source categories to simulated mercury deposition in any sub-area of the domain (i.e., any area comprised of one or more grid cells). In Figure 5-15 mercury deposition at the locations of the MDN monitoring sites in Virginia is broken down in various ways. In each case, the area represented is one 12 x 12 km grid cell.

In Figure 5-15, the total deposition for the grid cell is given at the top of the page. The pie chart in the upper left-hand corner of the display summarizes the percent contribution to total deposition from emissions versus IC/BCs. The bar chart in the upper right-hand corner attributes total (overall) and emissions-based deposition to wet and dry deposition. Note that the total or overall deposition is the sum of the deposition from both emissions and IC/BCs. In the next two pie charts, the contributions from emissions sources are broken out in detail. The middle pie chart includes all tags and the lower pie chart includes only the non-background/anthropogenic source tags. Without the IC/BC contribution, the lower pie chart allows a more detailed comparison of the local and regional source contributions.

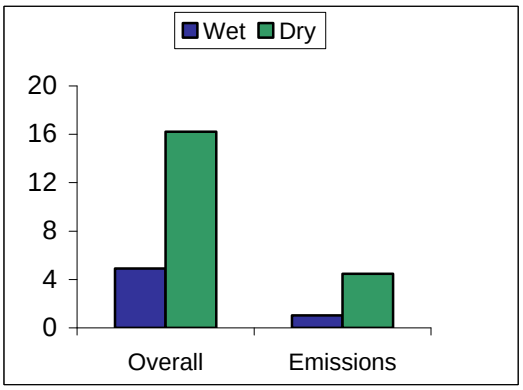
Figure 5-15a. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Culpeper MDN Monitoring Site (VA08).

Simulated Annual Hg Deposition for 2001 for Culpeper, VA (VA08): 21.11 g/km²

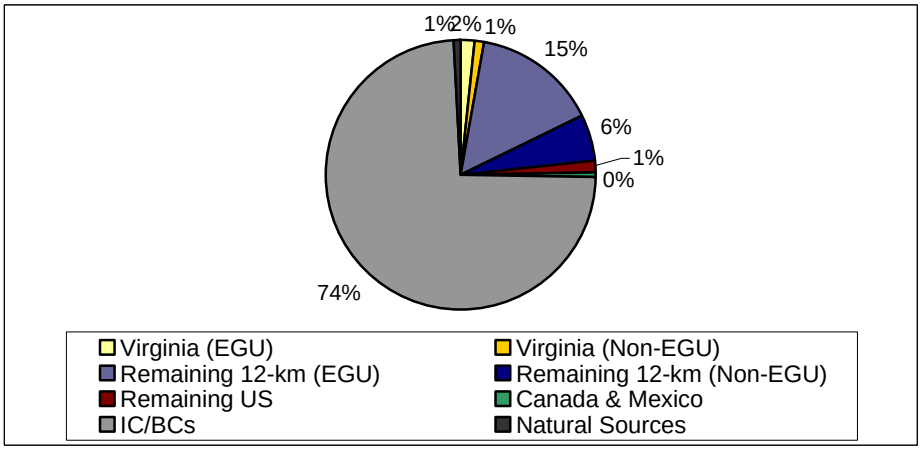
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

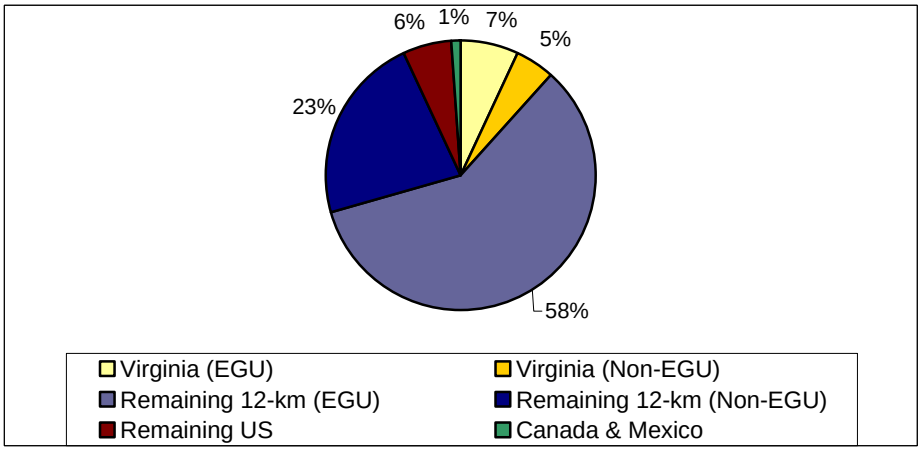
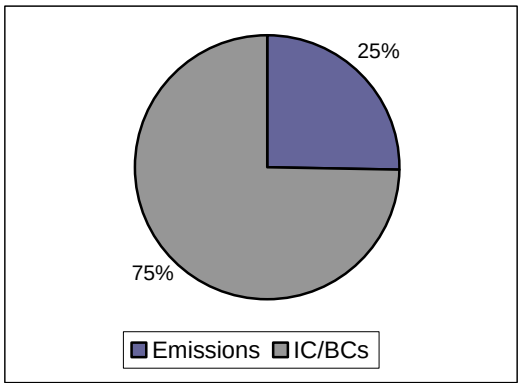


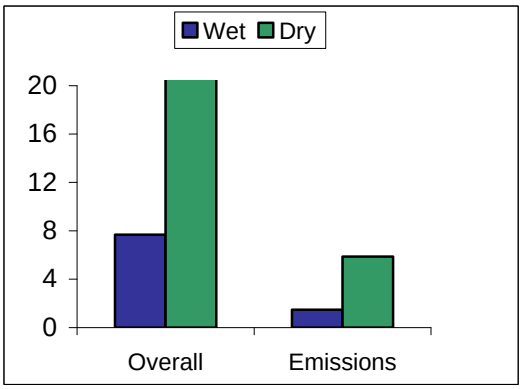
Figure 5-15b. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Shenandoah National Park MDN Monitoring Site (VA28).

Simulated Annual Hg Deposition for 2001 for Shenandoah, VA (VA28): 29.18 g/km²

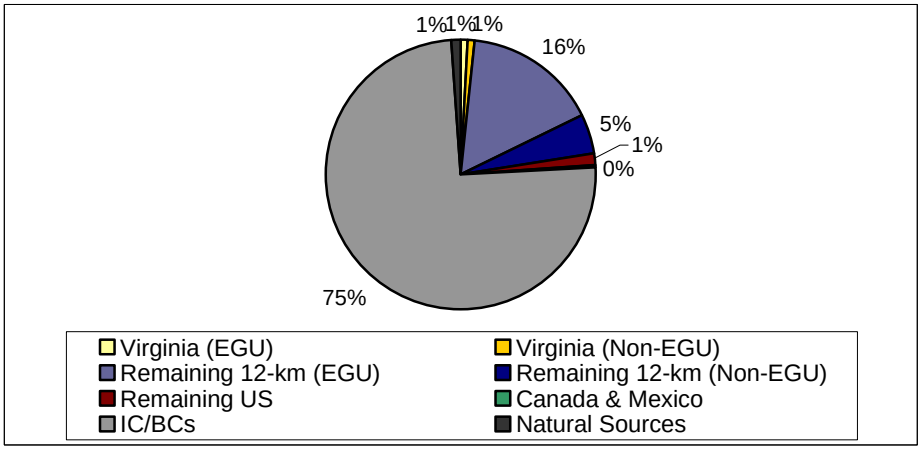
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

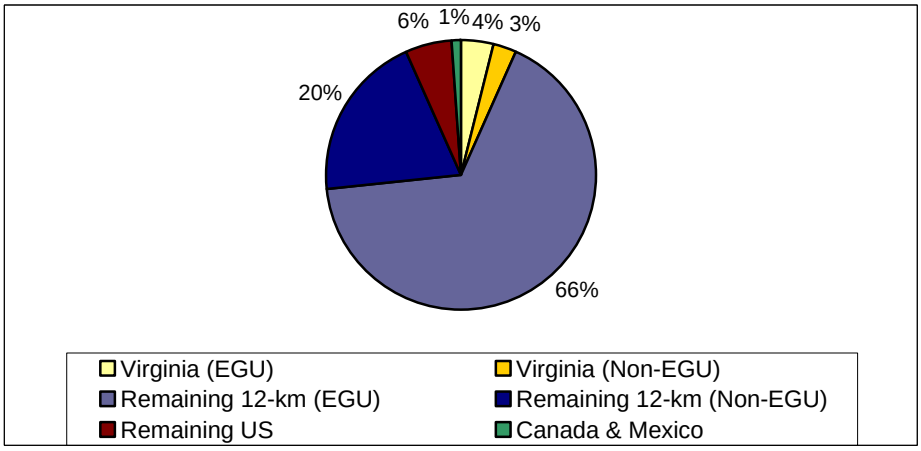
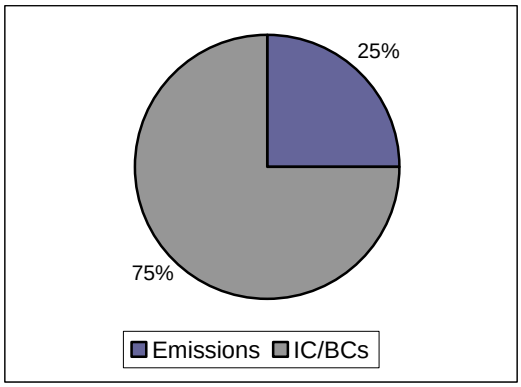


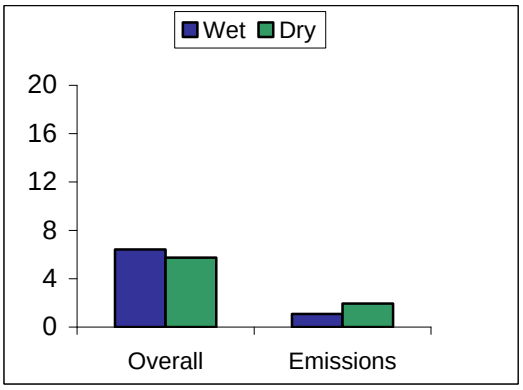
Figure 5-15c. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Harcum MDN Monitoring Site (VA98).

Simulated Annual Hg Deposition for 2001 for Harcum, VA (VA98): 12.16 g/km²

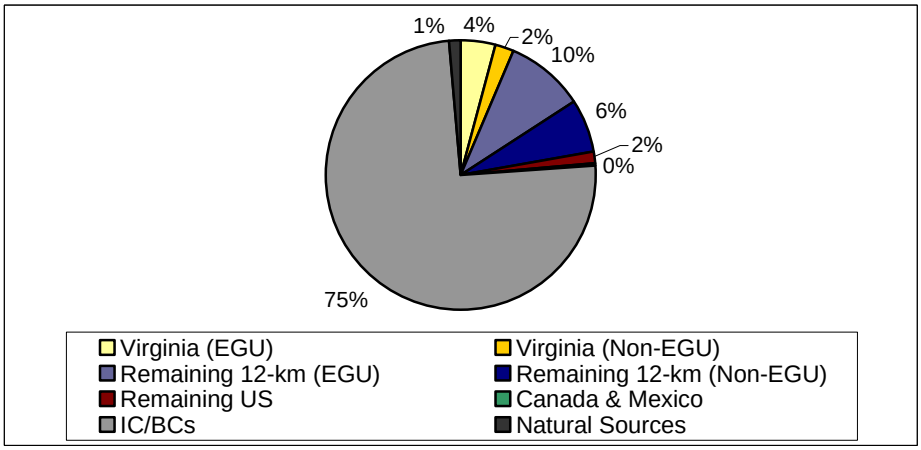
Emissions vs. IC/BC Contributions



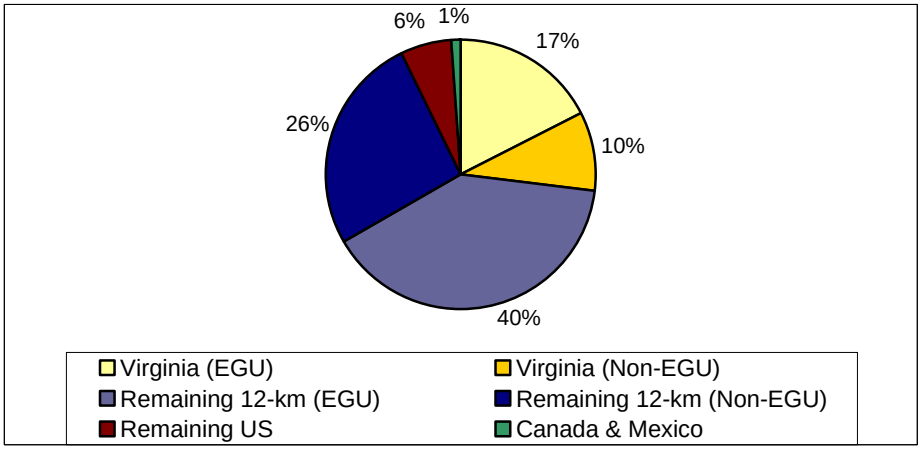
Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



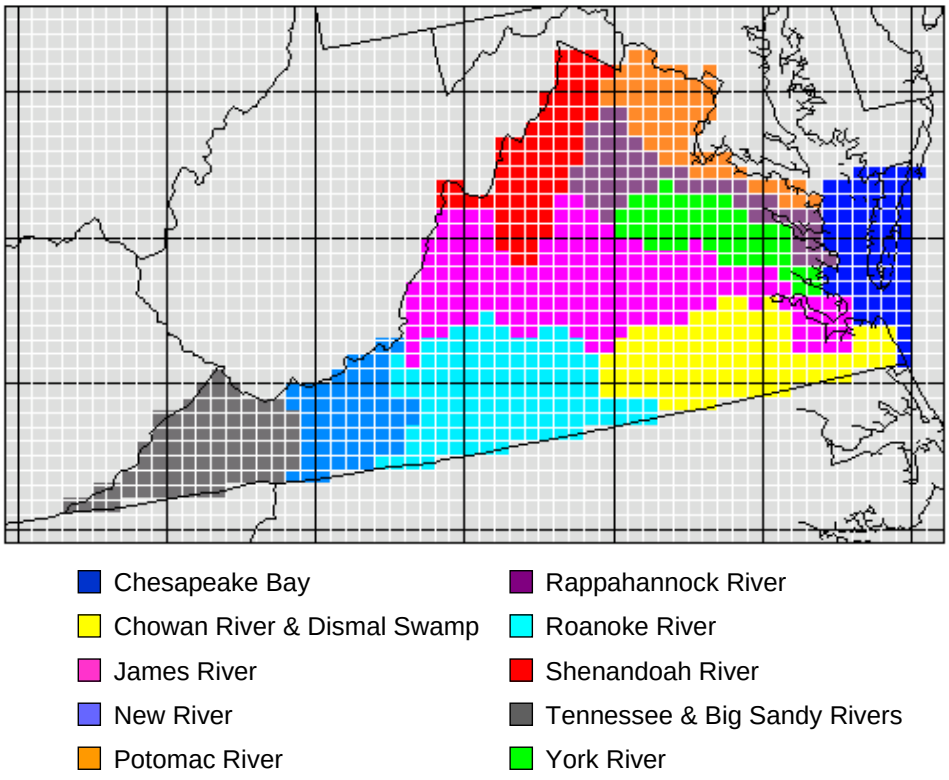
Contribution by Tag w/o Background & Natural Sources



For all three MDN sites, the IC/BCs (global background) contribute about 75 percent of the simulated mercury deposition. For the Culpeper and Shenandoah sites, dry deposition is greater than wet deposition by a factor of two or more, for both overall deposition and emissions-based deposition. For the Harcum site, wet deposition is greater than dry when overall deposition is considered. This is likely because a portion of the grid cell is over water which limits dry deposition. For Culpeper, the non-background/anthropogenic portion of the contribution is broken down as follows: Virginia EGU sources (7 percent), Virginia non-EGU sources (5 percent), other 12-km grid EGU sources (58 percent), other 12-km non-EGU sources (23 percent), remaining U.S. sources (6 percent), and Canada and Mexico (1 percent). For Shenandoah, the non-background/anthropogenic contribution is broken down as follows: Virginia EGU sources (4 percent), Virginia non-EGU sources (3 percent), other 12-km grid EGU sources (66 percent), other 12-km non-EGU sources (20 percent), remaining U.S. sources (6 percent), and Canada and Mexico (1 percent). For Harcum, the contribution from in-state sources is higher and is broken down as: Virginia EGU sources (17 percent), Virginia non-EGU sources (10 percent), other 12-km grid EGU sources (40 percent), other 12-km non-EGU sources (26 percent), remaining U.S. sources (6 percent), and Canada and Mexico (1 percent).

The next series of plots displays mercury deposition in this same manner for each of the major river basins in Virginia and the entire state. Figure 5-16 shows the locations of each of the major river basins (the reader is also referred to Figure 1-1 for more detail).

Figure 5-16. Map of the Major River Basins in Virginia and Corresponding CMAQ 12-km Grid Cells.

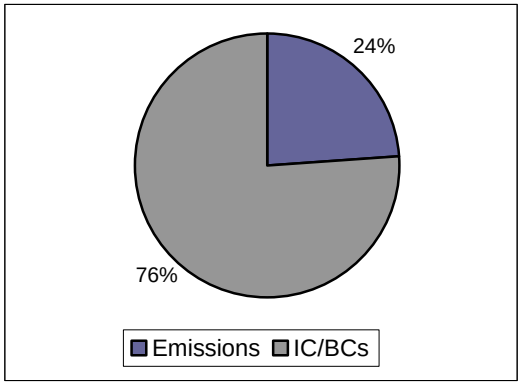


In Figure 5-17, mercury deposition and the sources contributing to deposition for each river basin and the entire state are presented. The results for the river basis are ordered alphabetically. In each case, the area represented consists of multiple grid cells. Deposition is given in terms of the deposition per square kilometer. This facilitates a comparison of the deposition results even though each area is a different size.

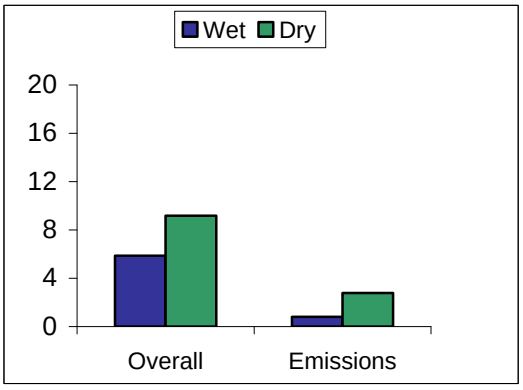
Figure 5-17a. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Chesapeake Bay, Atlantic Ocean, and Small Coastal Waters.

Simulated Annual Hg Deposition for 2001 for Chesapeake Bay: 15.04 g/km²

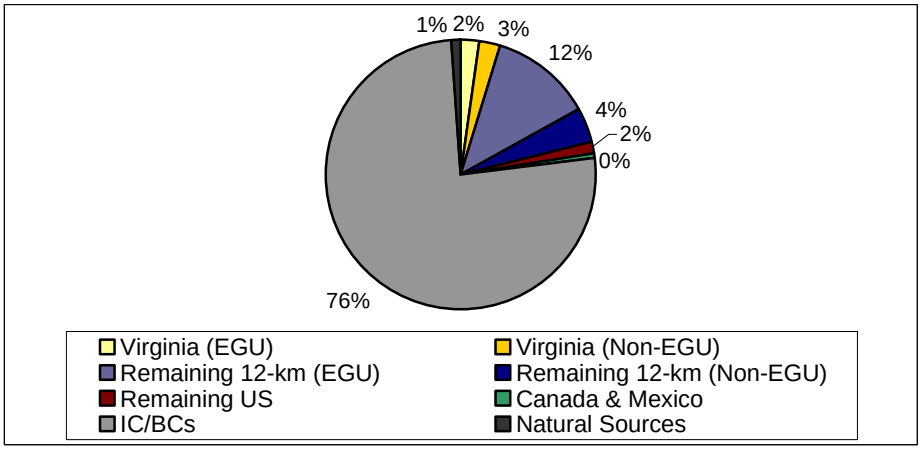
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

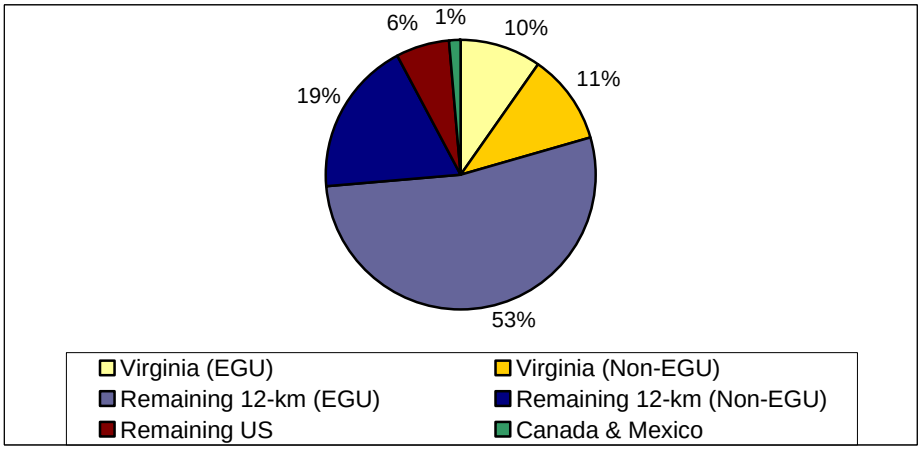
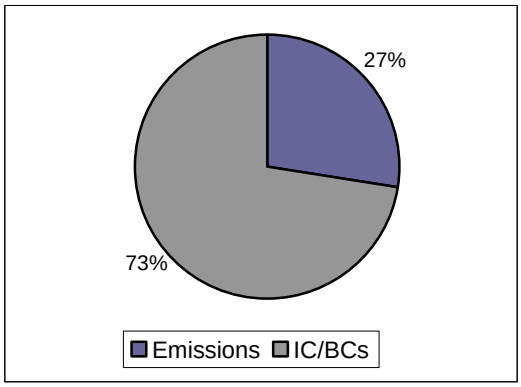


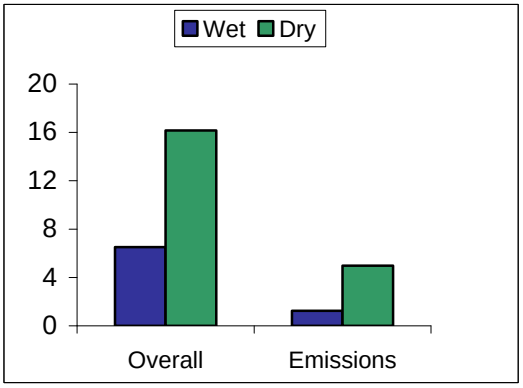
Figure 5-17b. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Chowan River Basin and Great Dismal Swamp.

Simulated Annual Hg Deposition for 2001 for the Chowan River Basin & Dismal Swamp: 22.68 g/km²

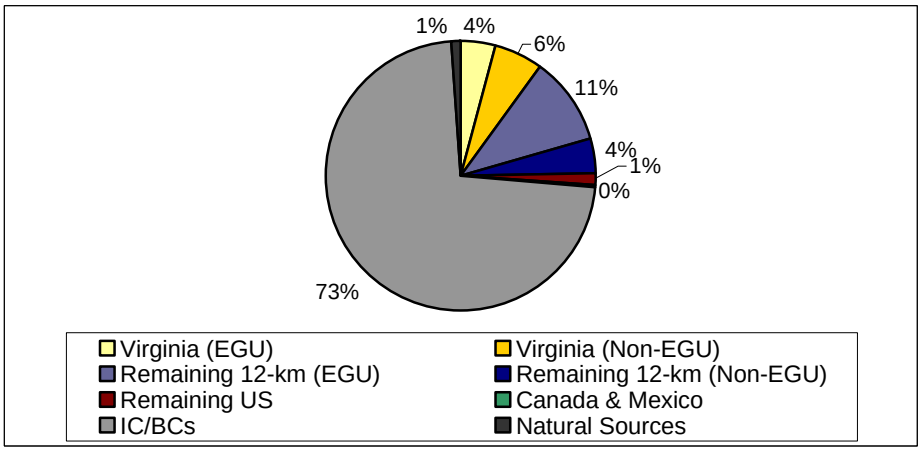
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

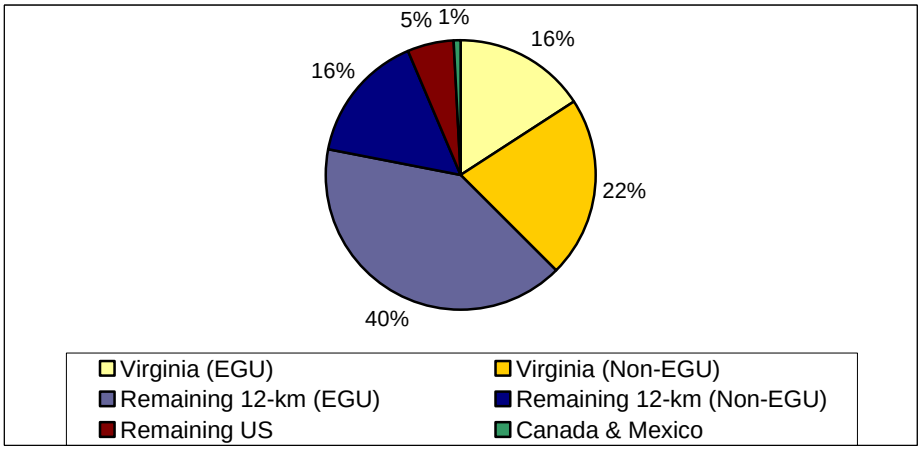
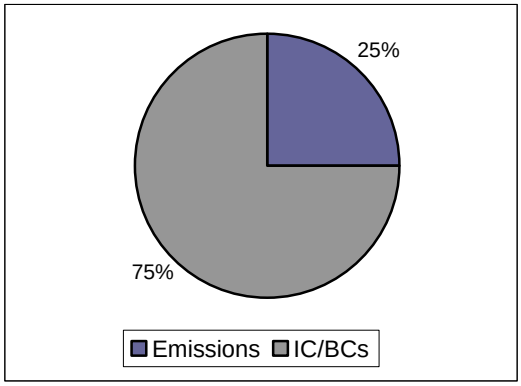


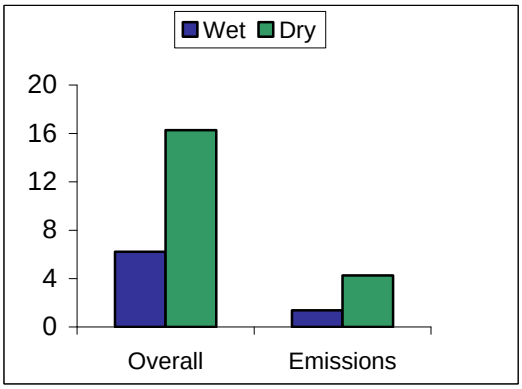
Figure 5-17c. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the James River Basin.

Simulated Annual Hg Deposition for 2001 for the James River Basin: 22.5 g/km²

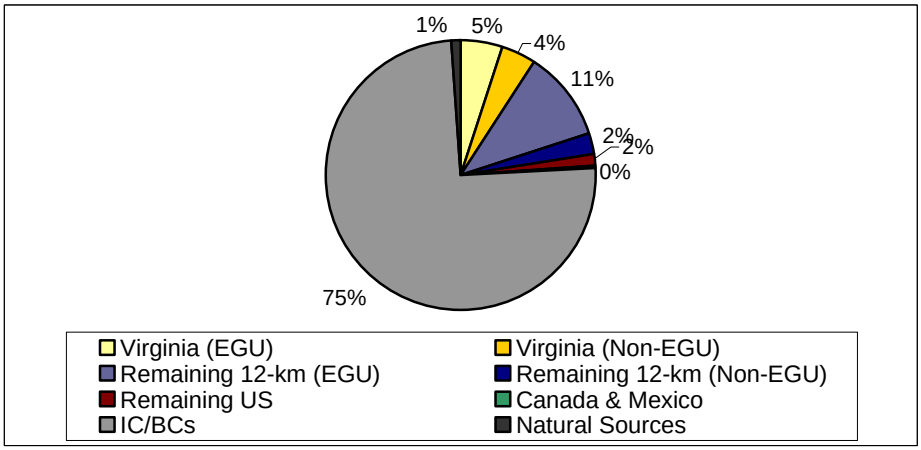
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

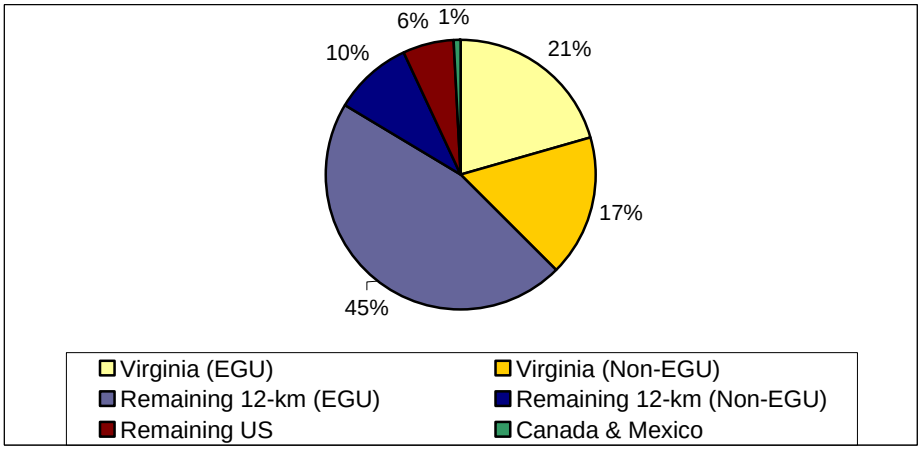
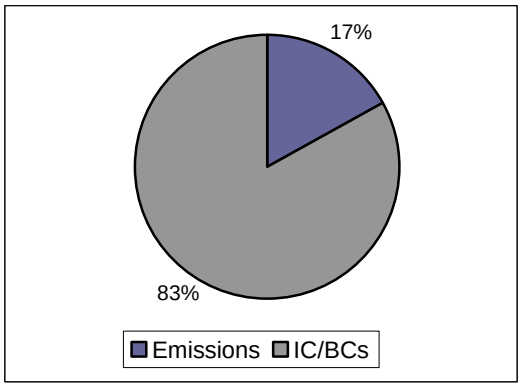


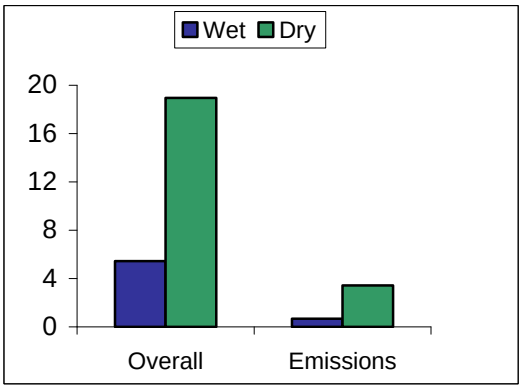
Figure 5-17d. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the New River Basin.

Simulated Annual Hg Deposition for 2001 for the New River Basin: 24.41 g/km²

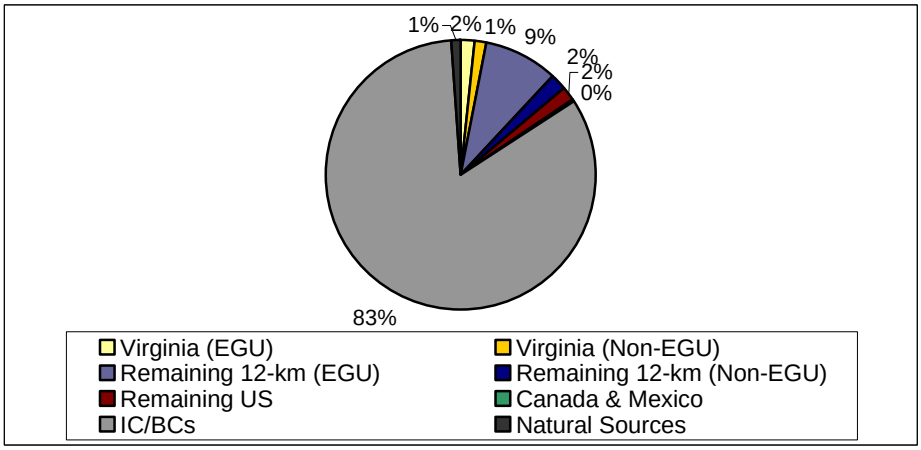
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

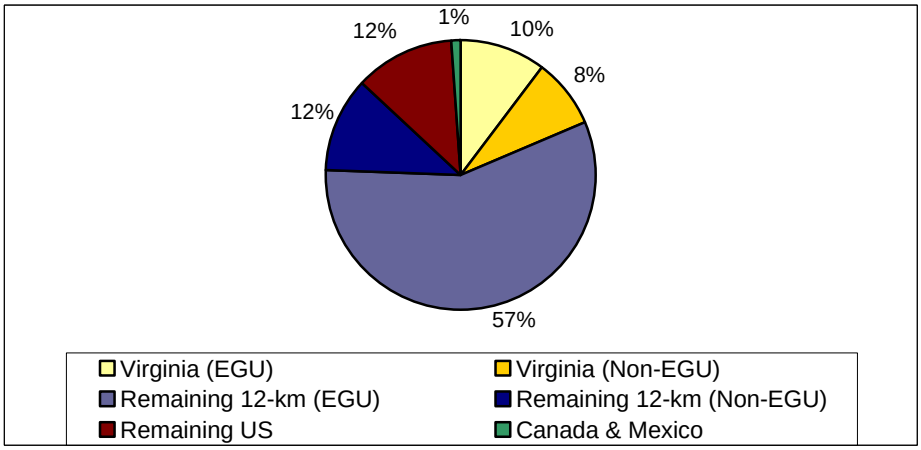
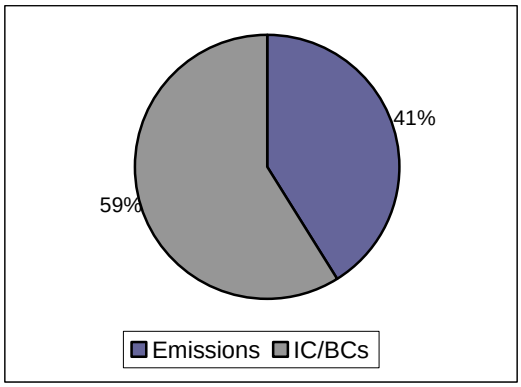


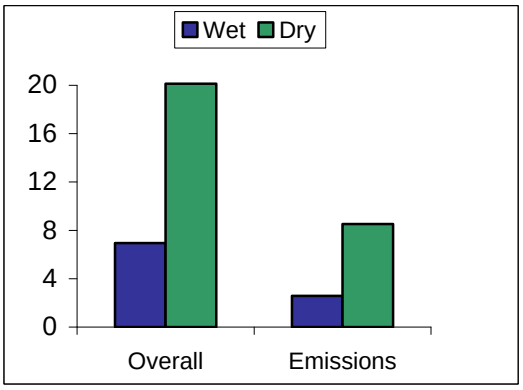
Figure 5-17e. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Potomac River Basin.

Simulated Annual Hg Deposition for 2001 for the Potomac River Basin: 27.07 g/km²

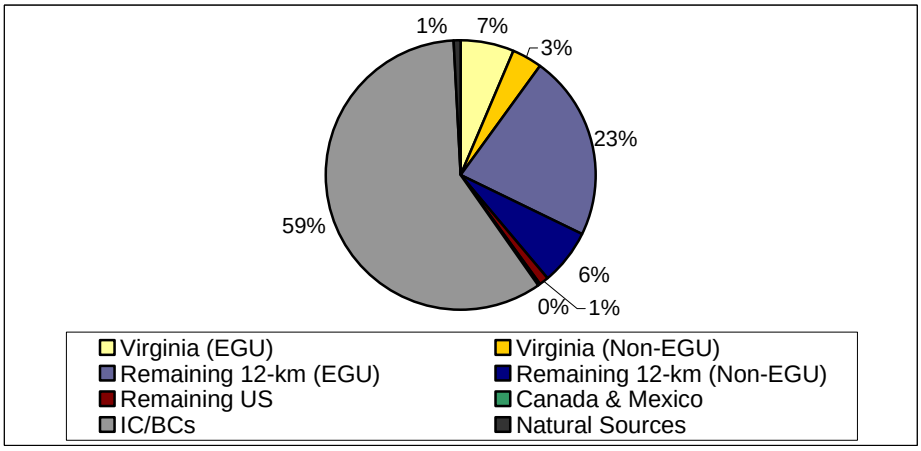
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

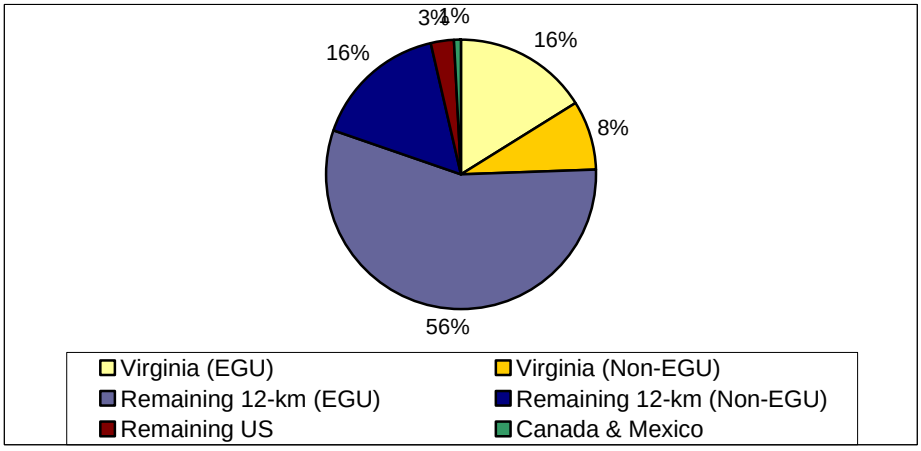
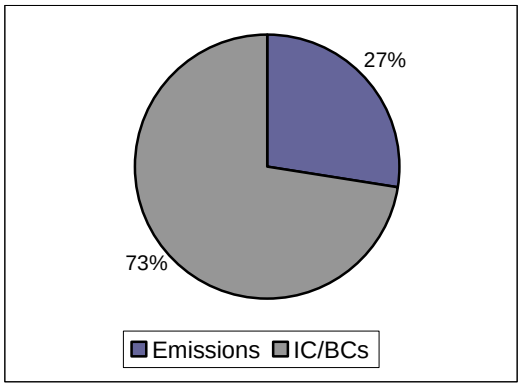


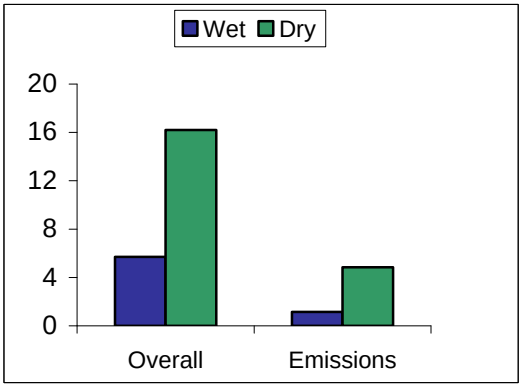
Figure 5-17f. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Rappahannock River Basin.

Simulated Annual Hg Deposition for 2001 for the Rappahannock River Basin: 21.9 g/km²

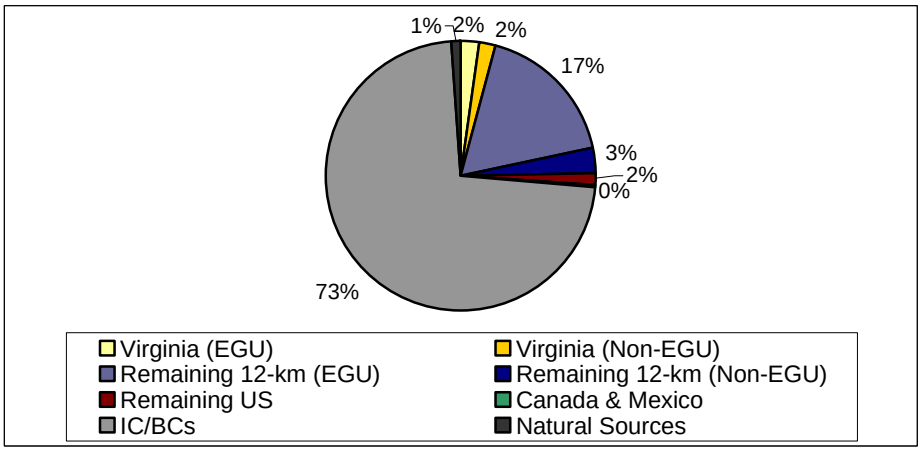
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

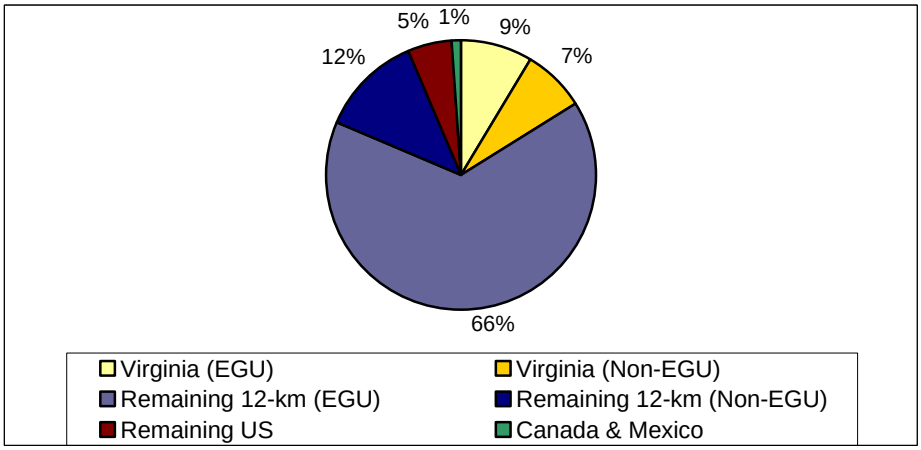
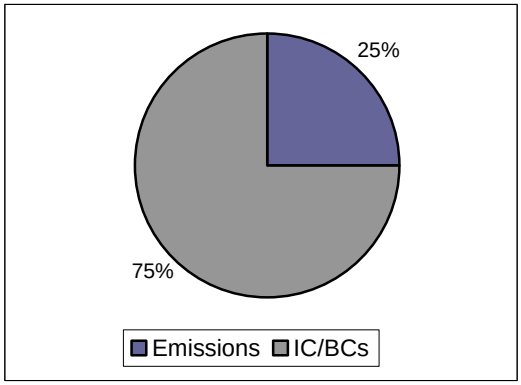


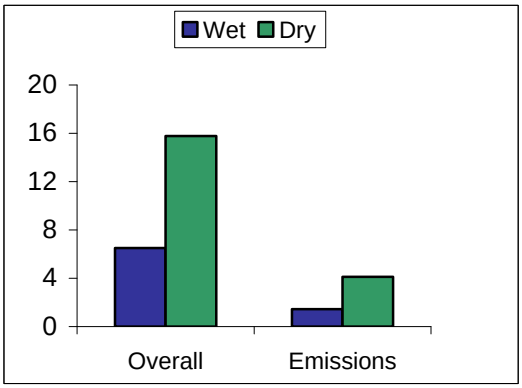
Figure 5-17g. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Roanoke River Basin.

Simulated Annual Hg Deposition for 2001 for the Roanoke River Basin: 22.26 g/km²

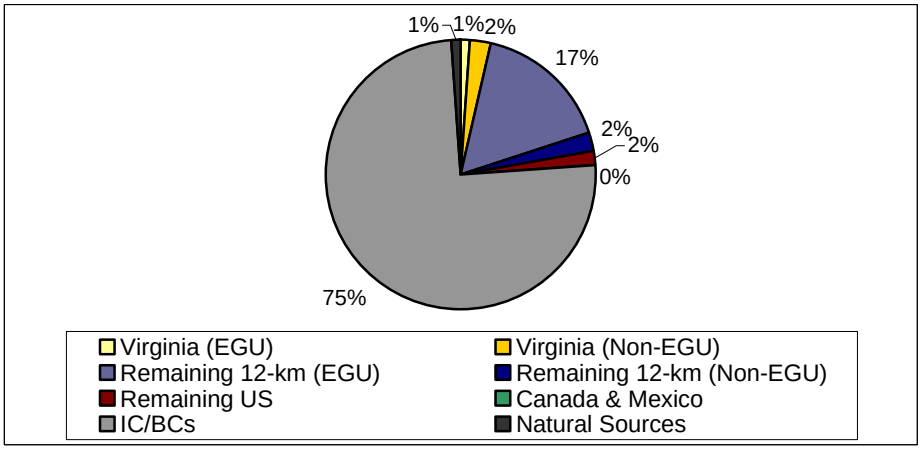
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

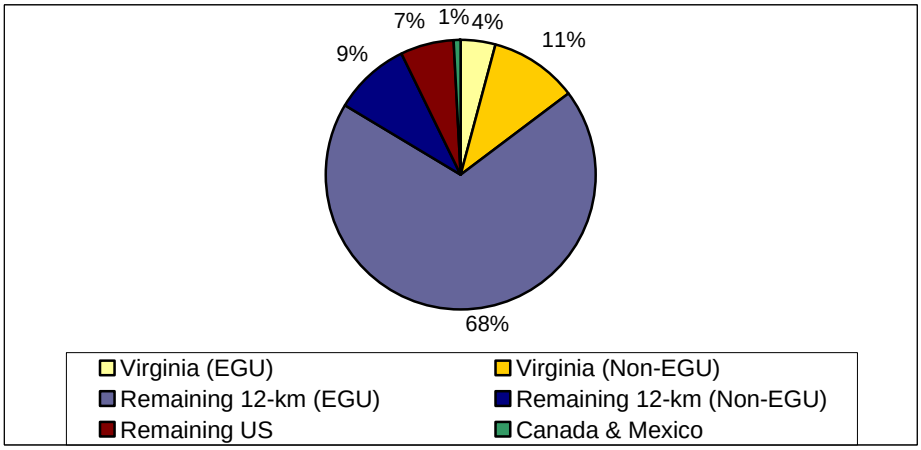
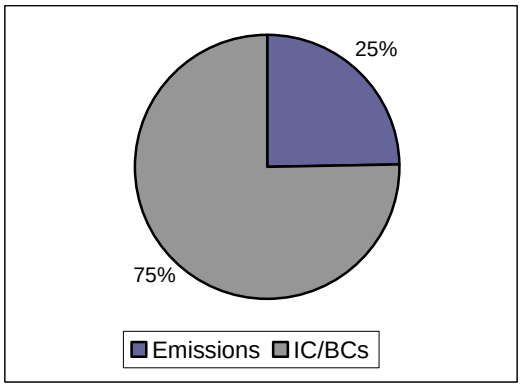


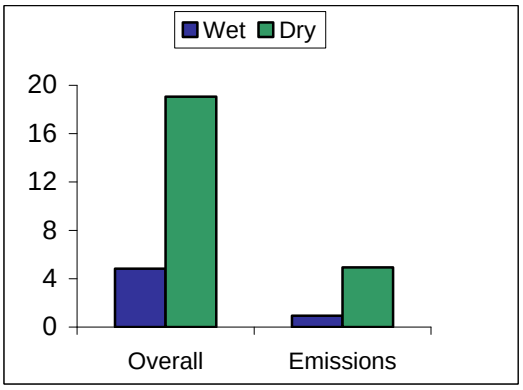
Figure 5-17h. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Shenandoah River Basin.

Simulated Annual Hg Deposition for 2001 for Shenandoah River Basin: 23.9 g/km²

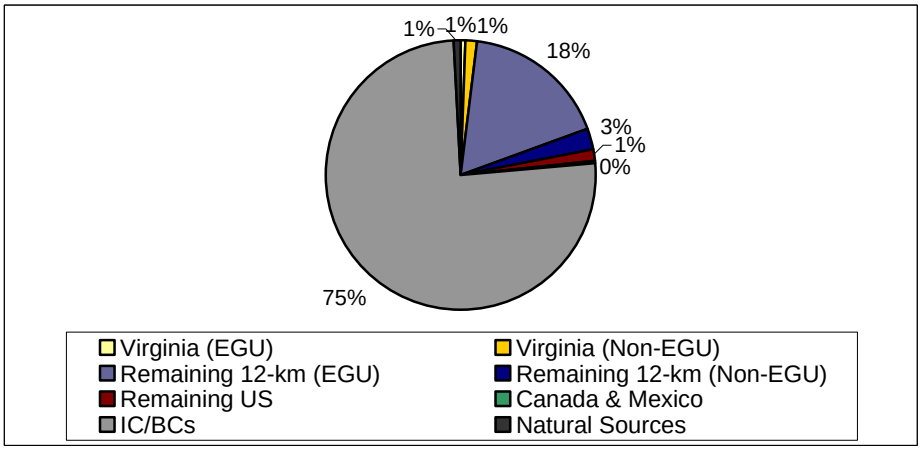
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

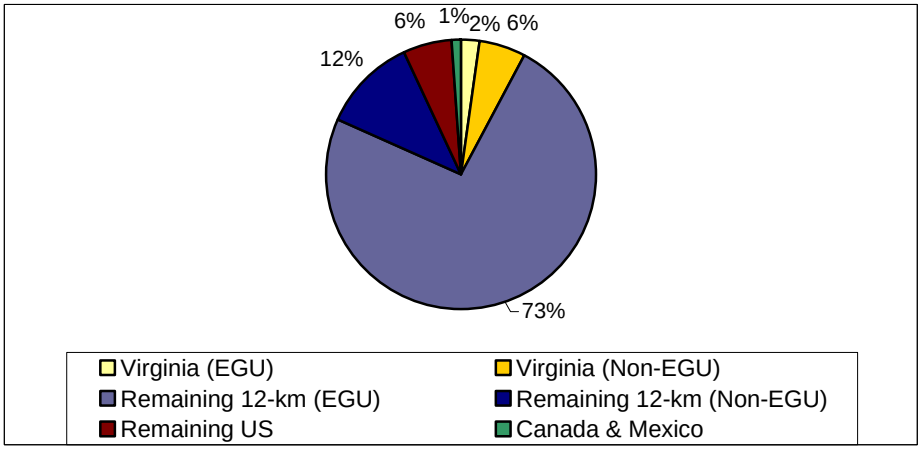
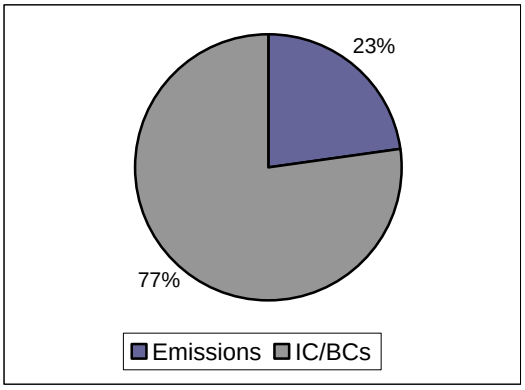


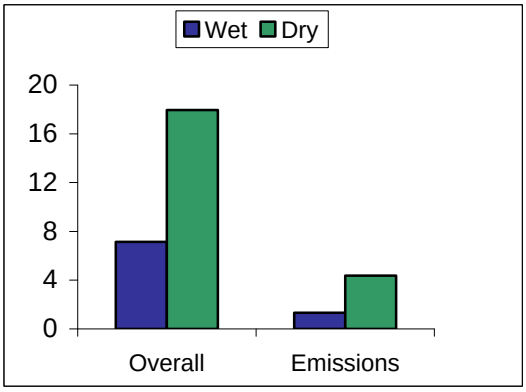
Figure 5-17i. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Tennessee and Big Sandy River Basins.

Simulated Annual Hg Deposition for 2001 for the Tennessee & Big Sandy River Basins: 25.1 g/km²

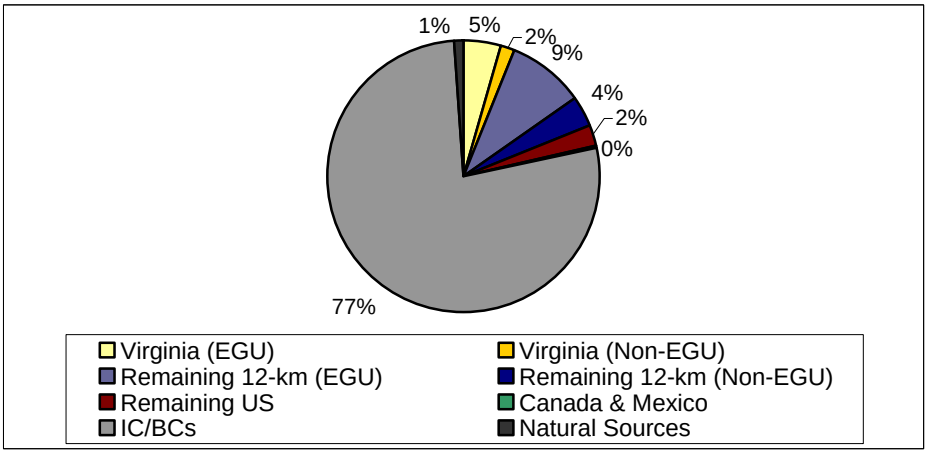
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

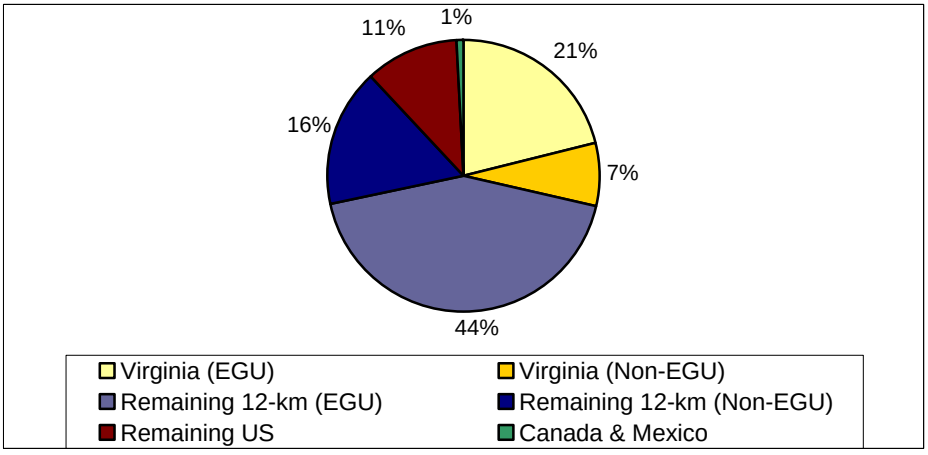
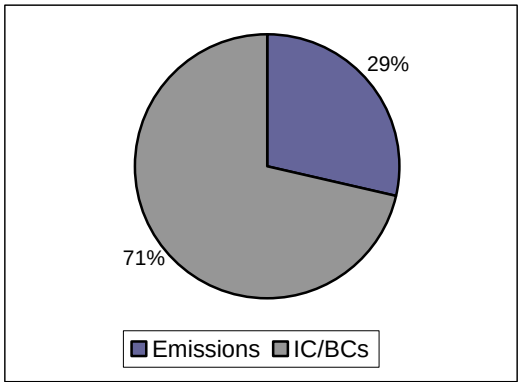


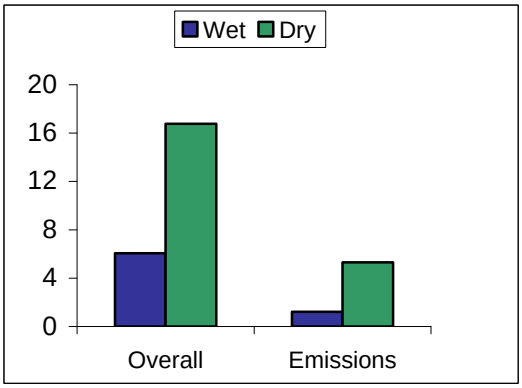
Figure 5-17j. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the York River Basin.

Simulated Annual Hg Deposition for 2001 for the York River Basin: 22.82 g/km²

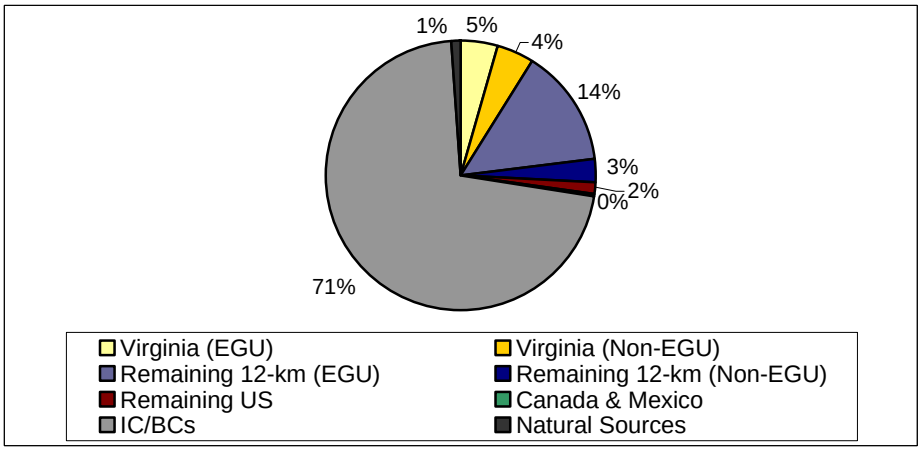
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

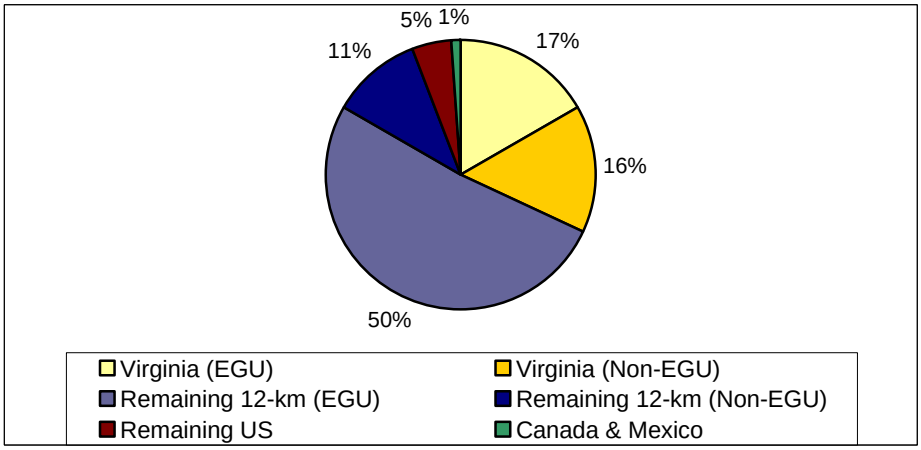
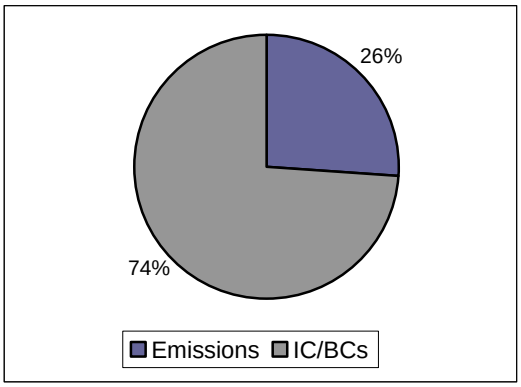


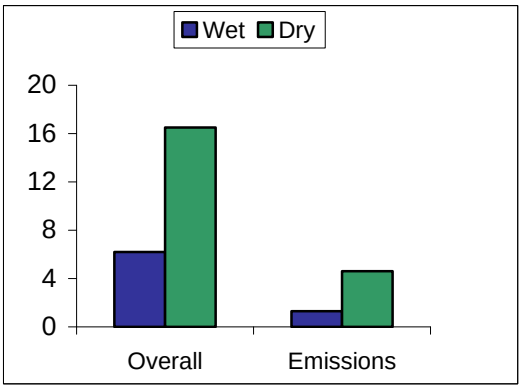
Figure 5-17k. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for Virginia.

Simulated Annual Hg Deposition for 2001 for Virginia: 22.69 g/km²

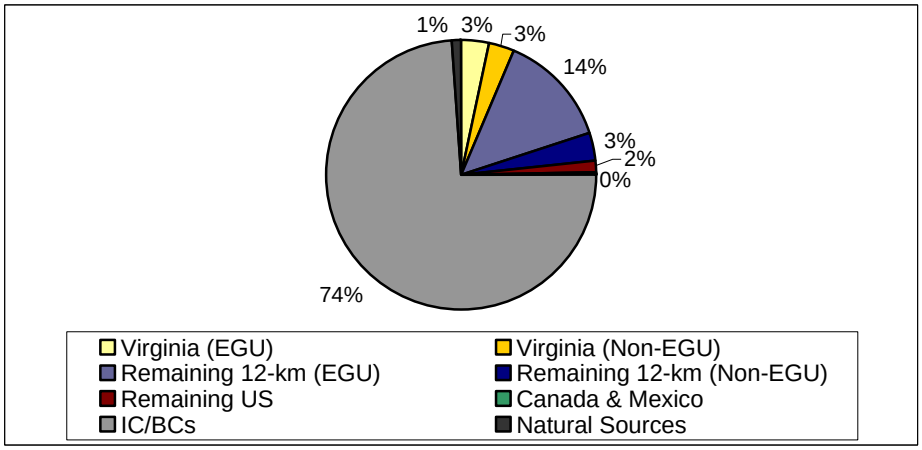
Emissions vs. IC/BC Contributions



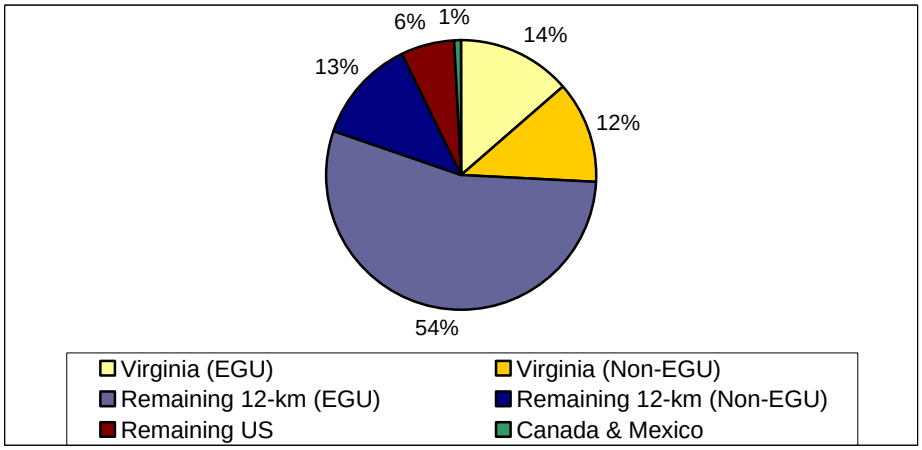
Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources



Future-year Modeling

CMAQ was applied for 2010, 2015 and 2018, using emissions projected to these years (as presented in Section 3). The future-year modeling results are presented in the remainder of this section.

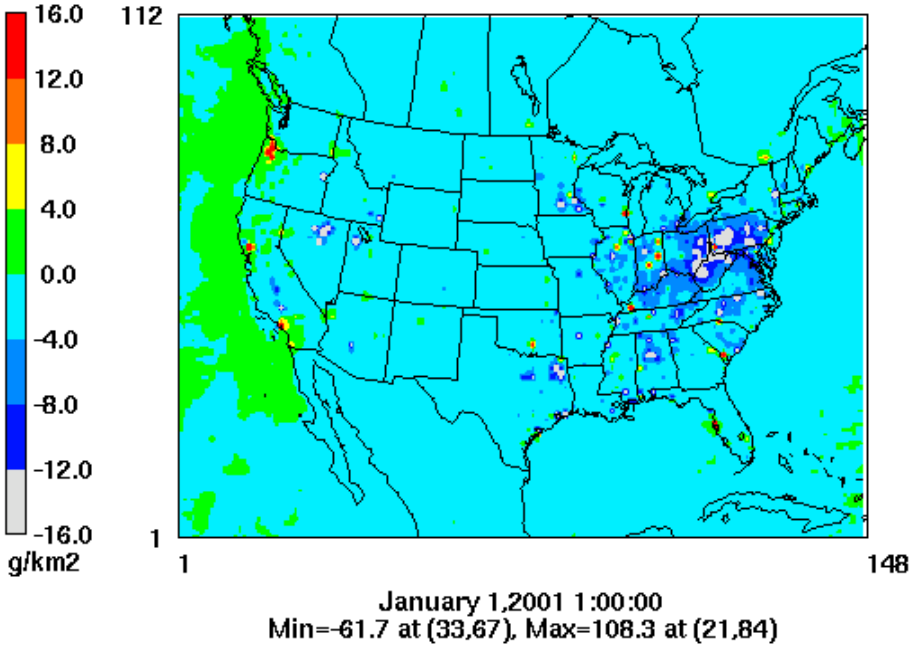
5.1.5. 2010, 2015 and 2018 Modeling Results

For each future year, the simulated change in overall mercury deposition both statewide and within the key areas of interest was examined.

Figures 5-18 through 5-20 display the location and magnitude of the differences in simulated mercury deposition for 2010, 2015, and 2018. Each figure consists of two parts. The first part shows the differences for the 36-km domain and the second part shows the differences for the 12-km subdomain. The differences are calculated as future-year minus base-year, so a negative value indicates a reduction in mercury deposition for the future year.

Figure 5-18. Difference in CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (g km^{-2}) for the 2001 Simulation Period: 2010 Minus Base.

(a) 36-km Domain



(b) 12-km Subdomain

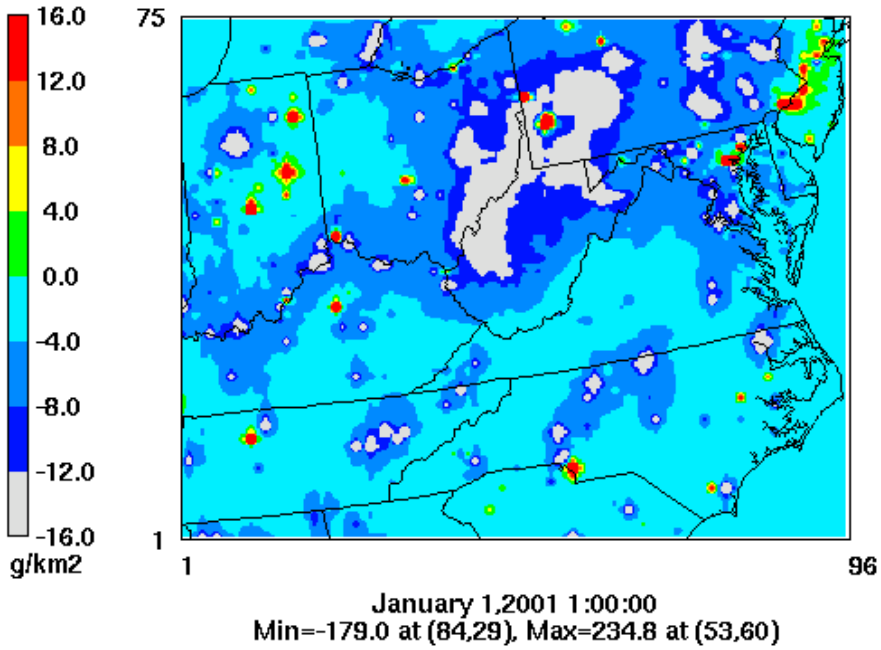
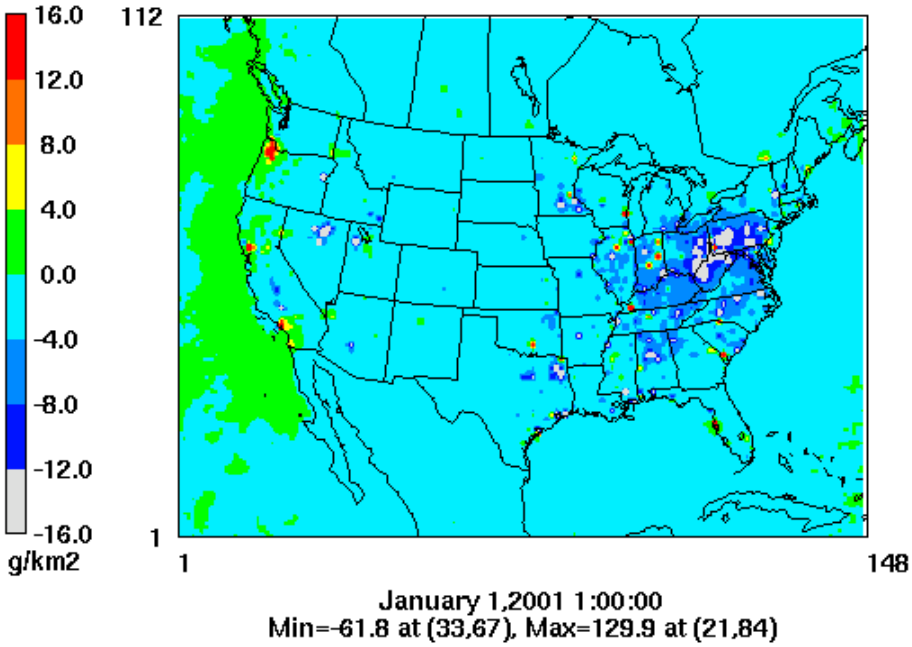


Figure 5-19. Difference in CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (g km^{-2}) for the 2001 Simulation Period: 2015 Minus Base.

(a) 36-km Domain



(b) 12-km Subdomain

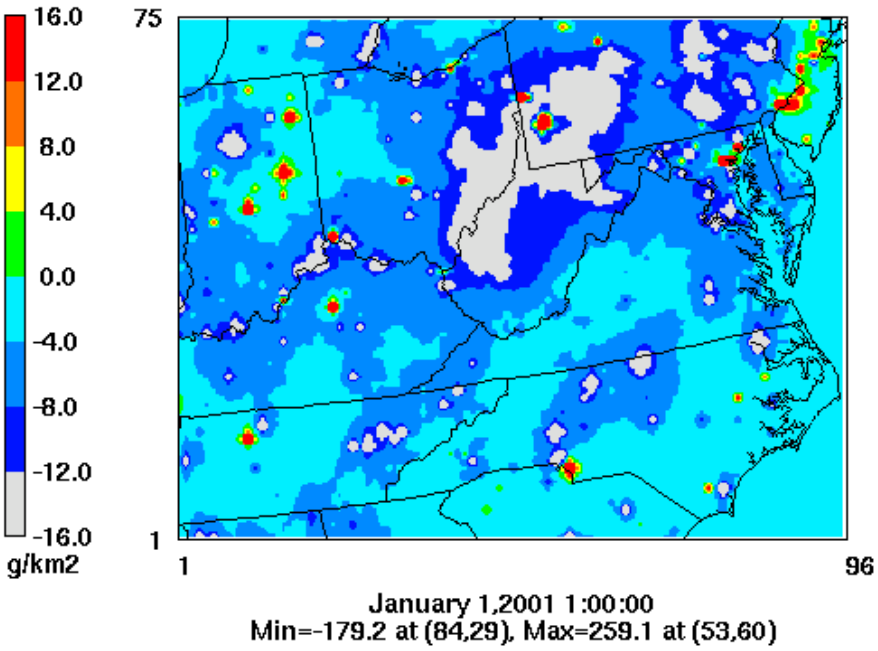
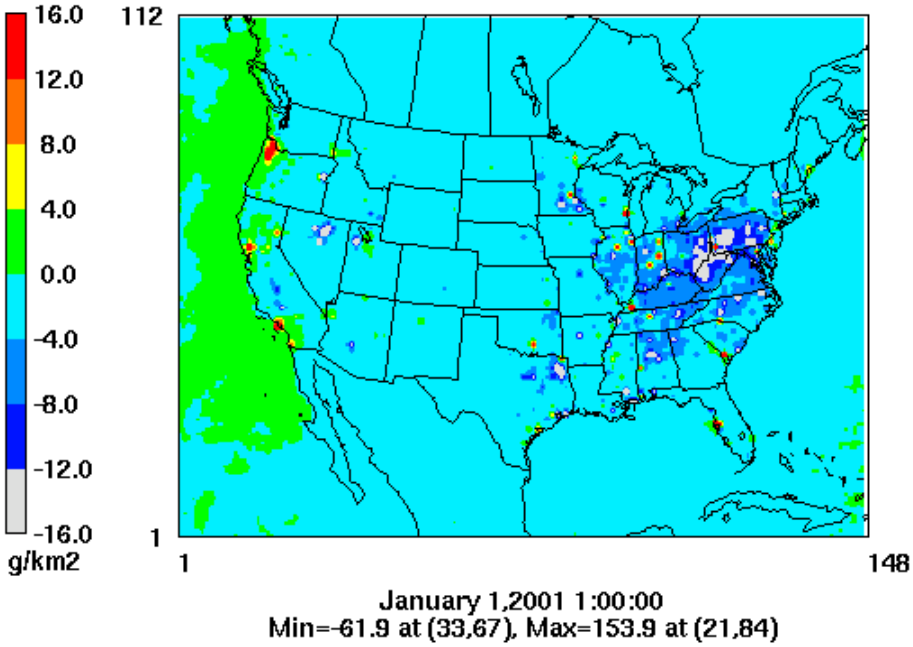
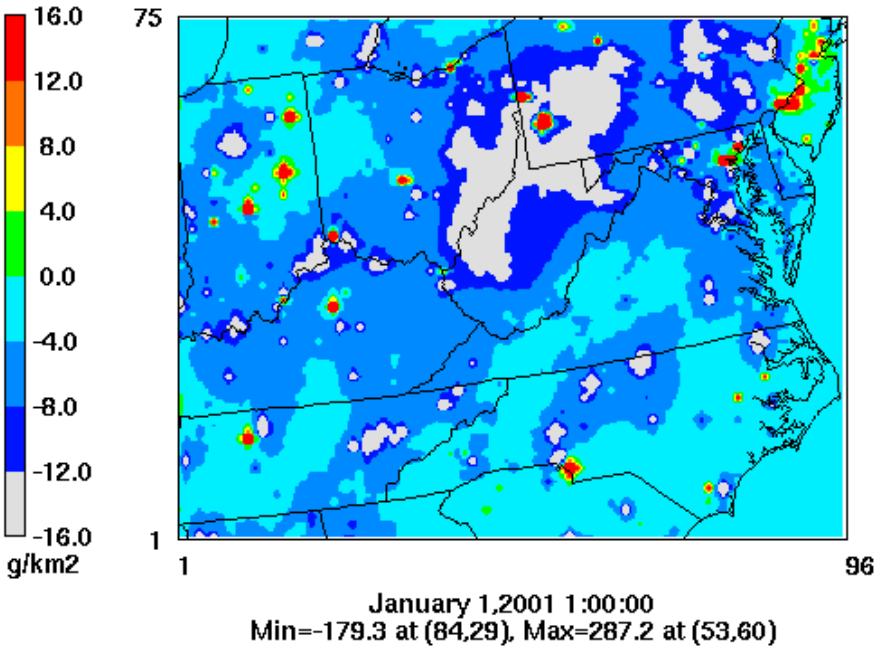


Figure 5-20. Difference in CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (g km^{-2}) for the 2001 Simulation Period: 2018 Minus Base.

(a) 36-km Domain



(b) 12-km Subdomain



The difference plots indicate that simulated mercury deposition over Virginia is lower for all three future years – by up to 8 g km^{-2} for most areas and by larger amounts for some more isolated areas. A comparison of the plots for all three years shows that most of this reduction occurs between the base year and 2010. Outside of Virginia, the area of greatest reduction (for both the 12- and 36-km grids) is along the Ohio River Valley. There are also isolated areas of increase that are due to increases in the mercury emissions in the modeling inventories. These increases may be the result of increases in emissions due to projected growth for a source or industry sector. None of the red areas are due to the addition of "generic" EGU units. Rather, they coincide with either non-EGU sources in the future-year inventory that are not in the base-year inventory or increases in emissions for existing sources. In some cases the increases may be due to inconsistencies between the base- and future-year emissions in the national emission inventories, which were used for states other than Virginia.

Figure 5-21 further summarizes the projected deposition changes for each of the major river basins in Virginia. The size of the area is different for each river basin. To allow a comparison of the results among the river basins, the first plot (Figure 5-21a) gives the average deposition for each river basin in units of g km^{-2}. Another way to compare the base and future-year results is to sum the deposition over each river basin. This information is presented in Figure 5-21b which gives total deposition in units of kg. Both plots show that the amount of reduction between modeled years is greatest between the base year and 2010. Of course, this period is also the longest in terms of the number of years represented. The reductions are much smaller between 2010 and 2015 and then 2015 and 2018. Figure 5-21a shows that the Potomac River Basin has the highest simulated deposition per unit area, but also experiences the greatest reduction between the base and future years. Figure 5-21 shows that the James River Basin (one of the largest in terms of area) has the highest overall amount of simulated mercury deposition and that this is reduced by about 16 percent by 2010. Additional analysis of these results is presented in Section 7.

Figure 5-21a. CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (g km^{-2}) for the Major River Basins in Virginia for 2001/2002, 2010, 2015 and 2018: Deposition Amount per Unit Area.

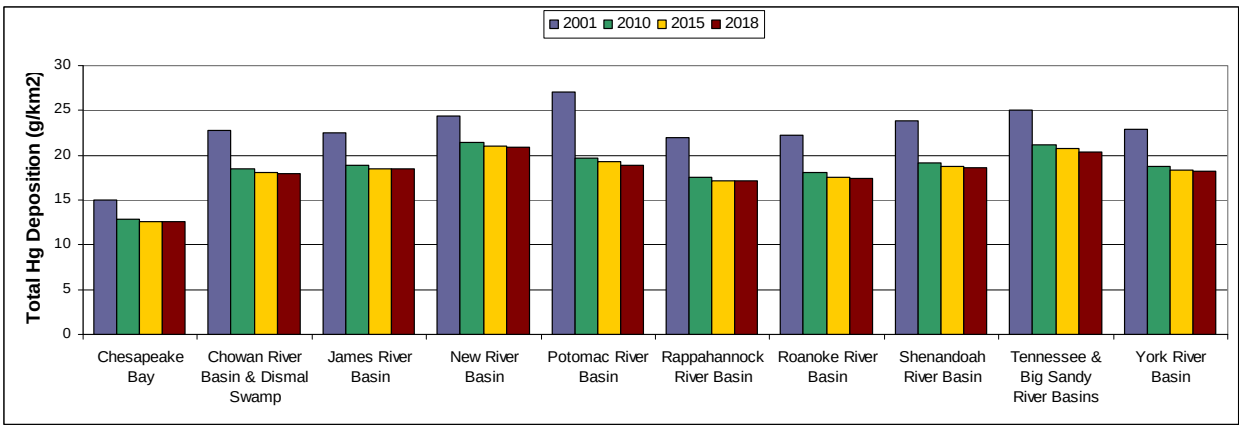
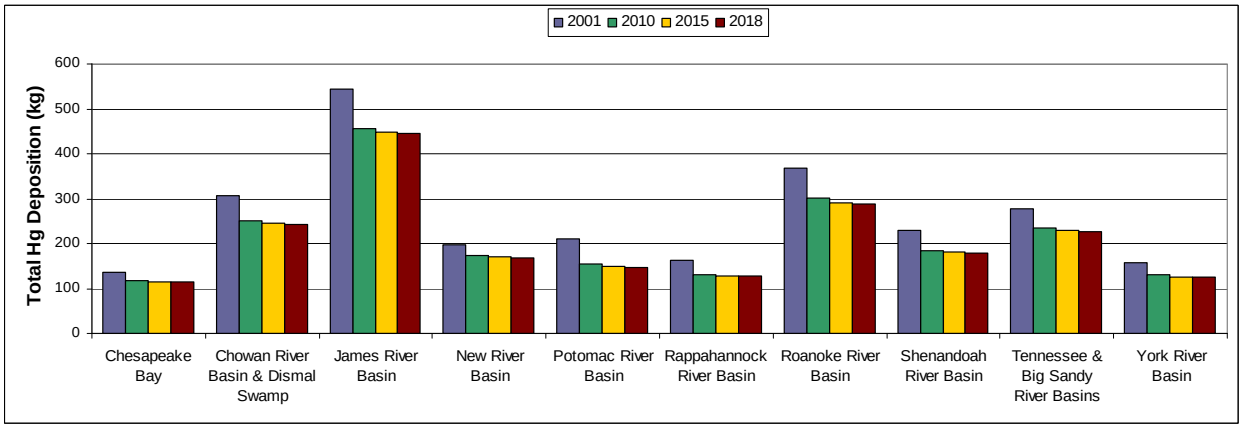


Figure 5-21b. CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (kg) for the Major River Basins in Virginia for 2001/2002, 2010, 2015 and 2018: Deposition Total for the Area.

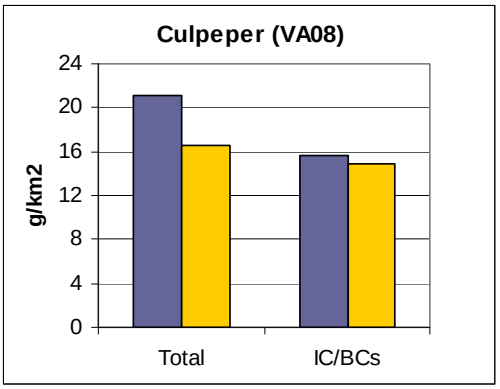


5.1.6. 2018 Contribution Analysis for Virginia

For 2018, the same CMAQ/PPTM scenarios that were run for the baseline were also run for the future year. The PPTM results were used to attribute the future-year reductions in mercury deposition for 2018 for each area of interest to the specific tagged sources or source categories.

We begin with the results for the MDN monitoring sites. In Figure 5-22, total mercury deposition and deposition associated with each tagged source category or area is plotted for each MDN monitoring site and for the base year and 2018. Total deposition and the IC/BC contribution are plotted in the upper bar chart. The results for the remaining tags are plotted in the lower bar chart, using a reduced scale range (to facilitate the comparison of the base and future year results for the smaller contributors). Note also that the scales differ among the sites.

Figure 5-22a. CMAQ/PPTM 12-km Mercury Tagging Results for the Culpeper MDN Monitoring Site (VA08) for 2001/2002 and 2018.



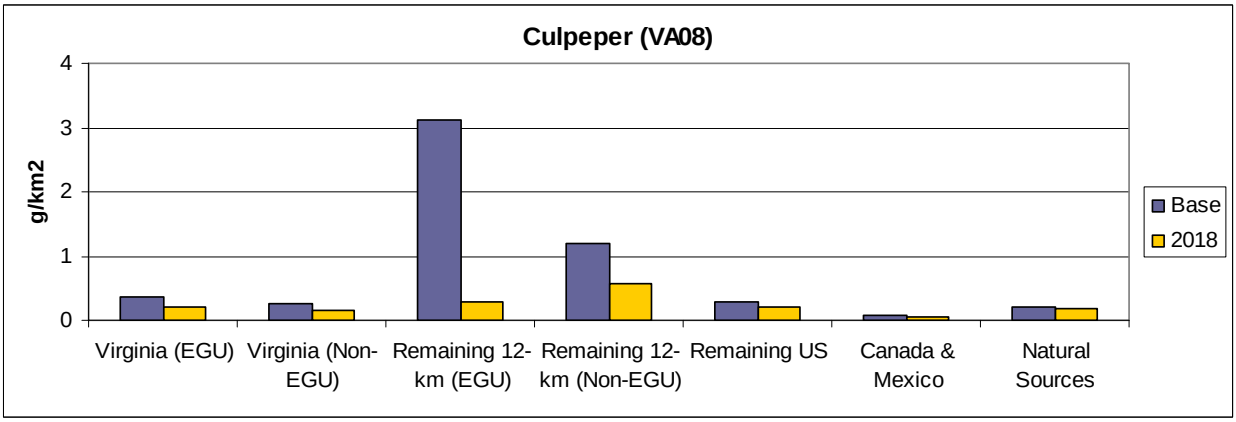
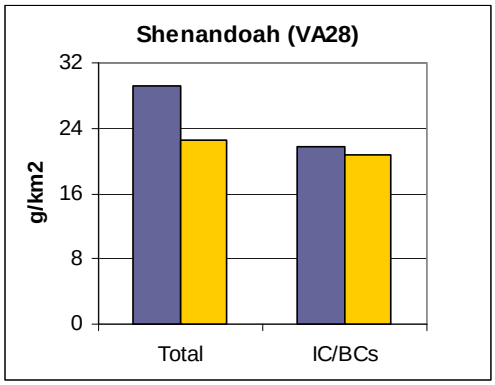


Figure 5-22b. CMAQ/PPTM 12-km Mercury Tagging Results for the Shenandoah National Park MDN Monitoring Site (VA28) for 2001/2002 and 2018.



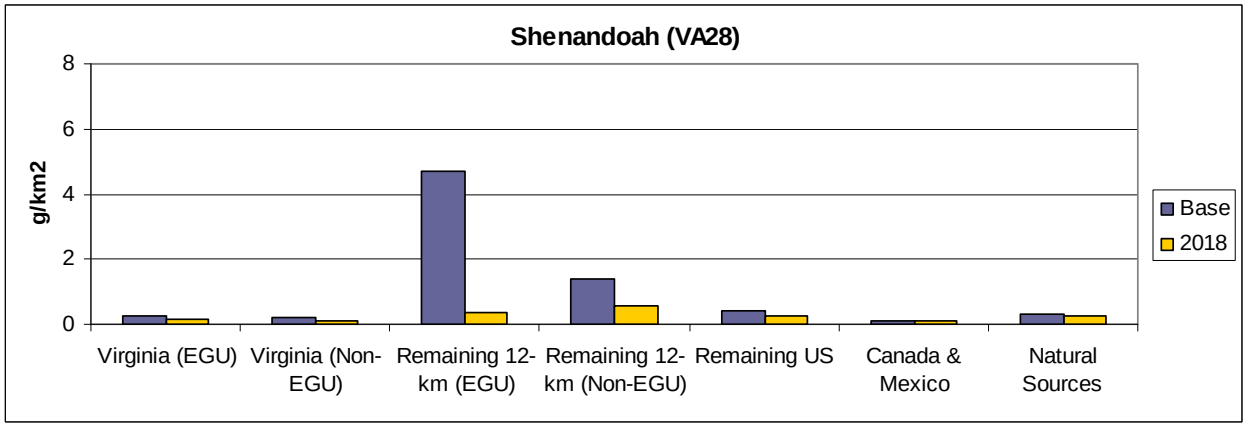
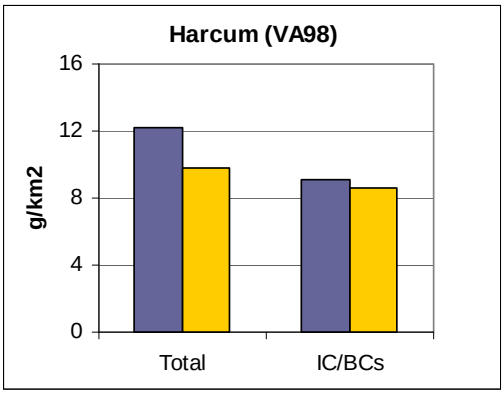
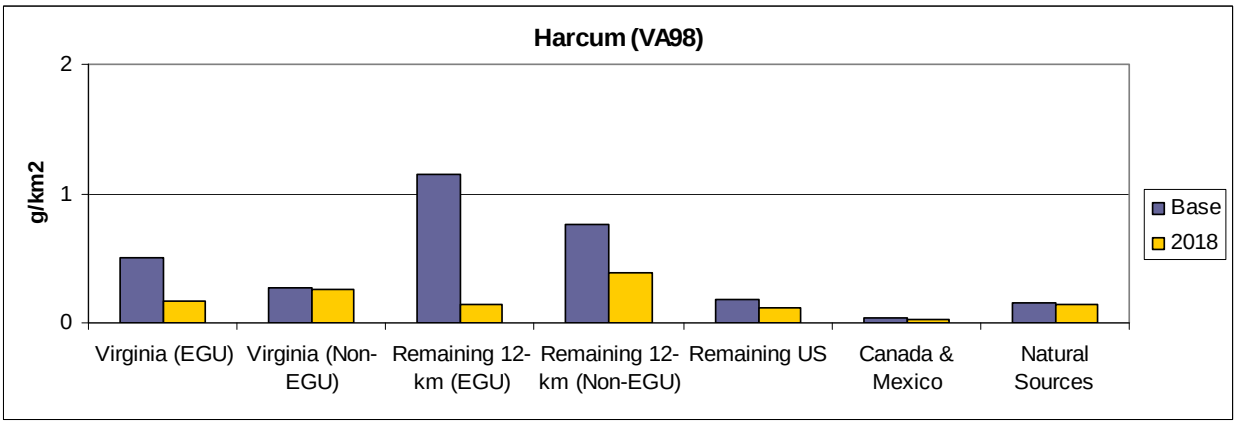


Figure 5-22c. CMAQ/PPTM 12-km Mercury Tagging Results for the Harcum MDN Monitoring Site (VA98) for 2001/2002 and 2018.

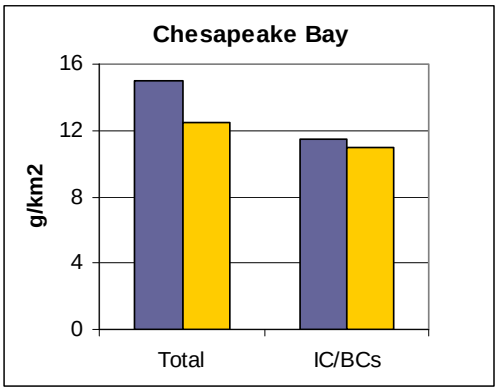




For all three MDN sites, simulated mercury deposition is about 20 percent lower for 2018 compared to the base year. A majority of this reduction is attributable to reductions in emissions from EGU and non-EGU sources in the surrounding states (remainder of the 12-km domain). Lower emissions from Virginia EGU sources are also important to the overall reduction at Harcum. Although the differences between the 2018 and base contributions are relatively small for the other categories, the contributions from all tags are lower for 2018. While the IC/BCs and natural emissions used as input to the model are the same for both years, there is also a reduction in the contribution from these tags. This is due to lower regional-scale concentrations of ozone and other species in the future year, which results in less conversion of HG0 (from the boundary conditions and natural emissions) to HG2 and less deposition. Recall that most of the mercury deposition is in the form of HG2.

Figure 5-23 displays this same information for each of the major river basins in Virginia.

Figure 5-23a. CMAQ/PPTM 12-km Mercury Tagging Results for the Chesapeake Bay, Atlantic Ocean, and Small Coastal Waters for 2001/2002 and 2018.



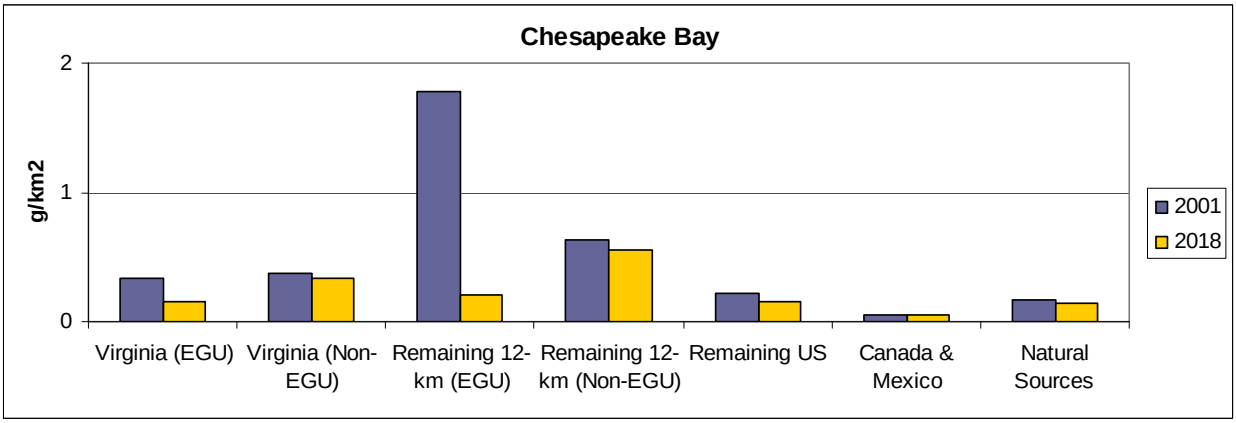
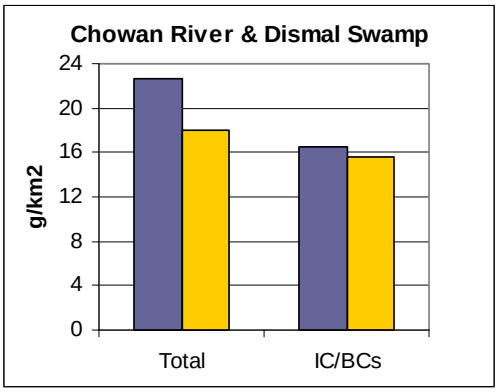


Figure 5-23b. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Chowan River Basin and Great Dismal Swamp for 2001/2002 and 2018.



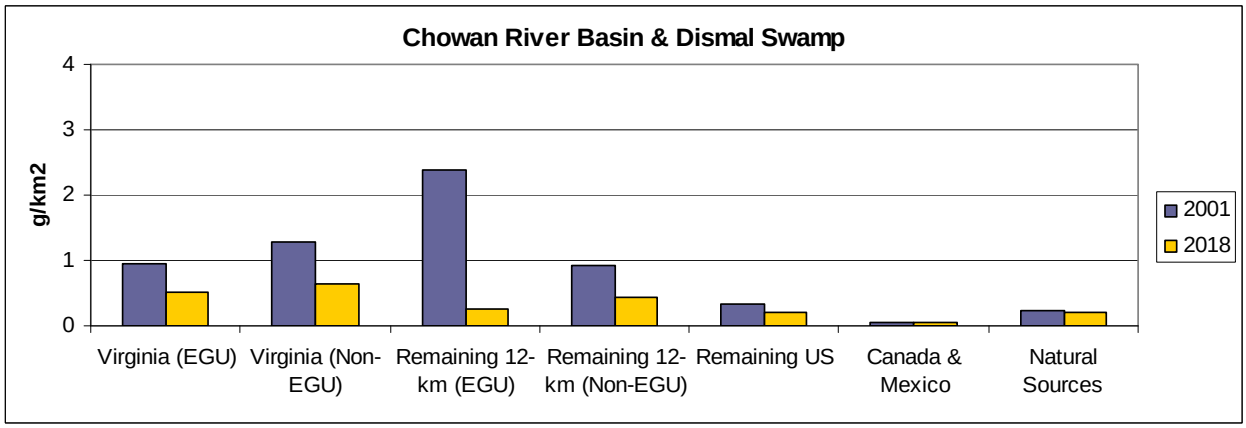
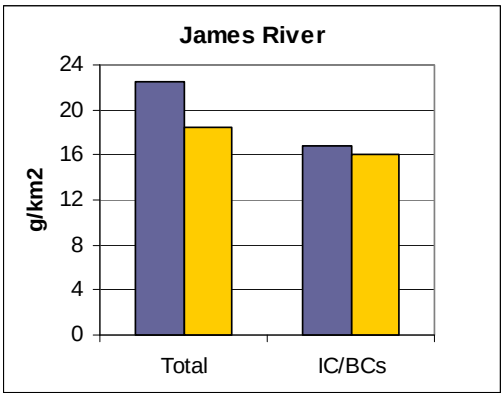


Figure 5-23c. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the James River Basin for 2001/2002 and 2018.



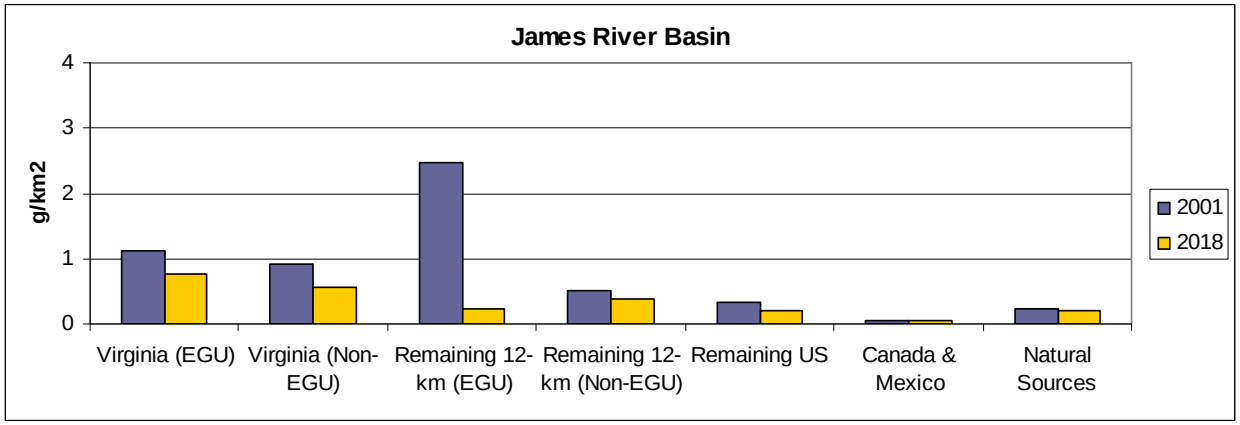
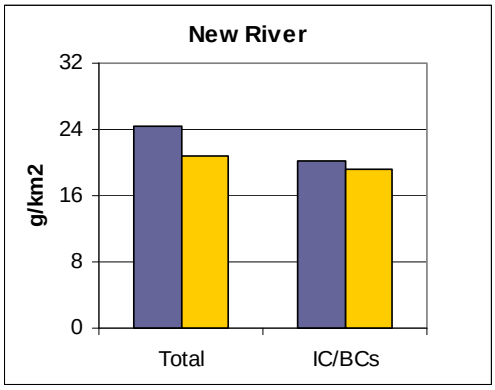


Figure 5-23d. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the New River Basin for 2001/2002 and 2018.



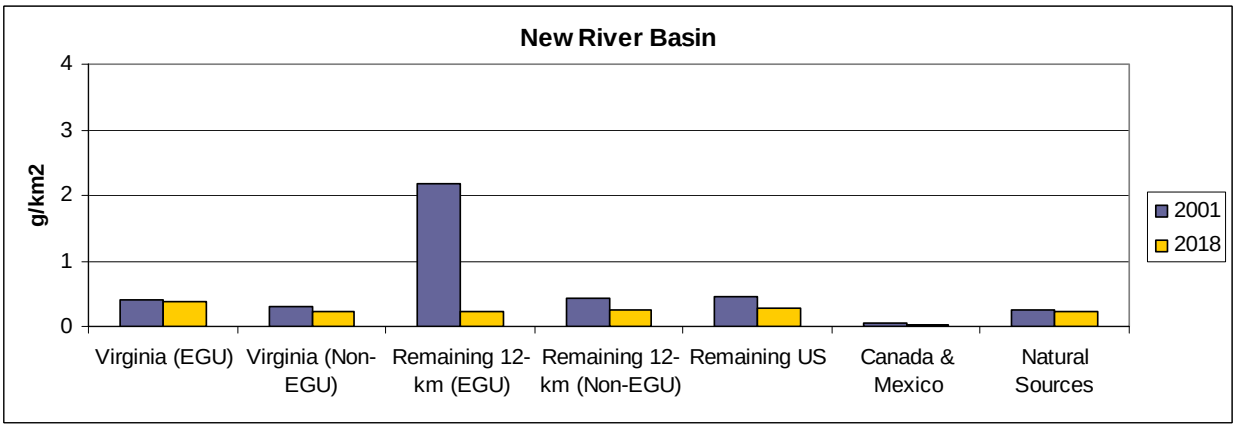
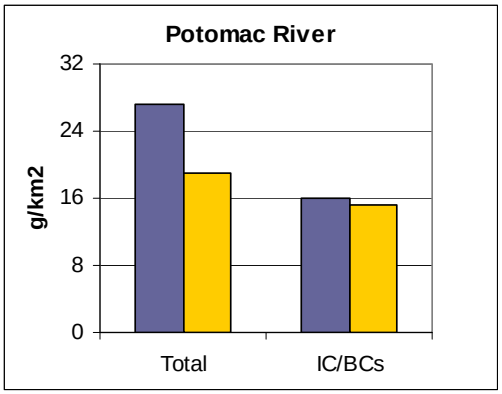


Figure 5-23e. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Potomac River Basin for 2001/2002 and 2018.



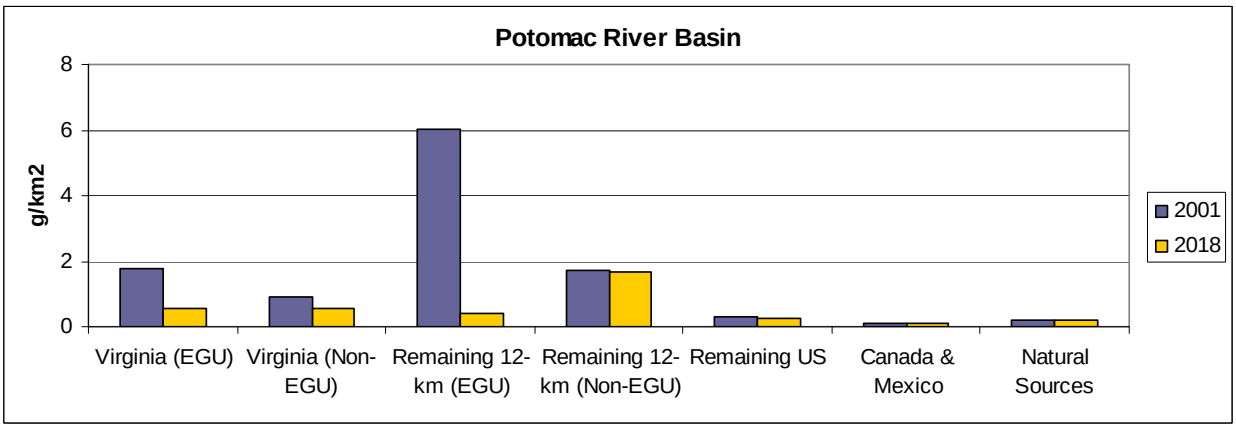
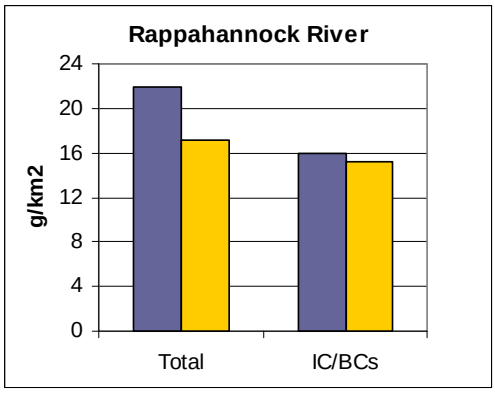


Figure 5-23f. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Rappahannock River Basin for 2001/2002 and 2018.



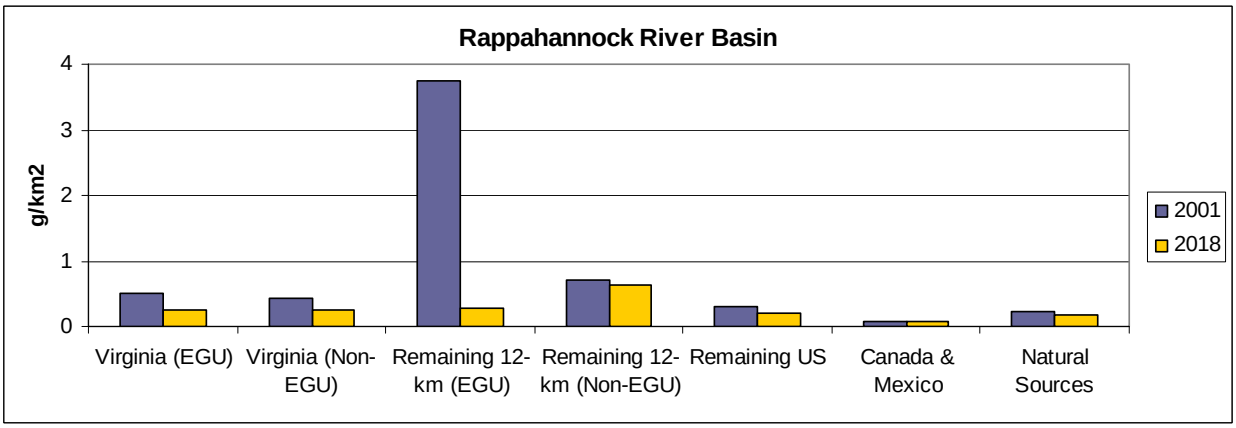
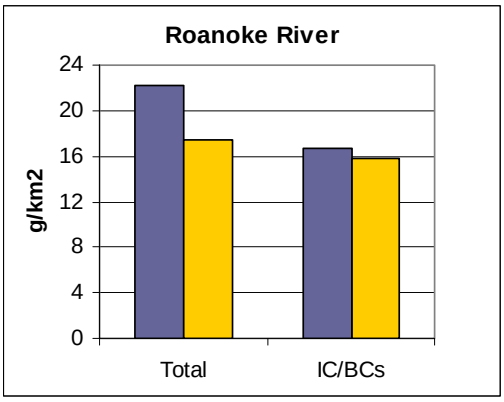


Figure 5-23g. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Roanoke River Basin for 2001/2002 and 2018.



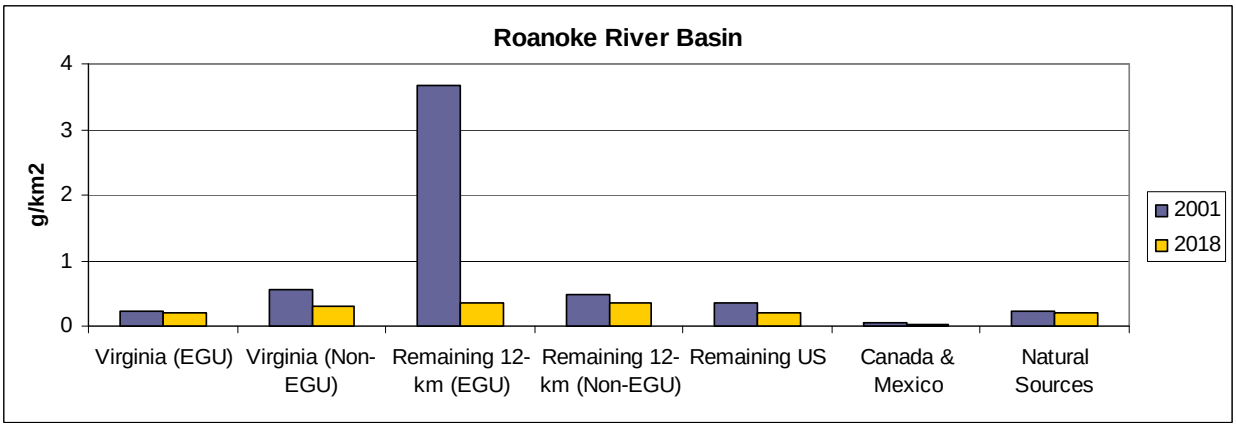
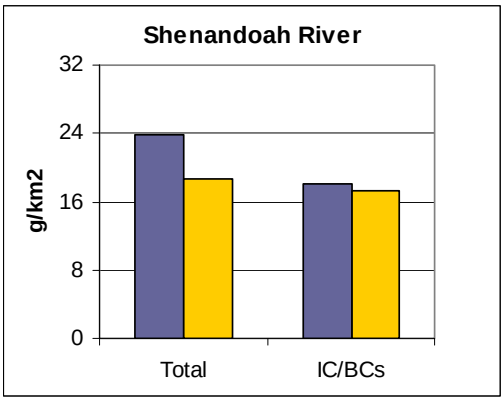


Figure 5-23h. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Shenandoah River Basin for 2001/2002 and 2018.



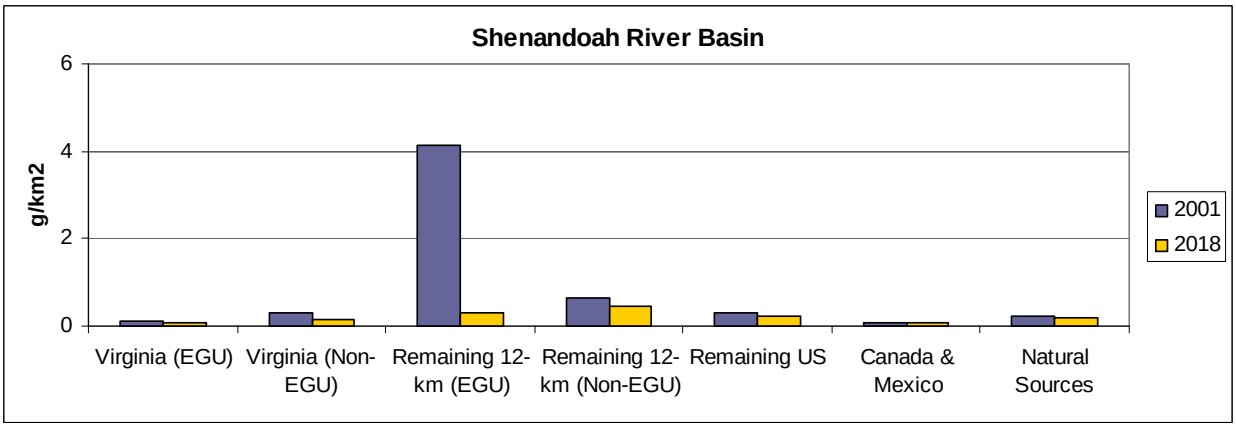
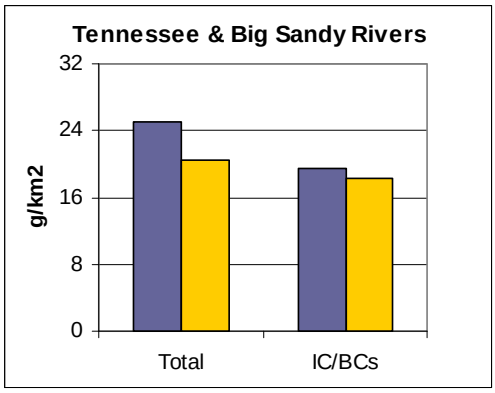


Figure 5-23i. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Tennessee and Big Sandy River Basins for 2001/2002 and 2018.



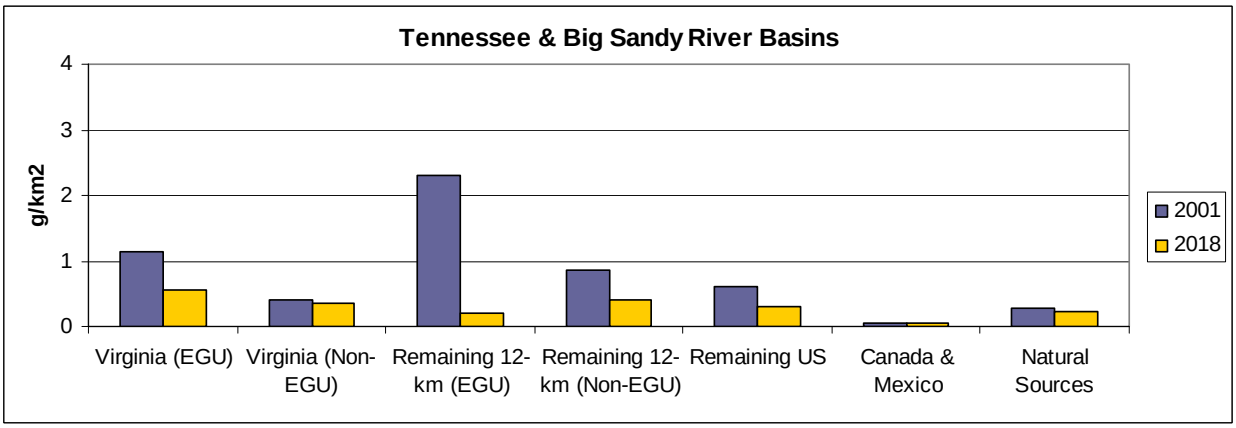
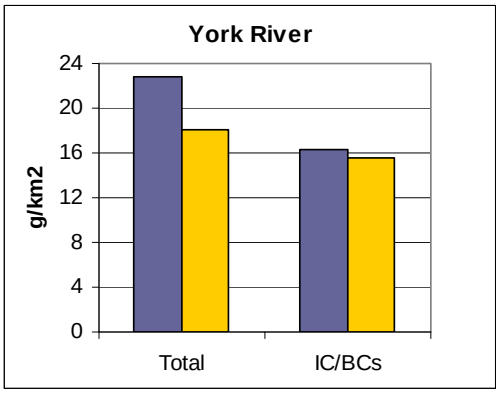


Figure 5-23j. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the York River Basin for 2001/2002 and 2018.



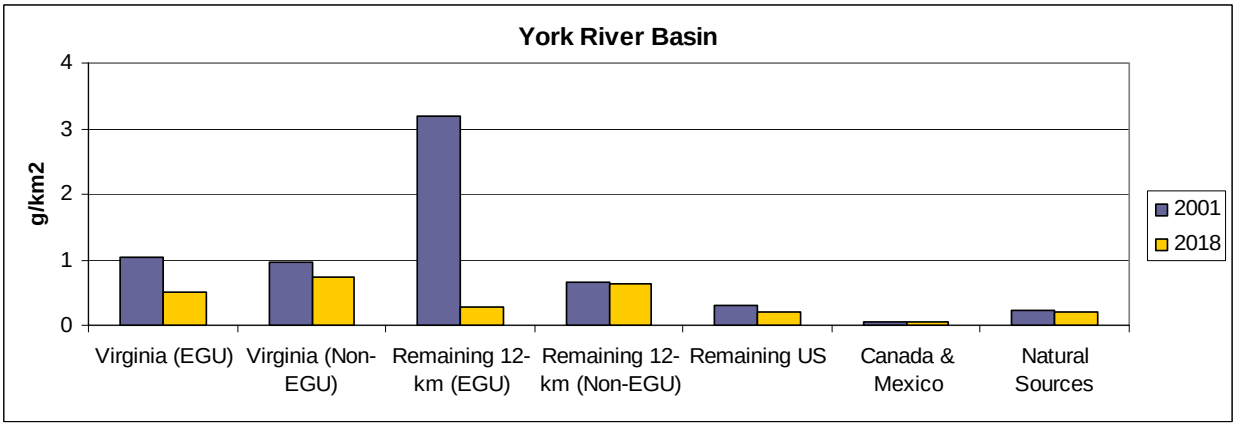


Figure 5-23 shows that, for all of the Virginia river basins, lower mercury deposition in 2018 is primarily driven by the reduction in emissions from EGU sources in the surrounding states between the base year and 2018. The other tagged source categories and regions vary in importance among the river basins. For example, reductions in emissions from the Virginia EGU and non-EGU sources as well as the non-EGU sources in the surrounding states also play a significant role in lowering simulated mercury deposition for the Chowan River Basin and Dismal Swamp between the base year and 2018. Reductions in emissions from the Virginia EGU and non-EGU sources (but not the non-EGU sources in the surrounding states) result in lower simulated mercury deposition for the James River and York River Basins. Additional analysis of these results is presented in Section 7.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6. AERMOD Modeling Results

AERMOD was applied for the 15 sources in Virginia with the greatest mercury emissions, ranked according to the VDEQ 2002 emissions inventory data. As noted in Section 4, AERMOD was applied separately for each source and for elemental, reactive gaseous, and particulate-bound mercury. The results of the AERMOD application are presented in this section of the report.

In this section, the key metric used for the presentation of the AERMOD results is the average annual mercury deposition, averaged over all receptors in the 3-km area surrounding each source. This metric was calculated for wet, dry and total deposition and for HG0, HG2 and HGP.

In addition to this metric, graphs displaying the spatial distribution of mercury deposition for each source-receptor area and bar charts comparing the deposition amounts for the various facilities were also prepared. These were prepared for wet, dry and total deposition and for HG0, HG2 and HGP.

6.1. Sensitivity Simulations

Following the initial application of AERMOD, the annual deposition plots for each facility and corresponding receptor area were reviewed. As discussed in Section 4, the plots of wet, dry, and total deposition were also reviewed and the deposition of HG0, HG2 and HGP were compared to the speciation of the emissions. Three key findings emerged from this review: 1) dry deposition is greater than wet deposition for all facilities, 2) maximum wet deposition tends to occur in the receptor cells closest to the facility, and 3) maximum dry deposition tends to occur further away from the facility location. The finding related to wet deposition is consistent with wash out of the emissions near the facility when precipitation is occurring. The finding related to dry deposition is consistent with expected plume behavior under a variety of meteorological conditions and transport of the emissions to a downwind location before deposition occurs.

The initial AERMOD results also indicated that deposition amount is not directly proportional to the emissions totals for the top 15 sources, which are listed together with their base-year emissions in Table 4-1 (presented earlier). The units for deposition are micrograms per square meter ($\mu g\ m^{-2}$). The ranking of the facilities with respect to emissions totals is different from the ranking based on total (wet plus dry) deposition amount. As an example, the annual emissions and simulated deposition amounts for the top two facilities are provided in Table 6-1. The average stack height and exit velocity of the emissions for each facility are also provided in the table; the averages are taken over all stacks that comprise the facility.

Table 6-1. AERMOD Mercury Emissions Rates, Average Stack Parameters, and Simulated Total Deposition Amounts for Two Facilities.

Facility Name	Rank	Total Hg Emissions (lbs/yr)	Average Stack Height (m)	Average Exit Velocity ($m\ s^{-1}$)	Average Annual Hg Dep ($ug\ m^{-2}$)	EGU?
Dominion - Chesterfield Power Station	1	358.83	93.7	22.1	28.1	EGU
Chaparral Steel	2	292.30	23.2	6.1	38.3	Non-EGU

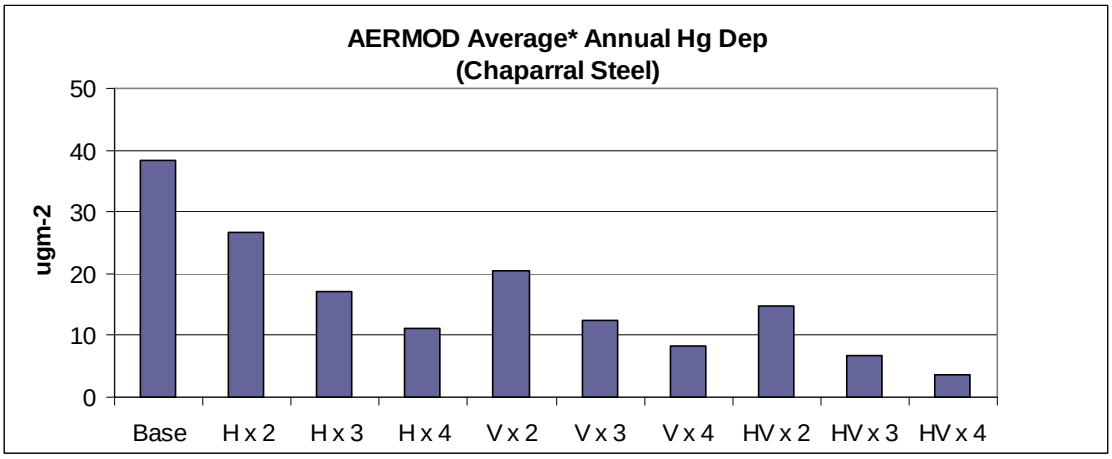
Even though the emissions are greater for the Chesterfield Power Station, the local deposition amounts are greater for Chaparral Steel. The maximum deposition for the Chesterfield Power Station is simulated to occur approximately 750 m away from the source, while that for Chaparral Steel occurs within 100 m of the source. The meteorological inputs for these two facilities are based on the same surface and upper-air meteorological data. Thus, it was concluded that the differences in deposition are not due to differences in meteorology. Some sensitivity simulations were conducted to examine the relationship of the stack parameters to the simulated deposition for the Chaparral Steel source under the meteorological conditions represented in this study. The goal was to examine and explain the modeling results, and not to conduct a rigorous test of the sensitivity of AERMOD to various parameters.

In series of simulations, the stack heights for Chaparral Steel were increased by factors of 2, 3 and 4. In a second series of simulations, the exit velocities for Chaparral Steel were increased by factors of 2, 3 and 4. Finally, both the stack heights and exit velocities were increased by these same factors. The results are presented in Table 6-2 and plotted in Figure 6-1 (annual average only). In presenting the results of the sensitivity tests, the deposition amounts are total (wet plus dry) deposition.

Table 6-2. AERMOD Annual Simulated Total Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility for a Variety of Alternative Stack Parameters.

Scenario	Average Stack Height (m)	Average Exit Velocity (m s^{-1})	Average Annual Hg Dep (ug m^{-2})
Base (Actual Stack Parameters)	23.2	6.1	38.3
Stack Height x 2	46.4	6.1	26.6
Stack Height x 3	69.6	6.1	17.1
Stack Height x 4	92.8	6.1	11.2
Exit Velocity x 2	23.2	12.2	20.5
Exit Velocity x 3	23.2	18.3	12.4
Exit Velocity x 4	23.2	24.4	8.4
Stack Height & Exit Velocity x 2	46.4	12.2	14.8
Stack Height & Exit Velocity x 3	69.6	18.3	6.7
Stack Height & Exit Velocity x 4	92.8	24.4	3.5

Figure 6-1. AERMOD Annual Simulated Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility for a Variety of Alternative Stack Parameters.



** Average over 3km sq. area surrounding facility.*

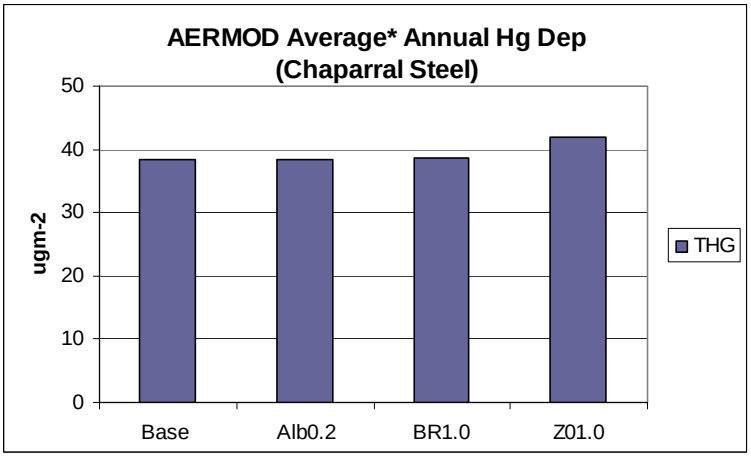
The simulated deposition is sensitive to the stack parameters. Increasing stack height and exit velocity, both separately and in combination, lowers the amount of deposition in the receptor area. The last scenario, in which both the stack heights and the exit velocities are multiplied by a factor of 4, results in comparable stack parameters but much lower deposition amounts compared to the Dominion facility. Thus while stack parameters can be important, these results indicate that the deposition differences between these to facilities are also influenced by other factors (such as number of stacks, emissions rates, temperatures and speciation), that are not examined here.

We also examined the sensitivity of the AERMOD results to the surface characteristics. In another series of simulations, a uniform albedo, Bowen ratio, and roughness length were applied in preparing the meteorological input files for this same Chaparral Steel facility. The albedo specifies the reflectivity of the surface, the Bowen ratio is an indicator of surface moisture, and the roughness length is related to the height of obstacles that might affect wind flow. The values applied are 0.2 for albedo, 1.0 for the Bowen ratio, and 1.0 for roughness length. These values are within the range of typical values for a variety of land-use types and seasons. In the base AERMOD run, these parameters were specified for the four land-use sectors that surround the facility (comprised mostly of mixed forest, pasture, wooded wetland, evergreen forest, and residential land) and for each season. The albedo values range from 0.13 to 0.17 with an average value of 0.15. The Bowen ratios range from 0.31 to 0.86 and average to 0.65. The roughness lengths range from 0.56 to 1.2, with an average of 0.93. Both AERMET and AERMOD were rerun for this test. The results are presented in Table 6-3 and Figure 6-2 (annual average only).

Table 6-3. AERMOD Annual Simulated Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility Assuming Uniform Surface Characteristics.

Scenario	Average Annual Hg Dep (ug m^{-2})
Base (Variable Surface Characteristics)	38.3
Uniform Albedo = 0.2	38.3
Uniform Bowen Ratio = 1.0	38.7
Uniform Roughness Length = 1.0	41.8

Figure 6-2. AERMOD Annual Simulated Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility Assuming Uniform Surface Characteristics.



** Average over 3km sq. area surrounding facility.*

The AERMOD results are not very sensitive to variability in the surface characteristics for the ranges examined here.

Finally, the use of alternative deposition parameters was examined. Small changes in the air and water diffusivity values for HG0 and HG2 resulted in very slight changes in simulated deposition. Use of an alternative particle size distribution for HGP, however, did have an effect on the simulated deposition of particulate-bound mercury. Wesely et al. (2002) gives several alternatives to specifying the fine particle fraction and mass mean diameter for HGP. In the base run, the recommended values, which are 0.8 micron for the fine particle fraction and 0.4 micron for the mean particle diameter, were used. There is little variation among the alternative estimates of fine particle fraction, and, therefore, the use of different values for this parameter was not tested. An alternative value for the diameter is given as 0.8 micron and since this is quite different from the recommended value, a sensitivity test was conducted using this alternate value. The results are presented in Table 6-4.

Table 6-4. AERMOD Annual Simulated Particulate Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility for an Alternate Particle Size Parameter.

Scenario	Average Annual HgP Dep (ug m^{-2})
Base (Particle Diameter = 0.4mm)	1.4
Particle Diameter = 0.8 mm	4.0

The AERMOD results for particle deposition are sensitive to the specification of particle diameter and deposition increases with particle size.

From this analysis it is concluded that AERMOD-based deposition is influenced by the stack parameters for that facility. Increasing stack height and exit velocity, both separately and in combination, reduces the amount of deposition in the receptor area. For several of the sensitivity scenarios, the simulation results for Chaparral Steel are comparable to the results for the Dominion Chesterfield Power Station. Since both sites use the same meteorological data and have similar emissions (Chesterfield actually has greater emissions), the differences in deposition are likely attributable to the differences in stack parameters.

More generally, it was also found that the AERMOD results are not very sensitive to variability in the surface characteristics for the ranges examined here and that they are sensitive to the specification of particle size.

6.2. Base- and Future-year Modeling Results

The base-year emissions for the top 15 sources and the corresponding base-year simulation results for all facilities are listed in Table 6-5. The table gives total modeled deposition which includes both wet and dry deposition from elemental (HG0), reactive gaseous (HG2) and particulate mercury (HGP). Note that the average deposition is averaged over a three square kilometer area surrounding the source.

Table 6-5. AERMOD Annual Simulated Mercury Deposition (μg m^{-2}) for the Base Year (2001/2002).

Facility Name (Abbreviation)	Rank	2002 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})
Dominion - Chesterfield Power Station (CHST)	1	358.83	28.15
Chaparral Steel (CHAP)	2	292.30	38.35
Dominion—Bremo (BRMO)	3	167.73	10.31
American Electric Power- Clinch River (CLCH)	4	159.21	11.10
Dominion - Chesapeake Energy Center (CHSP)	5	157.38	12.51
Potomac River Generating Station (POTO)	6	118.26	64.99
Dominion - Yorktown Power Station (YORK)	7	107.64	2.72
Jewel Coke Company LLP (JEWL)	8	105.62	8.04
Dominion-Possum Point Power Station (POSS)	9	100.19	16.20
Stone Container Enterprises (Smurfit) (SMUR)	10	77.76	27.48
Stone Container Corporation –Hopewell (HOPE)	11	69.69	12.48
American Electric Power (Glen Lyn) (GLEN)	12	65.14	13.06
Intermet Foundry Archer Creek (ARCH)	13	65.01	11.10
RES dba Steel Dynamics (RES)	14	60.80	9.32
Spruance Genco LLC (SPRU)	15	55.50	13.36

Both the base-year emissions and the AERMOD-derived deposition values (annual average) are displayed in Figure 6-3. The relative contributions of HG0, HG2 and HGP are shown in the bar charts.

Figure 6-3a. 2002 Baseline Emissions for the Top 15 Virginia Facilities.

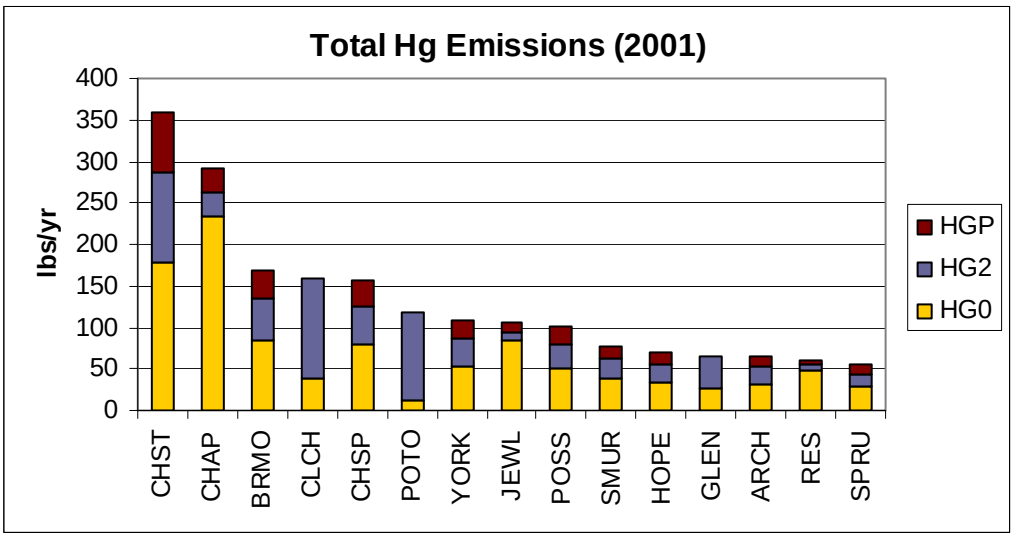
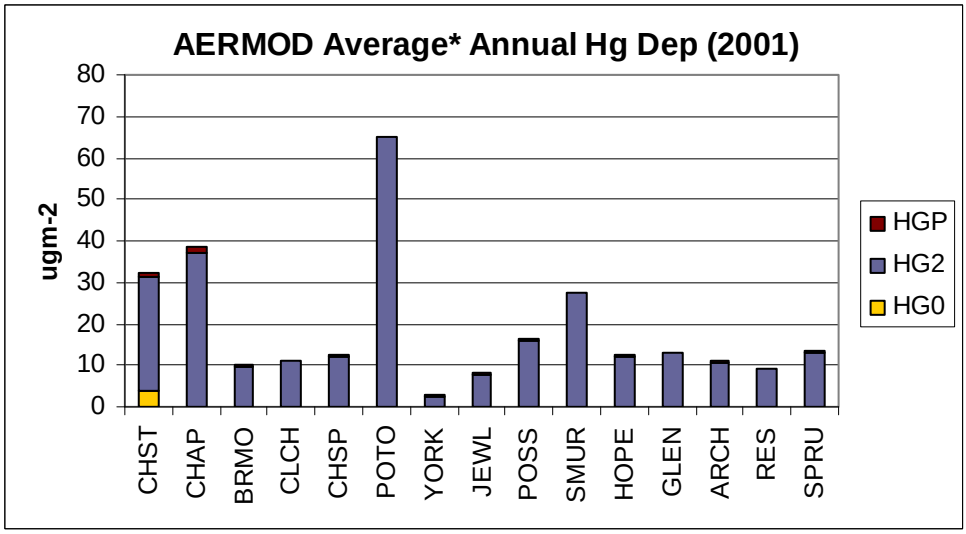


Figure 6-3b. AERMOD Annual Simulated Mercury Deposition (μg m^{-2}) for the Base Year (2001/2002) for the Top 15 Virginia Facilities.



** Average over 3-km sq. area surrounding facility.*

For reference, the base- and future-year emissions for the top 15 sources are listed in Table 4-4 (presented earlier). The corresponding future-year AERMOD simulation results for all facilities are listed in Tables 6-6a through c. The tables give total simulated deposition which includes both wet and dry deposition from HG0, HG2, and HGP.

Table 6-6a. AERMOD Annual Simulated Mercury Deposition (μg/m^2) for 2010.

Facility Name (Abbreviation)	Rank	2010 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})
Dominion - Chesterfield Power Station (CHST)	1	183.15	23.39
Chaparral Steel (CHAP)	2	100.50	13.34
Dominion—Bremo (BRMO)	3	172.74	10.61
American Electric Power- Clinch River (CLCH)	4	80.00	5.56
Dominion - Chesapeake Energy Center (CHSP)	5	81.05	6.45
Potomac River Generating Station (POTO)	6	72.37	39.46
Dominion - Yorktown Power Station (YORK)	7	105.85	2.73
Jewel Coke Company LLP (JEWL)	8	106.91	8.13
Dominion-Possum Point Power Station (POSS)	9	1.99	0.11
Stone Container Enterprises (Smurfit) (SMUR)	10	80.57	27.86
Stone Container Corporation –Hopewell (HOPE)	11	9.66	1.47
American Electric Power (Glen Lyn) (GLEN)	12	67.09	13.45
Intermet Foundry Archer Creek (ARCH)	13	21.77	3.79
RES dba Steel Dynamics (RES)	14	21.57	3.30
Spruance Genco LLC (SPRU)	15	25.95	6.25

Table 6-6b. AERMOD Annual Simulated Mercury Deposition (μg/m^2) for 2015.

Facility Name (Abbreviation)	Rank	2015 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})
Dominion - Chesterfield Power Station (CHST)	1	151.47	19.89
Chaparral Steel (CHAP)	2	50.50	6.79
Dominion—Bremo (BRMO)	3	189.88	11.68
American Electric Power- Clinch River (CLCH)	4	81.00	5.48
Dominion - Chesapeake Energy Center (CHSP)	5	89.09	7.08
Potomac River Generating Station (POTO)	6	72.37	39.46
Dominion - Yorktown Power Station (YORK)	7	73.46	1.93
Jewel Coke Company LLP (JEWL)	8	106.91	8.13
Dominion-Possum Point Power Station (POSS)	9	1.49	0.10
Stone Container Enterprises (Smurfit) (SMUR)	10	82.36	28.13
Stone Container Corporation –Hopewell (HOPE)	11	9.79	1.50
American Electric Power (Glen Lyn) (GLEN)	12	73.74	14.77
Intermet Foundry Archer Creek (ARCH)	13	12.87	2.30
RES dba Steel Dynamics (RES)	14	12.65	1.94
Spruance Genco LLC (SPRU)	15	28.53	6.87

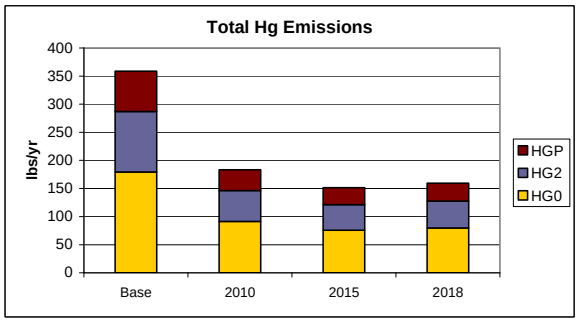
Table 6-6c. AERMOD Annual Simulated Mercury Deposition (μg/m^2) for 2018.

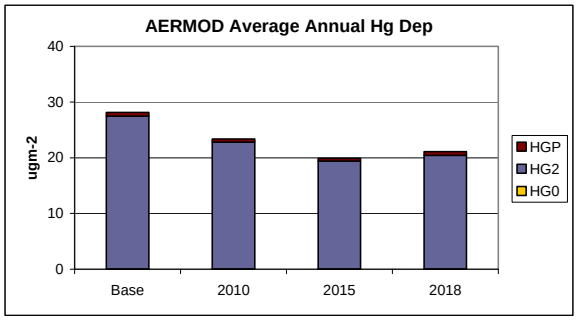
Facility Name (Abbreviation)	Rank	2018 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})
Dominion - Chesterfield Power Station (CHST)	1	159.39	21.09
Chaparral Steel (CHAP)	2	50.50	6.79
Dominion—Bremo (BRMO)	3	200.38	12.31
American Electric Power- Clinch River (CLCH)	4	81.00	5.48
Dominion - Chesapeake Energy Center (CHSP)	5	94.01	7.47
Potomac River Generating Station (POTO)	6	29.77	16.25
Dominion - Yorktown Power Station (YORK)	7	31.19	0.87
Jewel Coke Company LLP (JEWL)	8	106.91	8.13
Dominion-Possum Point Power Station (POSS)	9	1.25	0.09
Stone Container Enterprises (Smurfit) (SMUR)	10	83.41	28.29
Stone Container Corporation –Hopewell (HOPE)	11	9.87	1.52
American Electric Power (Glen Lyn) (GLEN)	12	77.82	15.61
Intermet Foundry Archer Creek (ARCH)	13	13.89	2.48
RES dba Steel Dynamics (RES)	14	13.65	2.09
Spruance Genco LLC (SPRU)	15	30.11	7.24

Finally, the base- and future-year emissions and corresponding AERMOD results (annual average only) by facility are presented in Figures 6-4 through 6-18. Each figure has two parts, one for emissions and one for annual average deposition over the receptor area. Emissions and deposition are displayed as a stacked bar chart that shows the contributions from HG0, HG2 and HGP. The total deposition amount (which includes wet and dry deposition) is given for each simulation year in units of micrograms per square meter (μg m^{-2}). Note that the scales differ among the facilities, appropriate to the emissions and deposition amounts. Maximum deposition (not shown) responds to the emissions changes in a similar way.

Figure 6-4. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Chesterfield Power Station.

(a) (b)

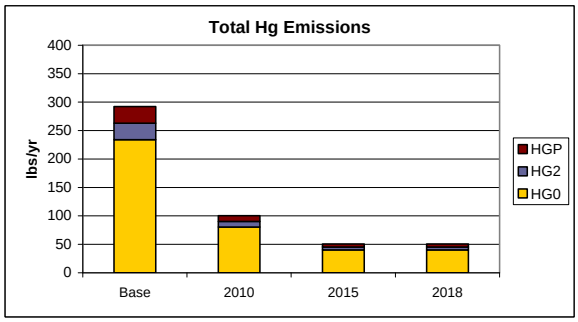


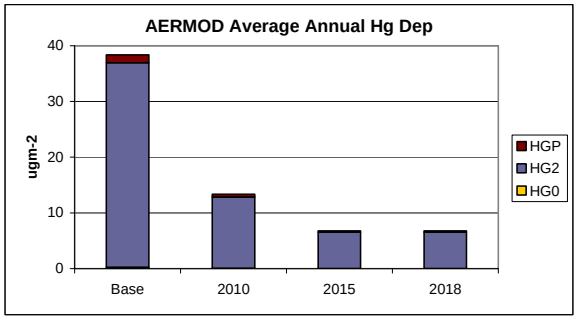


* Average over 3km sq. area surrounding facility.

Figure 6-5. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Chaparral Steel.

(a) (b)

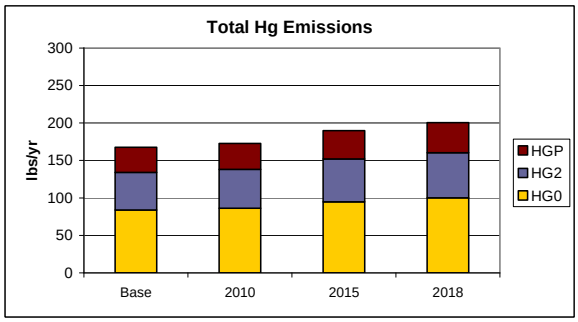


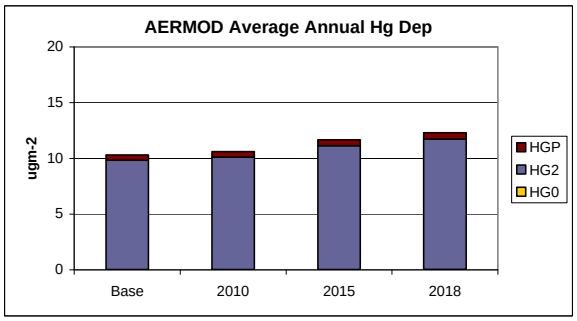


* Average over 3km sq. area surrounding facility.

Figure 6-6. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Bremo.

(a) (b)

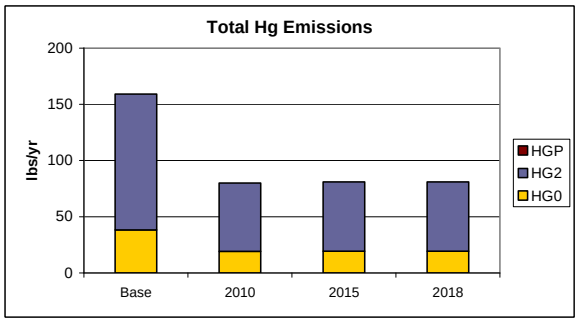


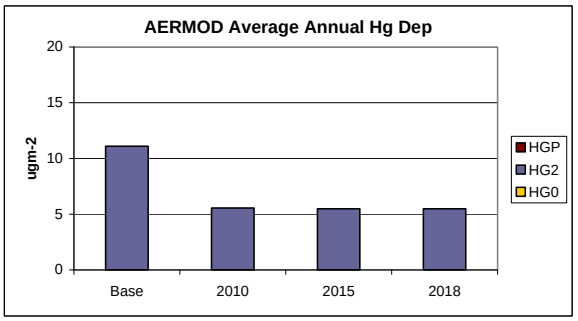


* Average over 3km sq. area surrounding facility.

Figure 6-7. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: American Electric Power—Clinch River.

(a) (b)

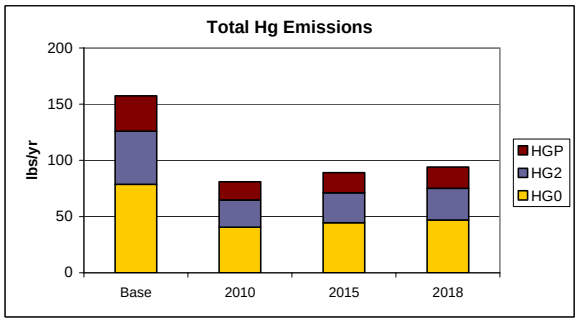


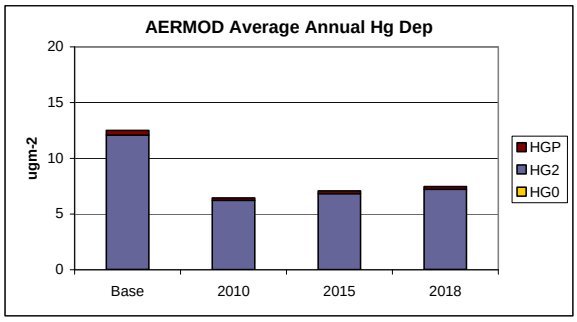


* Average over 3km sq. area surrounding facility.

Figure 6-8. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Chesapeake Energy Center.

(a) (b)

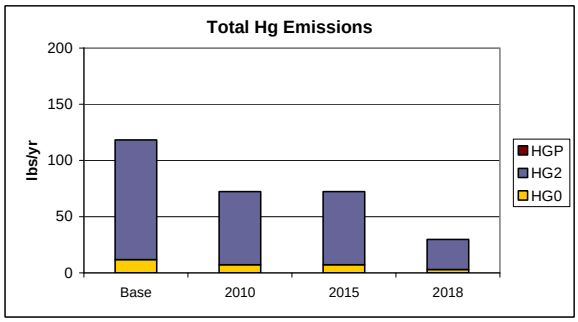


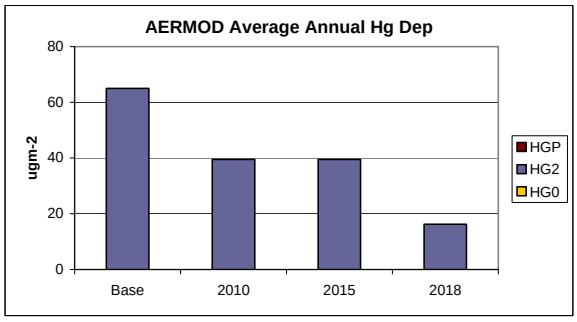


* Average over 3km sq. area surrounding facility.

Figure 6-9. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Potomac River Generating Station.

(a) (b)

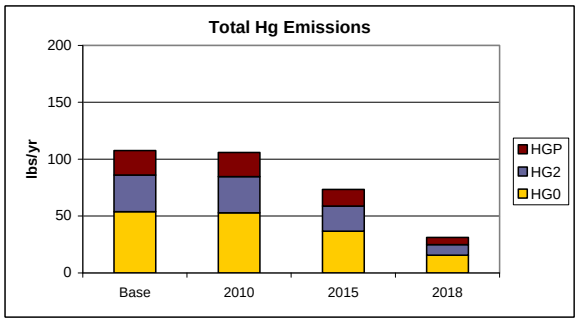


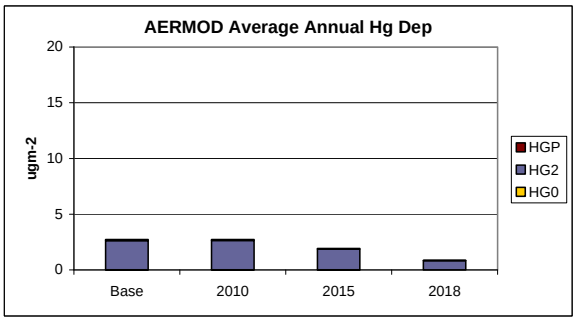


* Average over 3km sq. area surrounding facility.

Figure 6-10. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Yorktown Power Station.

(a) (b)

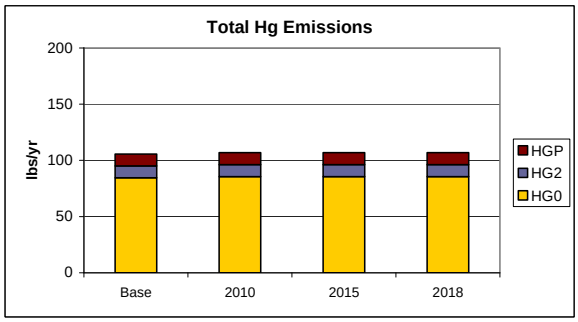


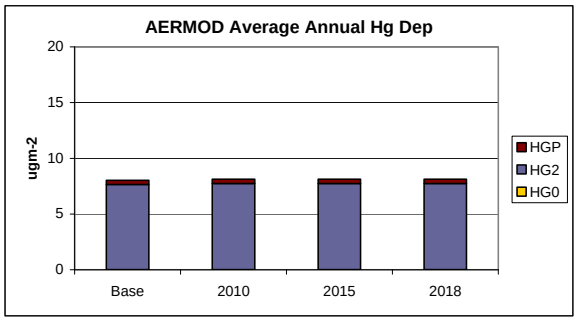


* Average over 3km sq. area surrounding facility.

Figure 6-11. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Jewell Coke Company.

(a) (b)

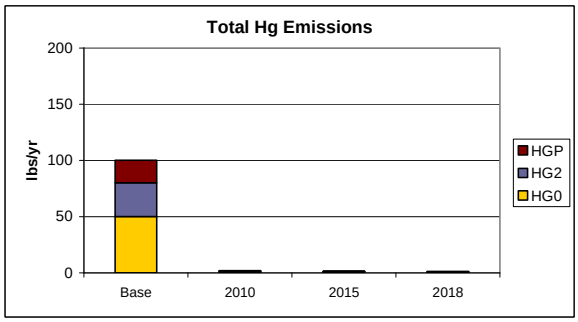


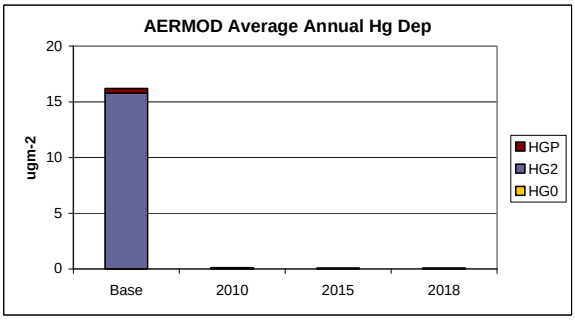


* Average over 3km sq. area surrounding facility.

Figure 6-12. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Possum Point Power Station.

(a) (b)

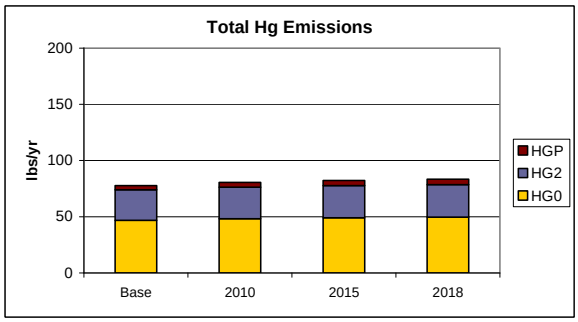


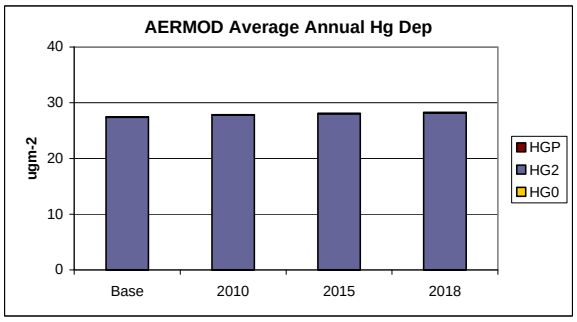


* Average over 3km sq. area surrounding facility.

Figure 6-13. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Stone Container Enterprises (Smurfit).

(a) (b)

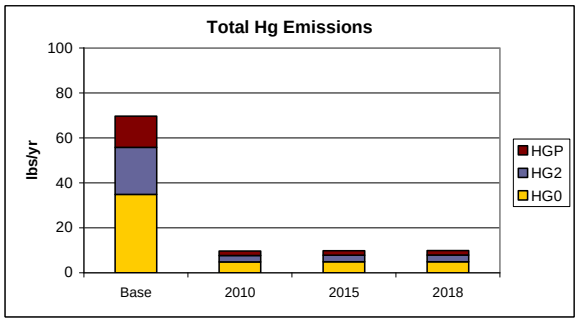


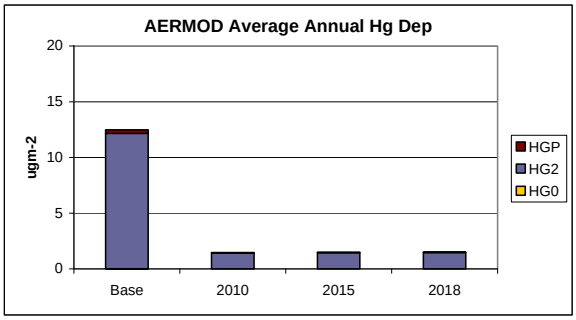


* Average over 3km sq. area surrounding facility.

Figure 6-14. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Stone Container Corporation—Hopewell.

(a) (b)

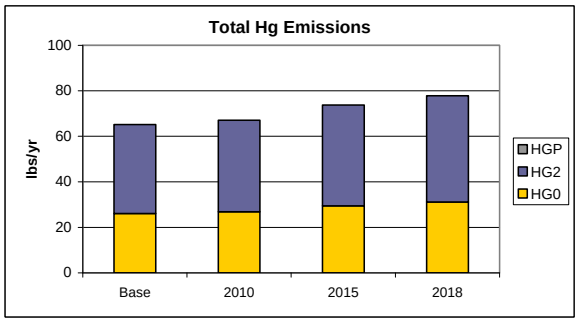


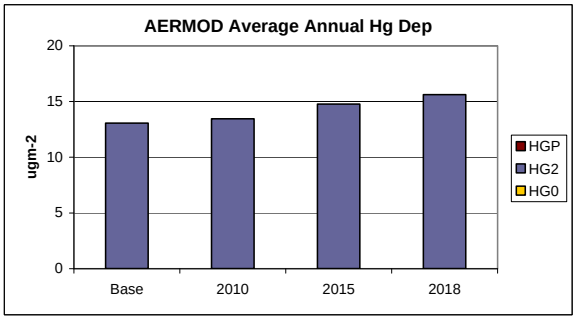


* Average over 3km sq. area surrounding facility.

Figure 6-15. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: American Electric Power—Glen Lyn.

(a) (b)

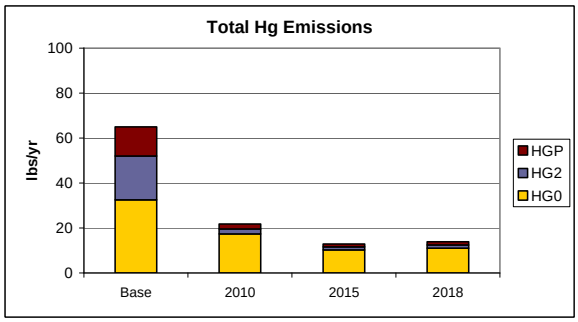


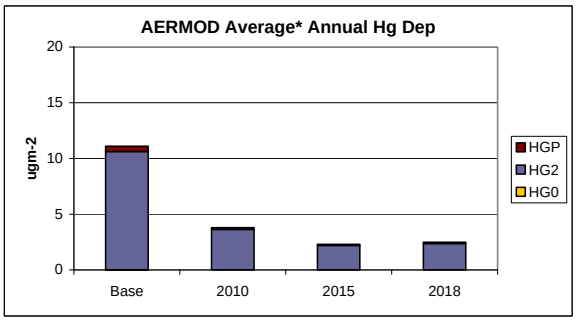


* Average over 3km sq. area surrounding facility.

Figure 6-16. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Intermet Foundry Archer Creek.

(a) (b)

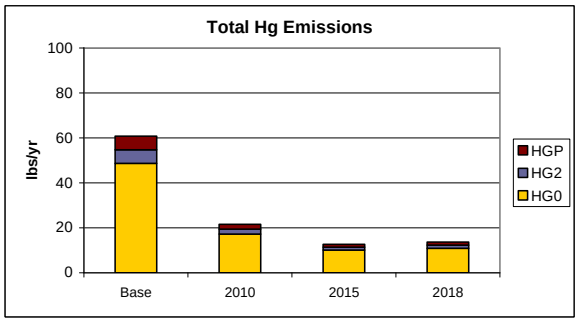


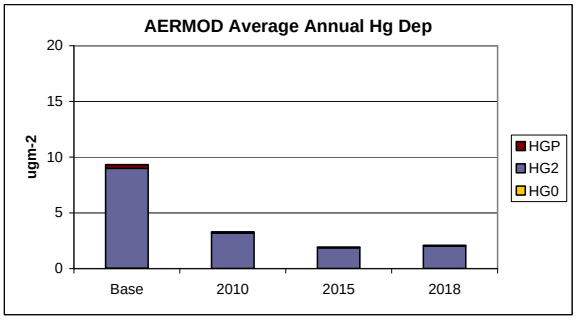


* Average over 3km sq. area surrounding facility.

Figure 6-17. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: RES dba Steel Dynamics.

(a) (b)

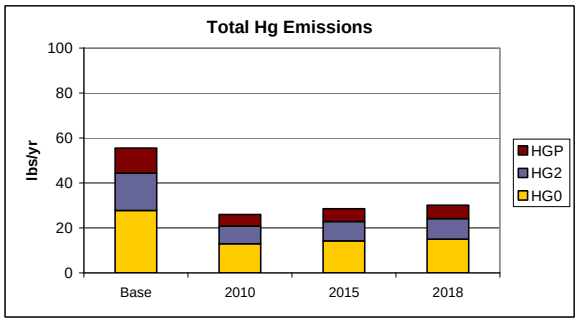


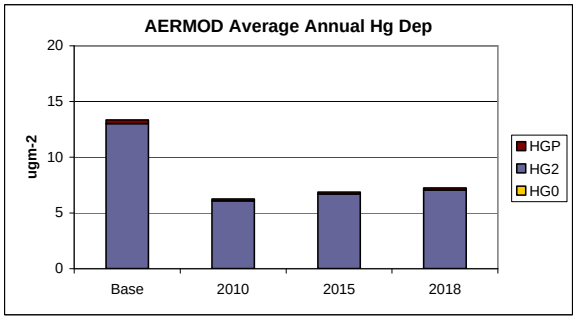


* Average over 3km sq. area surrounding facility.

Figure 6-18. AERMOD Emissions (a) and Annual Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Spruance Genco LLC.

(a) (b)





* Average over 3km sq. area surrounding facility.

The results for all facilities cannot be compared directly since the scales vary among the facilities.

For all facilities, the changes in simulated deposition track the changes in emissions quite closely, especially for HG2 and HGP. Since deposition of HG0 is small, changes in the HG0 emissions do not noticeably affect the deposition.

The largest reductions in both emissions and deposition tend to occur between the base year and 2010, but this varies by facility. Emission increases are associated with some of the facilities in 2015 and 2018 and these result in local deposition increases for the future years.

The growth and control assumptions were provided for each facility by the owner/operators and these vary by facility. A few examples follow. The changes in emissions for the Dominion Chesterfield Power Station (Figure 6-4) represent the effects of a combination of controls (scrubbers, flue gas desulfurization (FGD), and fabric filters (FF)) on the four units that comprise the power station. The emission reductions are offset by growth (apparent between 2015 and 2020). The emissions reductions for Chaparral Steel (Figure 6-5) are based on clean scrap requirements from the Electric Arc Furnace Area Source Maximum Available Control Technology (MACT) (40 CFR 63) and the permit limits for the facility. Emissions from the Dominion Bremo

plant (Figure 6-6) are projected to increase due to growth and no planned controls.[3] Non-specific planned controls account for the reductions for the AEP Clinch River facility (Figure 6-7).

Most of the local mercury deposition is in the form of HG2. A key conclusion of this analysis is that emissions reductions of HG2 at the top 15 facilities will reduce mercury deposition in the vicinity of the facilities. Additional analysis of these results is presented in Section 7.

[3] Note, however, that the Dominion Bremo plant is expected to eventually be converted to use natural gas fuel.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page

7. Summary Mercury Deposition Assessment

The mercury deposition modeling results are summarized in this section. Given the uncertainties associated with the modeling, the relative changes in both emissions and deposition are emphasized in this summary. Tables 7-1 and 7-2 summarize the emissions and mercury deposition changes simulated by CMAQ. The areas included in this summary are the CMAQ modeling domains, Virginia and the major water basins.

Table 7-1 displays the base- and future-year emissions for the 36-km grid, the 12-km grid, and Virginia. Emissions totals are given in Table 7-1a and percent reductions are given in Table 7-1b. Emissions are provided for EGU sources, non-EGU sources, non-point (area) sources, and all sources (total).

Table 7-1a. Mercury Emissions Totals (tons/year) for the CMAQ Modeling Domains and the Commonwealth of Virginia.

Region	EGU				Non-EGU				Non-Point				Total Emissions			
	2001/ 2002 *(tpy)*	2010 *(tpy)*	2015 *(tpy)*	2018 *(tpy)*	2001/ 2002 *(tpy)*	2010 *(tpy)*	2015 *(tpy)*	2018 *(tpy)*	2001/ 2002 *(tpy)*	2010 *(tpy)*	2015 *(tpy)*	2018 *(tpy)*	2001/ 2002 *(tpy)*	2010 *(tpy)*	2015 *(tpy)*	2018 *(tpy)*
36-km domain	54.8	32.1	28.7	25.6	53.4	38.6	41.5	44.8	7.9	6.9	7.3	7.8	116.1	77.5	77.6	78.1
12-km domain	22.6	9.5	8.0	7.3	15.5	10.4	11.0	11.6	2.2	2.1	2.2	2.2	40.3	22.0	21.1	21.2
Virginia	0.69	0.43	0.42	0.39	0.49	0.33	0.30	0.31	0.19	0.14	0.15	0.15	1.37	0.90	0.87	0.85

Notes:

(1) Emissions included in the 36-km and 12-km domains are for the U.S. only

(2) Point Source: 2002 emissions for Virginia are based on VDEQ 2002/EPA NEI 2002 Version 3 and the emissions for other state are based on the EPA 2002 NEI Version 3; 2010, 2015 and 2018 emissions for State of Virginia are based on VDEQ data, the emissions for other state are based on the EPA Clear Sky data

(3) Non-Point Source: 2002 Emissions are based on EPA 2002 NEI Version 3; 2010, 2015 and 2018 Emissions are based on the EPA Clear Skies data

Table 7-1b. Percent Change in Mercury Emissions Totals Compared to 2001/2002 for the CMAQ Modeling Domains and the Commonwealth of Virginia.

Region	EGU			Non-EGU			Non-Point			Total Emissions		
	2010 (%)	2015 (%)	2018 (%)	2010 (%)	2015 (%)	2018 (%)	2010 (%)	2015 (%)	2018 (%)	2010 (%)	2015 (%)	2018 (%)
36-km domain	-41.4	-47.6	-53.2	-27.7	-22.3	-16.1	-12.6	-7.6	-1.3	-33.2	-33.2	-32.7
12-km domain	-57.9	-64.6	-67.7	-32.9	-29.0	-25.2	-4.5	0	0	-45.4	-47.6	-47.4
Virginia	-37.7	-39.1	-43.5	-32.6	-38.8	-36.7	-26.3	-21.1	-21.1	-34.3	-36.5	-37.9

The majority of the emissions reductions are expected by 2010. These reflect expected reductions due to the Phase I CAIR controls and the original CAMR control provisions for the EGU sector and for those non-EGU units that are subject to CAIR. For the U.S. portion of the 36-km domain, compared to 2002, mercury emissions from EGUs are expected to drop by 41 percent in 2010 and by over 50 percent by 2018. For non-EGUs across the U.S., the mercury emissions are expected to be reduced by 28 percent in 2010, but increase slightly in 2015 and 2018 due to expected growth in the industrial sector. The non-point sector, which includes such sources as

residential/industrial fuel combustion, fluorescent lamp breakage, health services, agricultural production, waste disposal, landfills, and other combustion sources, are expected to decrease slightly (13.5 percent) in 2010, but increase slightly in 2015 and 2018 due to expected increases in population. Given the expected changes in the various sectors, total mercury emissions across the U.S. are expected to decrease by about 33 percent in 2010 and beyond compared to 2002. For the 12-km resolution domain, the mercury emissions from EGUs are expected to drop by a larger percentage in 2010 (~58 percent) due to the proximity of a large number of EGU sources in the Ohio River valley. In 2015 and 2018, further reductions are expected from the EGU sector. Similar to what is expected across the U.S., the non-EGU sector shows a substantial reduction in mercury emissions in 2010 (~33 percent), but a slight increase in 2015 and 2018, reflecting expected industrial growth. The total mercury emissions in the 12-km grid show about a 46 percent reduction in 2010 and beyond, compared to 2002. For Virginia, mercury emissions from EGUs are expected to be reduced by ~40 percent by 2010, with additional reductions in 2015 and 2018. For the non-EGU sector in Virginia, mercury emissions are expected to be reduced by about 32 percent in 2010, decrease further in 2015, but slightly increase in 2018. For the non-point sector in Virginia, mercury emissions are expected to decrease by about 24 percent in 2010 and basically stay the same beyond that. For Virginia, total mercury emissions are expected to decrease by about 34 percent in 2010, and slight decrease in 2015 and 2018.

Table 7-2 summarizes CMAQ-simulated base and future-year mercury deposition for Virginia and each of the major river basins. Deposition amounts (per unit area) are given in Table 7-2a and percent reductions are given in Table 7-2b. The values for Virginia and each river basin are calculated separately based on the simulated deposition within each region and the area encompassed by the region.

Table 7-2a. Mercury Deposition Totals (g km^{-2}) for Virginia and the Ten Major River Basins.

Region	2001/2002 (g km^{-2})	2010 (g km^{-2})	2015 (g km^{-2})	2018 (g km^{-2})
Virginia	22.7	18.6	18.2	18.1
Chesapeake Bay	15.0	12.8	12.6	12.5
Chowan River Basin & Dismal Swamp	22.7	18.5	18.0	18.0
James River Basin	22.5	18.9	18.5	18.4
New River Basin	24.4	21.4	21.0	20.9
Potomac River Basin	27.1	19.7	19.3	18.9
Rappahannock River Basin	21.9	17.6	17.2	17.1
Roanoke River Basin	22.3	18.1	17.5	17.4
Shenandoah River Basin	23.9	19.1	18.7	18.6
Tennessee & Big Sandy River Basins	25.1	21.2	20.7	20.4
York River Basin	22.8	18.7	18.3	18.1

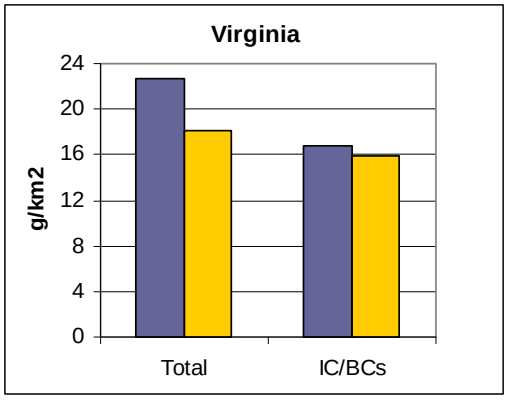
Table 7-2b. Percent Change in Mercury Deposition Totals (g km^{-2}) Compared to the 2001/2002 Base Scenario for Virginia and the Ten Major River Basins.

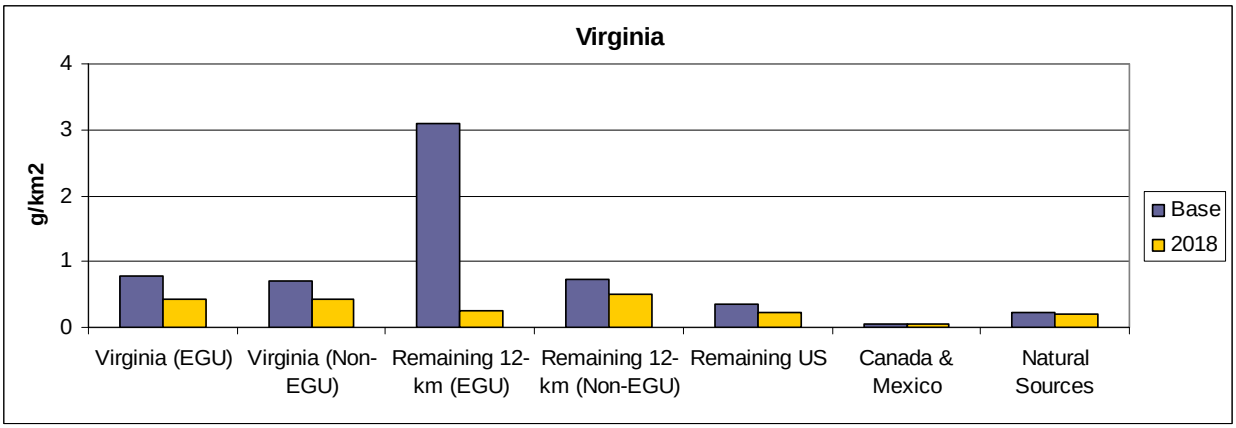
Region	2010 (%)	2015 (%)	2018 (%)
Virginia	-18.0	-19.9	-20.5
Chesapeake Bay	-14.8	-16.4	-16.7
Chowan River Basin & Dismal Swamp	-18.6	-20.6	-20.8
James River Basin	-16.3	-17.9	-18.2
New River Basin	-12.4	-13.9	-14.4
Potomac River Basin	-27.2	-28.8	-30.1
Rappahannock River Basin	-19.8	-21.6	-22.0
Roanoke River Basin	-18.5	-21.3	-21.7
Shenandoah River Basin	-20.0	-21.8	-22.0
Tennessee & Big Sandy River Basins	-15.7	-17.6	-18.7
York River Basin	-18.0	-19.9	-20.5

On a percentage basis, the greatest amount of reduction is simulated for the Potomac River Basin and the least amount is simulated for the New River Basin. In keeping with the emissions changes, the largest reductions in deposition occur between the base year and 2010.

In Section 5, the CMAQ/PPTM results showed the relative contribution from each of the tagged source regions and source categories to mercury deposition within each river basin for both 2001/2002 and 2018. Figure 7-1 presents this same information for the entire state. Again this shows that global background (IC/BC tag) is a primary contributor to simulated mercury deposition. The second largest contribution is from EGU sources in the surrounding states. This is followed by EGU sources in Virginia, non-EGU sources in Virginia, non-EGU sources in the surrounding states, sources in the remainder of the U.S., and natural sources.

Figure 7-1. CMAQ/PPTM 12-km Mercury Tagging Results for Virginia for 2001/2002 and 2018.





The contributions from all sources are lower for 2018. Although the IC/BC and natural emissions inputs are the same for both years, their contributions are lower for 2018 due to lower regional-scale ozone concentrations in the future year. Of primary interest is for this analysis is the change in contribution from the non-background/anthropogenic sources.

Table 7-3 summarizes the percent reduction for each tagged source region or category for 2018, relative to the contribution for that same category for the base scenario.

Table 7-3. Percent Change in Mercury Deposition Totals and Contributions (g km^{-2}) for 2018 Compared to the 2001/2002 Base Scenario, for Virginia and the Ten Major River Basins.

Region	Total (%)	Virginia (EGU) (%)	Virginia (Non-EGU) (%)	Remaining 12-km (EGU) (%)	Remaining 12-km (Non-EGU) (%)	Remaining US (%)	Canada & Mexico (%)	IC/BCs (%)	Natural Sources (%)
Virginia	-20.4	-43.3	-38.1	-91.6	-29.7	-37.0	-4.0	-5.0	-15.1
Chesapeake Bay	-16.7	-55.4	-9.6	-88.2	-12.4	-29.7	-3.6	-4.4	-11.0
Chowan River Basin & Dismal Swamp	-20.8	-46.2	-50.9	-89.5	-52.9	-33.8	-3.5	-4.8	-14.0
James River Basin	-18.2	-30.7	-37.9	-91.2	-27.2	-34.8	-4.3	-4.9	-15.2
New River Basin	-14.4	-5.0	-26.7	-89.9	-39.9	-41.6	-5.3	-5.0	-16.3
Potomac River Basin	-30.1	-68.6	-37.0	-93.0	-4.0	-28.3	-2.8	-4.6	-14.6
Rappahannock River Basin	-22.0	-48.4	-37.5	-92.3	-8.1	-30.5	-2.9	-4.6	-14.6
Roanoke River Basin	-21.7	-12.9	-44.1	-90.6	-24.8	-38.5	-5.8	-5.4	-16.0
Shenandoah River Basin	-22.0	-38.2	-56.3	-93.1	-29.8	-33.0	-3.6	-4.4	-16.0
Tennessee & Big Sandy River Basins	-18.7	-50.5	-13.9	-91.0	-53.8	-49.1	-5.8	-5.8	-16.5
York River Basin	-20.5	-50.4	-24.7	-91.5	-7.1	-30.7	-3.1	-4.8	-14.5

These results show that the 20.4 percent reduction in mercury deposition for Virginia is associated with a 43.3 percent reduction in deposition from EGU sources in the state, a 38.1 percent reduction in deposition from non-EGU sources in the state, a 91.6 percent reduction in deposition from EGU sources in the surrounding states, etc.

Since each of the source regions and categories contribute different amounts to the total mercury deposition, it is also of interest to attribute the overall change in total deposition to the change in contribution from each tagged region or category. This information is summarized in Table 7-4. Since the emissions changes are similar for all three future-years, it is expected that the attribution of the changes for 2018 can be applied for all years.

Table 7-4. Portion of Overall Percent Reduction in Mercury Deposition for 2018 Attributable to Each Tagged Source Region and Category, for Virginia and the Ten Major River Basins.

Region	Virginia (EGU) (%)	Virginia (Non-EGU) (%)	Remaining 12-km (EGU) (%)	Remaining 12-km (Non-EGU) (%)	Remaining US (%)	Canada & Mexico (%)	IC/BCs (%)	Natural Sources (%)
Virginia	7.2	5.7	61.0	4.6	2.8	0.0	18.0	0.8
Chesapeake Bay	7.4	1.4	62.7	3.1	2.6	0.1	20.0	0.7
Chowan River Basin & Dismal Swamp	9.2	13.9	45.1	10.4	2.3	0.0	16.6	0.7
James River Basin	8.4	8.5	54.9	3.5	2.7	0.1	20.4	0.8
New River Basin	0.6	2.4	55.6	5.0	5.4	0.1	28.9	1.2
Potomac River Basin	14.8	4.2	68.8	0.8	1.1	0.0	9.0	0.4
Rappahannock River Basin	5.1	3.3	72.1	1.2	1.9	0.0	15.1	0.7
Roanoke River Basin	0.6	5.2	68.7	2.5	2.8	0.0	18.8	0.8
Shenandoah River Basin	0.9	3.4	73.6	3.7	2.0	0.0	15.2	0.7
Tennessee & Big Sandy River Basins	12.2	1.2	44.3	9.9	6.4	0.1	23.8	1.0
York River Basin	11.1	5.1	62.3	1.0	2.0	0.0	16.6	0.7

Rather than summarizing the percent change in deposition for each individual tag, Table 7-4 gives the percent change in overall total deposition that is attributed to each tag. Based on this method of summarizing the reduction in mercury deposition, 7.2 percent of the overall simulated mercury reduction for Virginia is attributable to reductions in the emissions from EGU sources in the state, 5.7 percent is attributable to reductions in the emissions from non-EGU sources in the state, 61 percent is attributable to reductions in emissions from EGU sources in the surrounding states, etc. The results are different for each of the major river basins, but in all cases reductions in the emissions from EGU sources in the surrounding states are important to the overall reduction in mercury deposition.

In this study, AERMOD was used to examine the effects of emissions changes on local deposition. Tables 7-5 and 7-6 summarize these results in terms of the changes in emissions and simulated deposition amounts, on average, for the fifteen facilities in Virginia with the most mercury emissions in 2002. In addition, the average over the EGU and non-EGU facilities was also examined. Eight of the top fifteen facilities are EGUs and seven are in the non-EGU category.

Table 7-5 displays the average base and future emissions for the AERMOD sources (refer to Table 4-4 for more detail). Average emissions by category are given in Table 7-5a and percent reductions are given in Table 7-5b.

Table 7-5a. Average Mercury Emissions (lbs/yr) for the Top 15 Mercury Emitters in the Commonwealth of Virginia, Based on Emissions for 2002.

Grouping	2001/2002 (lbs/yr)	2010 (lbs/ yr)	2015 (lbs/yr)	2018 (lbs/yr)
EGU Sources (8)	154.3	95.5	91.6	84.4
Non-EGU Sources (7)	103.8	52.4	43.4	44.0
All 15 Sources	130.7	75.4	69.1	65.5

Table 7-5b. Percent Change in Mercury Emissions (lbs per year) for the Top 15 Mercury Emitters in the Commonwealth of Virginia, Based on Emissions for 2002.

Grouping	2010 (%)	2015 (%)	2018 (%)
EGU Sources (8)	-35.0	-36.6	-43.8
Non-EGU Sources (7)	-47.3	-52.8	-51.7
All 15 Sources	-40.7	-44.2	-47.5

Both EGU and non-EGU emissions are substantially reduced in all three future years. The largest reductions in both emissions and deposition tend to occur between the base year and 2010.

Table 7-6 summarizes the AERMOD-simulated deposition for the future-year scenarios, in terms of percent reduction for each grouping of sites.

Table 7-6. Percent Change in AERMOD Mercury Deposition Totals (μg m^{-2}) Compared to the 2001/2002 Base Scenario.

Grouping	2010 (%)	2015 (%)	2018 (%)
EGU Sources (8)	-37.3	-37.8	-49.9
Non-EGU Sources (7)	-45.8	-54.3	-53.8
All 15 Sources	-40.6	-44.1	-51.4

For this subset of sources, the local reduction in mercury deposition from non-EGU sources is, on average, greater than that for EGU sources. This is consistent with a greater reduction in emissions for the non-EGU sources.

We can qualitatively compare these results to the CMAQ modeling results. The CMAQ/PPTM results indicate that a 53 percent reduction in EGU mercury emissions for Virginia sources between 2002 and 2018 reduces the contribution of these EGU emissions to statewide mercury deposition by about 43 percent. The AERMOD results indicate that a 44 percent reduction in EGU emissions from the highest emitting sources reduces local mercury deposition by about 50 percent. For non-EGU sources, a 27 percent reduction in non-EGU mercury emissions for all Virginia sources between 2002 and 2018 reduces the contribution of these emissions to statewide mercury deposition by about 38 percent. The AERMOD results indicate that a 52 percent reduction in non-EGU emissions from the selected sources reduces local mercury deposition in the vicinity of these sources by about 54 percent. When compared in a relative sense, the CMAQ and AERMOD modeling results agree very well. The AERMOD results indicate that mercury reductions from a given facility within the state will reduce local mercury deposition by a percentage that is similar to the emissions reductions. On a statewide basis, the CMAQ results indicate that the average reduction in mercury deposition from facilities within the state is comparable, on a percentage basis, to the average emissions reduction. Both models indicate that in-state controls are effective in reducing the in-state contribution to mercury deposition.

8. References

Amar, P., D. Chock, A. Hansen, M. Moran, A. Russell, D. Steyn and W. Stockwell. 2005. "Second Peer Review of the CMAQ Model." Prepared for the Community Modeling and Analysis System Center, Carolina Environmental Program, Chapel Hill, North Carolina.

Boylan, J. 2005. "PM Model Performance Goal and Criteria." Presented at the National RPO Meeting, Denver Colorado.

Boylan, J. W. and A. G. Russell. 2006. PM and light extinction model performance metrics, goals, and criteria for three-dimensional air quality models. *Atmos. Environ.*, 40(26), 4946-4959.

Brieman, L., J. H. Friedman, R. A. Olshen, and C. J. Stone. 1984. Classification and Regression Trees. Wadsworth, Belmont, California.

Bullock, O.R., D. Atkinson, T. Braverman, K. Civerolo, A. Dastoor, D. Davignon, C. Hogrefe, J. Ku, K. Loman, T. Myers, C. Seigneur, N. Selin, G. Sistla and K. Vijayaraghavan. 2008. The North American mercury model intercomparison study (NAMMIS). (Parts 1 and 2 submitted to the Journal of Geophysical Research.)

Bullock, O.R., Brehme, K.A. 2002. Atmospheric mercury simulation using the CMAQ model: formulation description and analysis of wet deposition results. *Atmos. Environ.,* 36, 2135–2146.

Byun, D. W. and J. K. S. Ching. 1999. "Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System." U.S. EPA Office of Research and Development, Washington, D.C. (EPA/600/R-99/030).

Cohen, Mark. 2004. "Modeling the Fate and Transport of Atmospheric Mercury in the Chesapeake Bay Region." Presented at the NOAA Chesapeake Bay Office, Annapolis, Maryland (17 May).

Cohen, M., R. Artz, R. Draxler, P. Miller, L. Poissant, D. Niemi, D. Ratte, M. Deslauriers, R. Duval, R. Laurin, J. Slotnick, T. Nettesheim and J. McDonald. 2004. Modeling the atmospheric transport and deposition of mercury to the Great Lakes, *Environ. Res.*, 95, 247-265.

Dolwick, P., R. Gilliam, L. Reynolds and A. Huffman. 2007. Regional and local-scale evaluation of the 2002 MM5 meteorological fields for various air quality modeling applications. Extended abstract for the 6th Annual CMAS Conference, Chapel Hill, North Carolina (1-3 October).

Douglas, S., T. Myers and Y. Wei. 2006. "Implementation of Mercury Tagging in the Community Multi-scale Air Quality Model." Prepared for the U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. ICF International, San Rafael, California (06-051).

EPA. 1998. "User's Guide for the AERMOD Meteorological Preprocessor (AERMET)." EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.

EPA, 2003. "Technical Support Document for the Clear Skies Act 2003 Air Quality Modeling Analyses." EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.

EPA. 2004. "User's Guide for the AMS/EPA Regulatory Model—AERMOD." EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina (EPA-454/B-03-001).

EPA. 2005a. Technical Support Document for the Final Clean Air Mercury Rule: Air Quality Modeling, EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, March 2005. (http://www.epa.gov/ttn/atw/utility/aqm_oar-2002-0056-6130.pdf)

EPA. 2005b. Emissions Inventory and Emissions Processing for the Clean Air Mercury Rule (CAMR). EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, March 2005. (http://www.epa.gov/ttn/atw/utility/emiss_inv_oar-2002-0056-6129.pdf).

EPA. 2005c. "AERMOD Implementation Guide." EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.

EPA. 2006a. "Addendum User's Guide for the AMS/EPA Regulatory Model—AERMOD." EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.

EPA. 2006b. "Guidance on the Use of Models and Other Analyses for Demonstrating Attainment of Air Quality Goals for Ozone, $PM_{2.5}$, and Regional Haze," Draft 3.2, EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina (September 2006).

EPA. 2006c. "Addendum User's Guide for the AERMOD Meteorological Preprocessor (AERMET)." EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.

EPA. 2007a . EPA Toxics Release Inventory (TRI) data available at: http://www.epa.gov/tri/tridata.

EPA. 2007b. Personal communications with Ann Pope, EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina (April 2007).

EPA. 2007c . "AERSURFACE User's Guide." Draft Version.

McNally, D. 2003. "Annual Application of MM5 for Calendar Year 2001." Prepared for the U.S. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Myers, T., Wei, B. Hudischewskyj, J. Haney, and S. Douglas. 2006. "Model-Based Analysis and Tracking of Airborne Mercury Emissions that May Contribute to Water Quality Impacts." Prepared for the U.S. Environmental Protection Agency, Office of Water, Washington, D.C. ICF International, San Rafael, California (06-077).

NADP. 2008. Web site address: http://nadp.sws.uiuc.edu/mdn/.

NOAA. 2007. Web page on atmospheric deposition: http://noaa.chesapeakebay.net.

Salford Systems. 2007. CART user's guide online at: http://www.salford-systems.com/doc/CARTtrifold.ddf

Seigneur, C., P. Karamchandani, K. Lohman, K. Vijayaraghavan, and R. Shia. 2001. Multiscale modeling of the atmospheric fate and transport of mercury. *J. Geophys. Res.*, 106, 27,795-27,809.

Shia, R., C. Seigneur, P. Pai, M. Ko, and N. D. Sze. 1999. Global simulation of atmospheric mercury concentrations and deposition fluxes. *J. Geophys. Res.*, 99 , 23,747–23,760.

Steinberg, D., and P. Colla. 1997. CART—Classification and Regression Trees. Salford Systems, San Diego, CA.

Wesely, M. L., P. V. Doskey, and J. D. Shannon. 2002. "Deposition Parameterizations for the Industrial Source Complex (ISC3) Model." Environmental Research Division, Argonne National Laboratory, Argonne, Illinois (ANL/ER/TR-01/003).

Appendix A: Modeling Protocol

Virginia Department of Environmental Quality

Protocol for Mercury Deposition Modeling for the Virginia Mercury Study

Last Updated: February 28, 2008

07-027

Passion. Expertise. Results.

Virginia Department of Environmental Quality

Protocol for Mercury Deposition Modeling for the Virginia Mercury Study

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1. Introduction and Modeling Study Design

This protocol document outlines the methods and procedures followed in conducting mercury deposition modeling for the Commonwealth of Virginia. The initial version of this protocol document was prepared at the beginning of the study and was intended to provide a basis for study participants to review and comment on all aspects of the modeling analysis including the modeling tools and databases, modeling domain and simulation period, modeling procedures, quality assurance procedures, schedule, and communication structures. The protocol was used throughout the study to guide the progress of the modeling analysis and decisions made as the work progressed. This final version of the protocol document reflects the changes to the modeling approach and schedule that were incorporated throughout the study, such that all aspects of the modeling project are now accurately documented and the protocol can serve as a reference for future work and other studies. Although there are no current EPA guidelines for mercury deposition modeling, the modeling protocol and the modeling practices were designed to be consistent, wherever applicable, with current EPA guidelines for ozone and fine particulate modeling (EPA, 2006a).

This section of the protocol document summarizes the background and objectives of the study and provides an overview of the modeling study, including the modeling approach, project management and communication structures, schedule and deliverables for the study.

1.1. Background and Objectives

Human exposure to mercury is most commonly associated with the consumption of contaminated fish. Due to measured high levels of mercury in fish, at least 44 U.S. states have, in recent years, issued fish consumption advisories. These advisories typically suggest limits on the consumption of certain types of fish or recommend limiting or not eating fish from certain bodies of water because of unsafe levels of mercury contamination. States have identified more than 6,000 individual bodies of water as mercury impaired and have issued mercury fish advisories for more than 2,000 individual bodies of water.

Until 2002, significant mercury contamination in Virginia surface waters was known only in three rivers (the North Fork of the Holston River, the South River, and the South Fork of the Shenandoah River) and was associated with historical industrial releases. Since then, however, state monitoring efforts have identified mercury contamination in a number of surface waters without readily identifiable sources.

The Virginia Department of Environmental Quality (VDEQ) expanded its mercury monitoring in 2002 based on an increasing scientific understanding of mercury's environmental chemistry and discoveries in other states (e.g., Florida, Maryland) of mercury pollution in water bodies without direct sources. The 2002 monitoring effort focused on rivers of the coastal plain, mostly to the east of Interstate 95. As a result of this effort, Virginia found elevated mercury levels in some fish in the Blackwater River, the Great Dismal Swamp Canal, the Dragon Run Swamp, and the Piankatank River. Consistent with findings from Florida and elsewhere, these water bodies in Virginia possess characteristics favorable for the formation of the highly bio-accumulative form of mercury, methyl mercury. These characteristics include low dissolved oxygen, high organic matter, and low pH, and are most prevalent in the "backwaters" of the southeastern portion of the state.

The primary source of mercury to these water bodies is suspected to be atmospheric deposition. Until recently, there were three Mercury Deposition Network (MDN) sites located in Virginia, in Shenandoah National Park, Culpeper, and Harcum (the Culpeper site was discontinued in 2006). Data from these sites have contributed to the regional characterization of mercury transport and

wet mercury deposition in the Commonwealth. Additional monitoring at the Harcum site in 2005 revealed that dry deposition of reactive gaseous (divalent) mercury along the Piankatank River (near the Chesapeake Bay) and in upstream areas is an important contributor to the high mercury levels observed in the water and fish in the area.

Global, regional, and local sources of air mercury emissions contribute to the deposition, and understanding these contributions is an important step toward identifying measures that will effectively reduce mercury deposition and environmental mercury levels.

A key objective of the mercury deposition modeling analysis was to examine and quantify the contribution of regional and local emissions sources to mercury deposition throughout the Commonwealth, and to provide information to support the further analysis of the impact of mercury deposition on the environment.

For each of the bodies of water listed as impaired by Virginia, the Clean Water Act calls for the calculation of a Total Maximum Daily Load (TMDL). TMDLs identify the pollutant reductions or limits that are needed in order to achieve water quality standards. TMDLs must also allocate the reductions to the different sources of pollution, including air sources. Thus another key objective of the data and modeling analyses was to provide information that will enable VDEQ to conduct future TMDL studies.

Finally, the results of this study will also be used to support VDEQ's evaluation of potential measures needed to reduce mercury emissions in Virginia. Specifically, the data and modeling analysis results will allow VDEQ to evaluate the effectiveness of planned control measures and support the development of management strategies for meeting water quality criteria and protecting human health. A detailed analysis of mercury emissions inventory data was also conducted to supplement and enhance the overall reliability of the modeling study.

1.2. Conceptual Description of the Mercury Deposition Problem

A separate conceptual description report was prepared as part of the mercury deposition modeling study. This separate report includes an overview of mercury deposition, a summary of observed mercury deposition for Virginia and the surrounding states, and an analysis of meteorological and emissions related influences. The conceptual description has improved the overall understanding of the mercury problem and the relationships between meteorology and mercury deposition. The development of the conceptual model included the use of the Classification and Regression Tree (CART) analysis method (Brieman, 1984; Steinberg & Colla, 1997) to probe the relationships between meteorology and mercury deposition.

Mercury deposition data are available for three Mercury Deposition Network (MDN) sites in Virginia: Culpeper, Shenandoah National Park, and Harcum. The period of record for the MDN data is late 2002 through 2006 for Culpeper, late 2002 to present for Shenandoah, and approximately 2005 to present for the Harcum site. The Culpeper site is located in central Virginia, the Shendandoah site is located in mountainous northwestern Virginia, and the Harcum site is located along the southern portion of the inner coast of the Chesapeake Bay. Each measurement of wet deposition represents an approximate seven-day period. The conceptual model was developed based on data through 2005 and a portion of 2006 (based on the availability of the MDN data). Annual mercury wet deposition for these sites and for this period is summarized in Table 1-1.

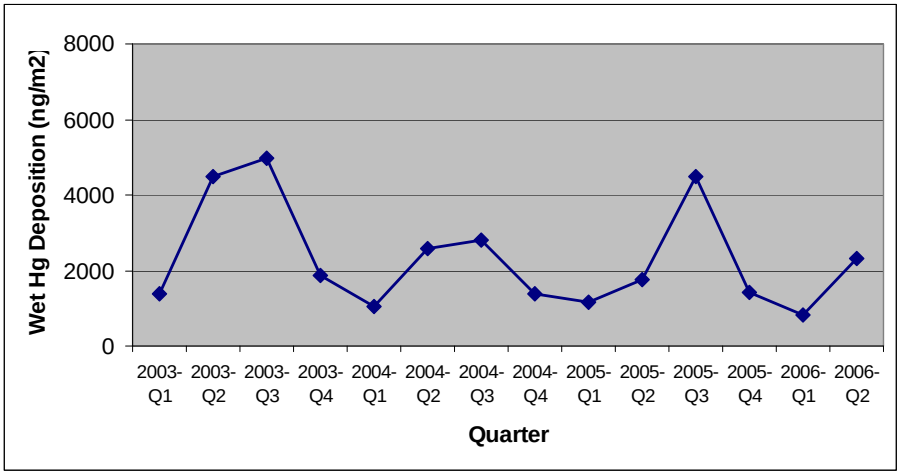
Table 1-1. Summary of Annual Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

Site Name (MDN ID)	Annual Observed Mercury Wet Deposition (ng m^{-2})		
	2003	2004	2005
Culpeper (VA08)	13,097	7,784	8,811
Shenandoah National Park (VA28)	11,922	9,727	7,074
Harcum (VA98)	—	—	8,218

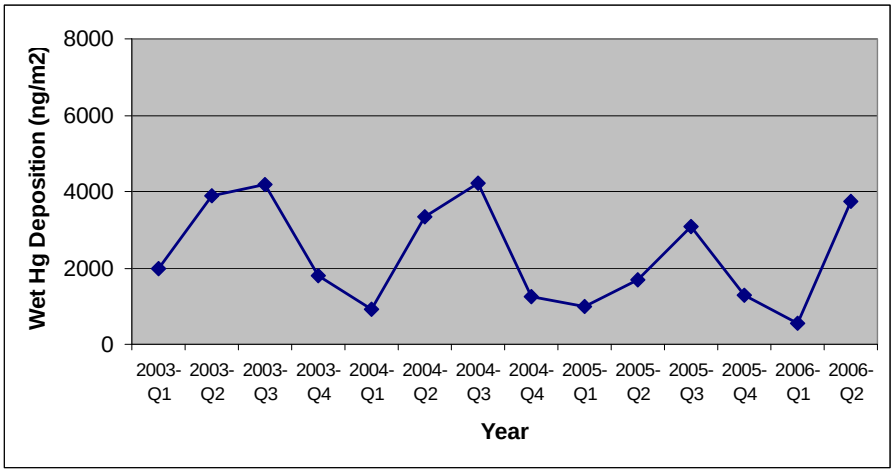
Within each calendar year, there are variations in deposition by week, month and quarter, primarily in accordance with variations in rainfall amount. Figure 1-1 suggests that mercury deposition (and thus rainfall amounts) appear to have an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively).

Figure 1-1. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

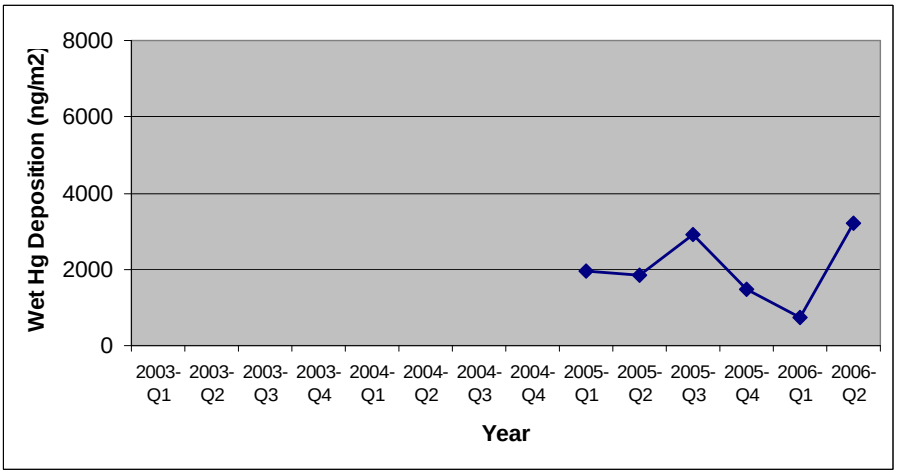
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



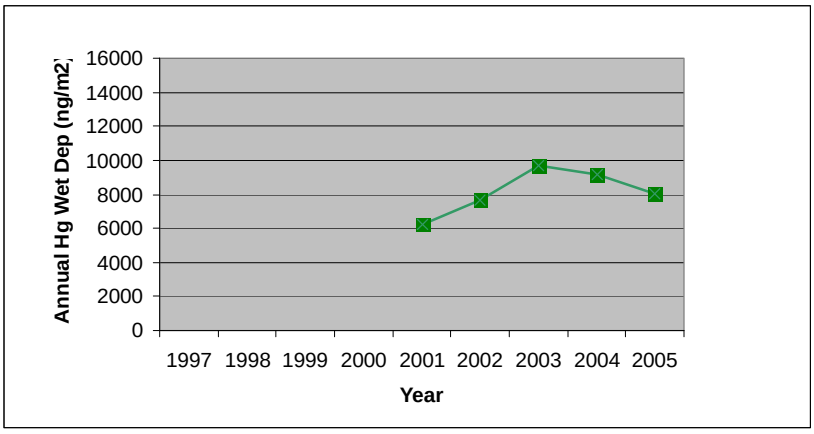
(c) Harcum (VA98)



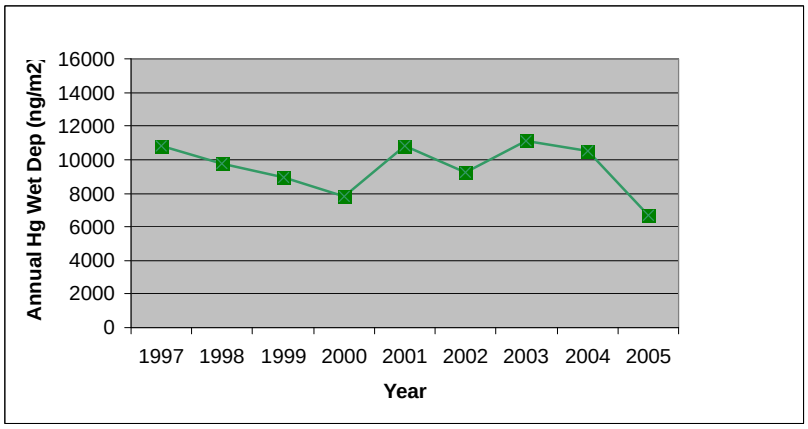
With only three full calendar years of data, it is difficult to assess annual variations and trends. Several MDN sites in nearby Pennsylvania and North Carolina have a somewhat longer period of record. These include Arendtsville, Pennsylvania (near Gettysburg, along the PA/MD border), Allegheny Portage Railroad National Historic Park in the southern Allegheny Mountains of Pennsylvania, and Pettigrew State Park in coastal, northeastern North Carolina. In addition to having longer data records, these sites also have some geographical similarities (with respect to location, elevation, and proximity to the coastline) to the three Virginia sites (Culpeper, Shenandoah, and Harcum, respectively). The observed annual variations in wet mercury deposition for these three neighboring sites are displayed in Figure 1-2.

Figure 1-2. Annual Observed Mercury Wet Deposition (ng m^{-2}) for Selected MDN Monitoring Sites in Pennsylvania and North Carolina.

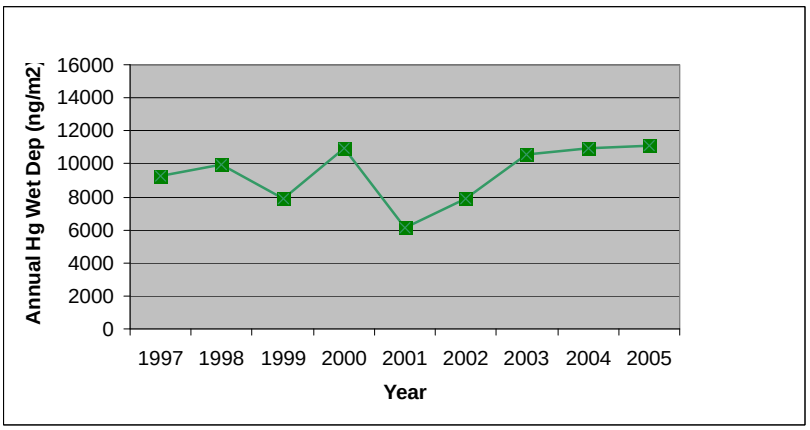
(a) Arendtsville, PA (PA00)



(b) Allegheny Portage Railroad National Historic Site, PA (PA13)



(c) Pettigrew State Park, NC (NC42)



For all three neighboring sites, there is significant year-to-year variation in mercury wet deposition and this most likely reflects year-to-year variability in the meteorological conditions, particularly rainfall. Additional analysis of the meteorology and emissions data, including the calculation of meteorologically adjusted mercury deposition trends is summarized in the conceptual model report.

1.3. Overview of the Modeling Approach

The modeling approach accounts for the different scales and chemical interactions important to mercury deposition through the combined use of a state-of-the-science regional modeling system with source-contribution-assessment capabilities, boundary conditions for the regional model based on global modeling, and Gaussian modeling for the detailed assessment of local contributions.

At the regional scale, we applied the latest version (version 4.6) of the Community Multiscale Air Quality (CMAQ) modeling system. The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere. The CMAQ modeling system supports the detailed simulation of mercury (Hg), including the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury.

The CMAQ Particle and Precursor Tagging Methodology (PPTM) for mercury was used in this study to provide detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources.

Boundary concentrations for the regional-scale modeling were extracted from global model simulation results.

At the local scale, the EPA Gaussian model AERMOD was applied for the 15 highest emitting point sources in Virginia, based on the 2002 emissions inventory. AERMOD was used to screen the top mercury emissions sources and to determine which have the potential to impact areas outside the vicinity of the source. AERMOD was then used to simulate the effects of future-year emission changes for the selected sources and their local areas.

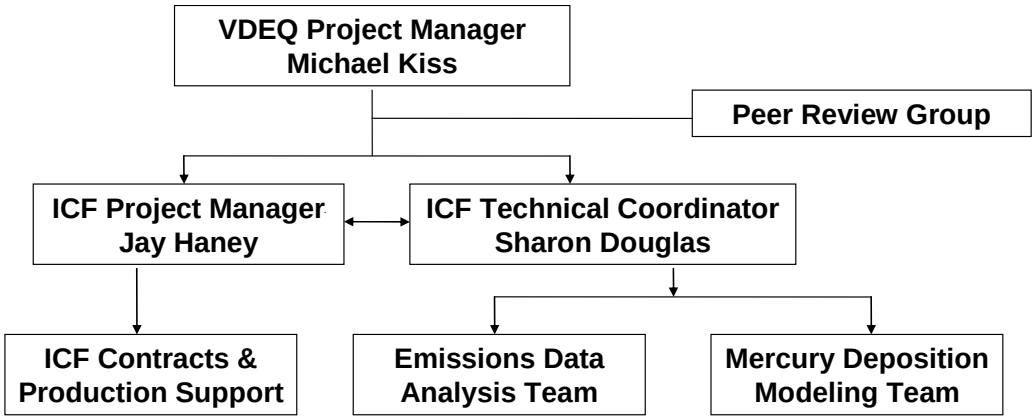
This combination of modeling tools has allowed us to address the variety of factors influencing mercury deposition in Virginia. Additional details regarding model selection, input preparation, and application and analysis procedures are provided later in the protocol document.

The modeling results provide a basis for quantifying the contribution of emissions sources to mercury deposition and examining the fate of mercury emissions from selected sources. For environmental planning purposes, the modeling results will be used by VDEQ to examine the effectiveness of control measures in reducing mercury concentrations in contaminated bodies of water and improving or maintaining water quality within the designated areas of interest in Virginia. By quantifying deposition, the modeling results will also provide a link between the analysis of mercury emissions and the assessment of the impacts of airborne mercury on fish tissue and human health.

1.4. Project Management and Communication Structures

This project was funded and managed by the Virginia Department of Environmental Quality (VDEQ). The mercury deposition modeling was conducted by ICF International. Note that the project also included a detailed analysis of mercury emissions inventory data to supplement and enhance the overall reliability of the modeling study. The overall project organization and communication structure is presented in Figure 1-3.

Figure 1-3. Project Organization Chart for the Virginia Mercury Study.



The majority of the technical work was conducted by ICF with VDEQ providing assessment and oversight. Ms. Diane Shotynski of Thruput and Mr. Tim Lavallee of LPES, Inc., both Virginia based consultants, assisted with the emission inventory review and literature search tasks.

Conference calls were held throughout the project to review project status, discuss technical issues and/or the resolution of technical difficulties. As problems were identified and corrective actions were required, ICF made the corrections to the approach or work product and documented the corrections.

ICF provided VDEQ with monthly progress reports summarizing work accomplished during each reporting period, problems encountered and how they were resolved, planned activities for the next reporting period, and status of deliverables. The monthly progress reports also included a summary of expenditures for the period and cumulative expenditures for the project.

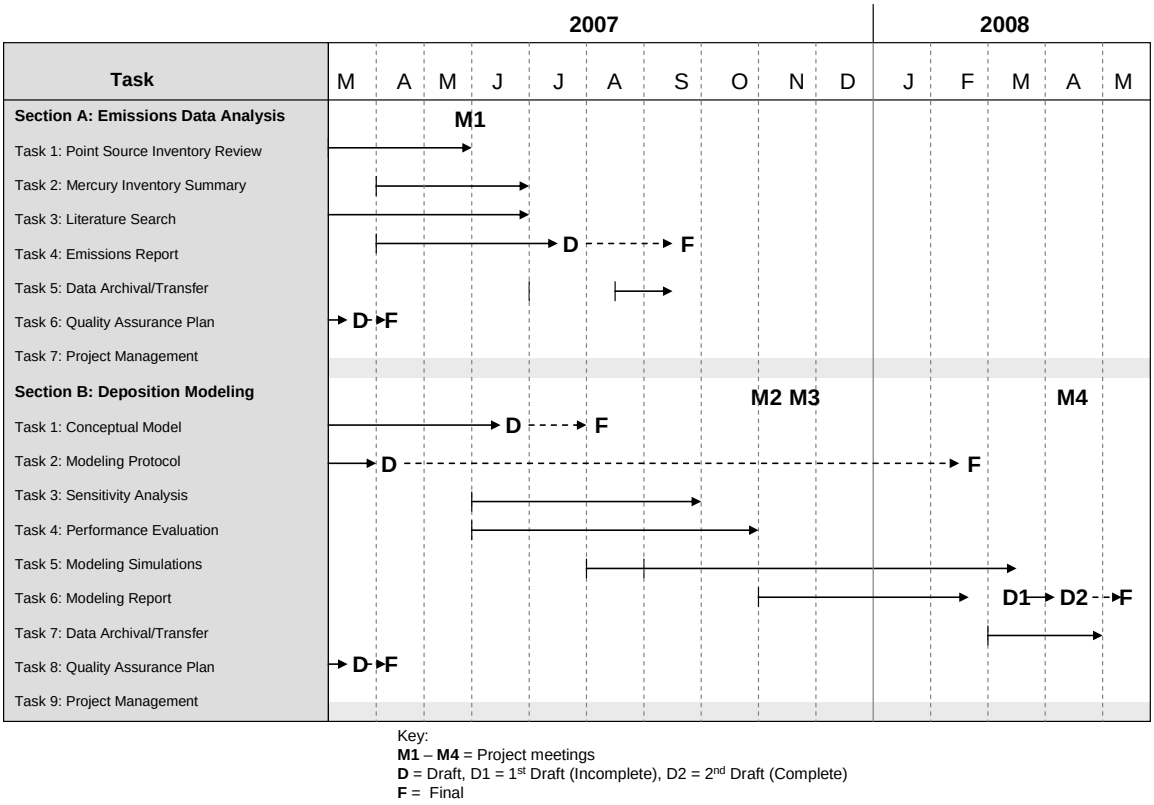
Peer review of the technical analysis, results, and reports was conducted as requested by VDEQ.

1.5. Schedule and Deliverables

The schedule for conducting the mercury deposition modeling is provided in Figure 1-4. The schedule for completing the emissions data analysis tasks is also included in this figure, since the results of this analysis were used in the modeling study.

Figure 1-4. Schedule for the Virginia Mercury Study.

(shading represents ongoing activity).



Key:
M1 – **M4** = Project meetings
D = Draft, D1 = 1st Draft (Incomplete), D2 = 2nd Draft (Complete)
F = Final

Major deliverables for work conducted under the emissions data analysis and deposition modeling components of the Virginia Mercury Study are listed and the completion dates are provided in Table 1-2.

Table 1-2a. Milestones and Deliverables for the Emissions Analysis Component of the Virginia Mercury Study.

Milestone/Deliverable	Completion Date
Tasks 1 & 2: Emissions Review & Summary	
Draft memorandum	4/4/2007
Task 3: Literature Search	
Draft memorandum	7/19/2007
Task 4: Emissions Report	
Draft emissions data analysis report	7/19/2007
Final emissions data analysis report	9/27/2007
Task 5: Data Archival/Transfer	
Transfer inventory files to VDEQ	9/29/2007
Task 6: Quality Assurance Plan	
Draft quality assurance plan	3/16/2007
Final quality assurance plan	4/6/2007
Task 7: Project Management	
Conduct 1st technical meeting	5/31/2007

Table 1-2b. Milestones and Deliverables for the Deposition Modeling Component of the Virginia Mercury Study.

Milestone/Deliverable	Completion Date
Task 1: Conceptual Model	
Draft conceptual model report	6/21/2007
Final conceptual mode report	8/2/2007
Task 2: Modeling Protocol	
Draft modeling protocol	4/6/2007
Updated modeling protocol	2/22/2008
Tasks 3: Sensitivity Analysis	
Draft report section on sensitivity analysis	3/15/2008
Task 4: Performance Evaluation	
Draft report section on model performance	3/15/2008
Tasks 5 & 6: Modeling Simulations & Report	
First draft mercury deposition modeling report	3/15/2008
Second draft mercury deposition modeling report	4/15/2008
Final mercury deposition modeling report	5/15/2008
Task 7: Data Archival/Transfer	
Transfer modeling files to VDEQ	4/30/2008
Task 8: Quality Assurance Plan	
Prepare draft quality assurance plan	3/16/2007
Prepare final quality assurance plan	4/6/2007
Task 9: Project Management	
Conduct 2nd technical meeting	11/8/2007
Conduct 3rd technical meeting	11/27-11/29/2007
Conduct 4th technical meeting	4/15/2008

2. Model Selection and Application Procedures

The modeling platform for the Virginia mercury deposition modeling study consists of three primary components: a grid-based air quality/deposition model, an emissions preprocessing system, and a Gaussian air quality model. The Community Multiscale Air Quality (CMAQ) model was used to simulate mercury deposition at the regional scale. The Sparse-Matrix Operator Kernel Emissions (SMOKE) emissions processing system was used to process the emissions for input to the CMAQ model. The EPA Gaussian model AERMOD was used to examine mercury deposition at the local scale for selected areas and sources.

The selection of modeling tools considered 1) technical formulation, capabilities, and features, 2) comprehensiveness of testing, and 3) demonstrated successful use in previous applications The rationale for selecting each of these modeling tools (in keeping with EPA guidance) is discussed in this section; an overview of each modeling tool and a brief discussion of the input requirements and application procedures are also provided. The meteorological and boundary condition inputs for this study will be obtained from prior studies and the tools used to prepare these inputs are discussed in the database section of the protocol (Section 3).

2.1. Selection and Overview of the Grid-based Mercury Deposition Model

2.1.1. Overview of CMAQ Version 4.6

The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere (Byun and Ching, 1999). The CMAQ model was designed as a “one-atmosphere” model and can be used to simulate ozone, particulate matter, and mercury. For mercury, CMAQ supports the detailed simulation of the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury. The latest version of CMAQ, version 4.6, was used for this study.

According to Bullock et al. (2007), the CMAQ model reflects the current state-of-the-science in simulating the atmospheric processes that influence the dispersion, advection, chemical transformation and deposition of mercury. The CMAQ model includes three mercury (Hg) species; elemental mercury (Hg^0), reactive gaseous mercury (RGM), and particulate mercury (PHg). RGM is known to be comprised almost entirely of divalent mercury (Hg^{2+}), since Hg compounds at other valence states tend to be chemically unstable in the atmosphere. PHg is also primarily comprised of divalent mercury, but may also include elemental mercury.

Mercury simulation capabilities were first incorporated into the CMAQ model by adding gaseous and aqueous chemical reactions involving mercury to the CMAQ chemical mechanism (Bullock and Brehme, 2002). Since that time, the chemical mechanism has been further updated to include additional reactions and updated information on reaction rates. The most recent changes to CMAQ for mercury include an improved dry deposition algorithm and the incorporation of natural mercury emissions. The CMAQ modeling system, including the mercury modeling component, has been peer reviewed (e.g., Amar et al., 2005).

In addition to the state-of-the science chemical mechanism for mercury, other key features of the CMAQ model in simulating mercury deposition include state-of-the-science advection, dispersion and deposition algorithms, the latest version of the Carbon Bond chemical mechanism (CB05), and the CMAQ Particle and Precursor Tagging Methodology (PPTM).

PPTM for mercury (Douglas et al., 2006) provides detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources.

The CMAQ model has been used by EPA to support the development of the Clean Air Mercury Rule (CAMR) (EPA, 2005a). This study included the evaluation of global modeling results to prescribe boundary conditions for CMAQ, evaluation of mercury deposition using MDN data, and assessment of the contribution of mercury emissions from coal-fired power plants on mercury deposition in the U.S.

CMAQ was also included in the North American Mercury Model Intercomparison Study (NAMMIS) for mercury (Bullock et al., 2008) and the performance and response of CMAQ was found to be reasonable and also consistent with that for the Regional Modeling System for Aerosols and Deposition (REMSAD), which has been widely applied and tested for mercury (e.g., Myers et al., 2006).

In summary, EPA (2006a) lists five factors to be considered in selecting a model for use air quality (and deposition) modeling studies. The selection of CMAQ, version 4.6, with PPTM capabilities addressed each of these factors.

- ***Documentation and past performance should be satisfactory.*** The CMAQ modeling system is well documented and comparisons with other models (e.g., Bullock et al., 2008) have demonstrated that CMAQ performance is reasonable and consistent with that for other models.
- ***The selected model should reflect the current state-of-the-science and include advanced features (e.g. source apportionment tools) as needed to support the model application.*** CMAQ version 4.6 reflects the current state-of-the-science in mercury chemistry and the PPTM feature supports the analysis of source contributions.
- ***Relevant experience of available staff and contractors should be consistent with choice of a model.*** ICF and VDEQ scientists are experienced in the use of CMAQ, including the PPTM capabilities.
- ***Time and resource constraints may be considered.*** The time and resource requirements for CMAQ are consistent with the schedule and budget for the mercury deposition analysis.
- **Consistency of the model with what was used in adjacent regional applications should be considered.** CMAQ was used by EPA for the CAMR modeling.

2.1.2. Input Requirements

The CMAQ model requires hourly, gridded input fields of several meteorological parameters including wind, temperature, water-vapor concentration, pressure, vertical exchange coefficients (K_v), cloud cover, and rainfall rate. The model also requires hourly, gridded, speciated precursor emissions as required for the simulation of ozone, particulates and mercury. In addition, the CMAQ modeling system requires specification of initial and boundary values for each species, topographic and land-use data, and photolysis rates. Several preprocessor programs are

available to aid the preparation of these input files. For this study, we used a combination of existing (from EPA) and newly derived datasets and these are described in some detail later in this section and in Section 3.

2.1.3. Application Procedures for the Virginia Mercury Deposition Modeling Study

CMAQ was applied for all gaseous, particulate, and mercury species and for the domain and simulation period discussed in Section 3 of this document. The modeling system was configured as follows:

Horizontal grid spacing:	36 & 12 km
Number of vertical layers:	14
Plume-in-grid treatment:	None
Gas phase chemical mechanism:	Carbon-Bond 05 (CB05)
Aerosol treatment:	AERO4/ISOROPIA
Mercury options	Gas and aqueous phase chemistry as implemented in CMAQ4.6; natural and reemission estimates included.
Source attribution method:	PPTM

2.2. Selection and Overview of the Emissions Preprocessing System

2.2.1. Overview of SMOKE

Model-ready mercury emissions for the application of CMAQ were prepared using the Sparse Matrix Operator Kernel Emissions (SMOKE) emissions processing system (CEP, 2004 and 2006). The SMOKE tool has been paired with CMAQ for most applications of the CMAQ modeling system to date. SMOKE is designed to convert emissions inventory data as well as calculated emissions estimates (e.g., mobile-source and biogenic emissions) into the formatted emission files required by CMAQ. Operations that are performed by SMOKE include spatial and temporal allocation of emissions, chemical speciation, and application of emissions controls.

SMOKE accounts for point-source, area-source, on-road mobile, non-road mobile, and natural (e.g., biogenic and geogenic) emissions—although not all of these are required for mercury deposition modeling. These emission components are processed separately and merged together in the final, model ready emissions inventory.

Key features of SMOKE that make it well suited for this project include 1) compatibility with CMAQ and PPTM and 2) compatibility with regional-scale mercury modeling conducted by EPA, such as the CAMR modeling (EPA, 2005b). The quality assurance and reporting features of SMOKE were used in this study. Version 2.3 of SMOKE was applied.

For this study, we used a combination of existing (EPA) and newly derived emissions datasets and these are described in some detail in this section and Section 3.

2.2.2. Input Requirements

SMOKE will accept mercury emissions data from point, area, mobile and natural/geogenic sources—as available. For this study, the input data consisted of point- and area source emissions data from version 3 of the 2002 National Emissions Inventory (NEI) for mercury and point-source data for sources in Virginia (provided by VDEQ and quality assured and updated for use in this study). Emissions for on-road and non-road mobile sources were not included since they were not available from the NEI in time for this study.

2.2.3. Application Procedures for the Virginia Mercury Deposition Modeling Study

SMOKE was used to generate hourly, gridded, speciated mercury emissions files for the domain and simulation period discussed in Section 3.

The reporting and quality assurance tools available in SMOKE were used to summarize and review the emissions and ensure the successful completion of each processing step.

SMOKE was also used to prepare the mercury tagging emissions for CMAQ PPTM using the procedures outlined by Douglas et al. (2006).

2.3. Selection and Overview of the Gaussian Plume Model

2.3.1. Overview of AERMOD

AERMOD is a steady-state Gaussian dispersion model designed to simulate the local-scale dispersion of pollutants from low-level or elevated sources in simple or complex terrain. It is an EPA “preferred” model (40 CFR Part 51, Appendix W, *Guideline on Air Quality Models*). Recent versions of AERMOD (EPA, 2006b) include algorithms for simulating deposition of gaseous and particulate pollutants. In this study, AERMOD was applied for selected point sources in the Virginia emissions inventory and was used to screen the mercury emissions sources and to determine whether they have the potential to impact areas outside the vicinity of the source. AERMOD was also used to simulate the effects of local emission changes for selected areas and sources.

The AERMOD modeling system consists of three components: the AERMOD dispersion model, the AERMET meteorological data preprocessor, and the AERMET terrain preprocessor. The dispersion algorithms are based on the fundamental concepts of planetary boundary layer meteorology. The airflow and stability characteristics (e.g., convective versus stable) as well as the vertical structure of the boundary layer are accounted for in simulating dispersion. Numerous features and options accommodate a variety of source types, pollutants, and land-use and topographical features.

Wet and dry deposition can be estimated using AERMOD. The wet deposition algorithms use a washout ratio that is dependent on precipitation rate and the properties of the pollutant being simulated. Dry deposition is based on aerodynamic resistance calculations, and the deposition velocities are calculated based on surface type and local meteorological conditions.

2.3.2. Input Requirements

AERMOD requires several input files:

The simulation control file specifies which options and features of AERMOD are to be applied, and contains information about the emissions sources (location, emissions rate, stack parameters, etc.) as well as the receptor locations (essentially the gridded geographical area over which the estimated concentrations and deposition amounts are calculated).

Two meteorological input files provide detailed information about 1) the characteristics of the boundary layer (wind, temperature, stability parameters) and 2) the vertical structure of temperature and wind near the source location. For deposition analyses, the boundary layer meteorological file includes information about pressure, relative humidity, cloud cover and precipitation.

Preparation of these inputs for the Virginia mercury study is discussed in Section 3 of this document.

2.3.3. Application Procedures for the Virginia Mercury Deposition Modeling Study

AERMOD was applied for the 15 sources in Virginia with the greatest mercury emissions and for the full annual simulation period.

The sources reflect several different types of facilities and a variety of species distributions, stack parameters, locations relative to sensitive watershed areas, and designated potentials for future control.

The receptor area for each source was defined following EPA guidance and consists of a 10 by 10 grid with grid cells of 100 x 100 m near the source that increase to 200 x 200 m and then to 500 x 500 m. The receptor area extends approximately 3000 m (3 km) in any direction of the source.

Meteorological inputs were prepared using available surface and upper-air meteorological data from nearby, geographically representative monitoring sites. The meteorological monitoring sites were paired with the source locations based on proximity, and similarities in geographical and land-use characteristics. Surface characteristics for processing of the meteorological inputs were defined based on 100 m resolutions U.S. Geological Survey (USGS) land-use data.

All other inputs to the modeling system were specified in accordance with EPA guidance on the use of AERMOD (using the EPA default parameters) (EPA, 2004). The default reactivity factor for divalent mercury was applied and the output includes information on wet, dry and total mercury deposition (EPA, 2006b).

As part of this study, sensitivity simulations were conducted to examine the sensitivity of the AERMOD results to selected input parameter specifications.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3. Simulation Period, Domain and Database Issues

3.1. Selection of the Simulation Period

Selection of the simulation period considered meteorological and emissions database availability and meteorological representativeness. The availability of meteorological inputs for CMAQ was an important factor in selecting the simulation period. Comprehensive, tested meteorological inputs for the modeling domain are available for two calendar years: 2001 and 2002. For both years, the meteorological inputs were prepared by EPA and were generated using the Fifth Generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5). The MM5-derived meteorological fields are available for both 36- and 12-km resolution.

Meteorological representativeness was also considered in selecting the modeling period. The representativeness of the two candidate periods varies seasonally. For example, 2001 is characterized by normal precipitation amounts during the summer months, for Virginia and most of the surrounding areas. This is offset, however, by less than normal precipitation during the fall period. Figure 3-1 shows the deviation from normal rainfall (based on 40 years of data) for the summer and fall of 2001. In contrast, 2002 is characterized by less than normal rainfall during the summer months followed by greater than normal rainfall toward the end of the year. This is displayed in Figure 3-2. Note that these plots were obtained from the NOAA web site. The precipitation plots for spring were comparable and one of the plots for winter was not available. Figures 3-3 and 3-44 show that temperatures during the summer months were normal for 2001 and higher than normal for 2002.

From this information, we concluded that 2001 is (meteorologically) a more suitable year for mercury deposition modeling, primarily because the summer of 2002 was characterized by lower than normal rainfall amounts in Virginia and surrounding states. We gave somewhat more weight to the summer months in making this assessment, since precipitation is highest, on average, during the summer months compared to the other seasons (by as much as 40 to 50 percent). Since summer can be an important time for mercury wet deposition, 2002 is not an ideal meteorological base year for the modeling exercise.

Consequently, the annual simulation period for the mercury deposition modeling was selected to be 2001. Sensitivity testing was conducted to examine the differences in the CMAQ results due to the use of the 2002 versus 2001 meteorological inputs.

Figure 3-1a. Deviation from Normal Precipitation for Summer 2001.

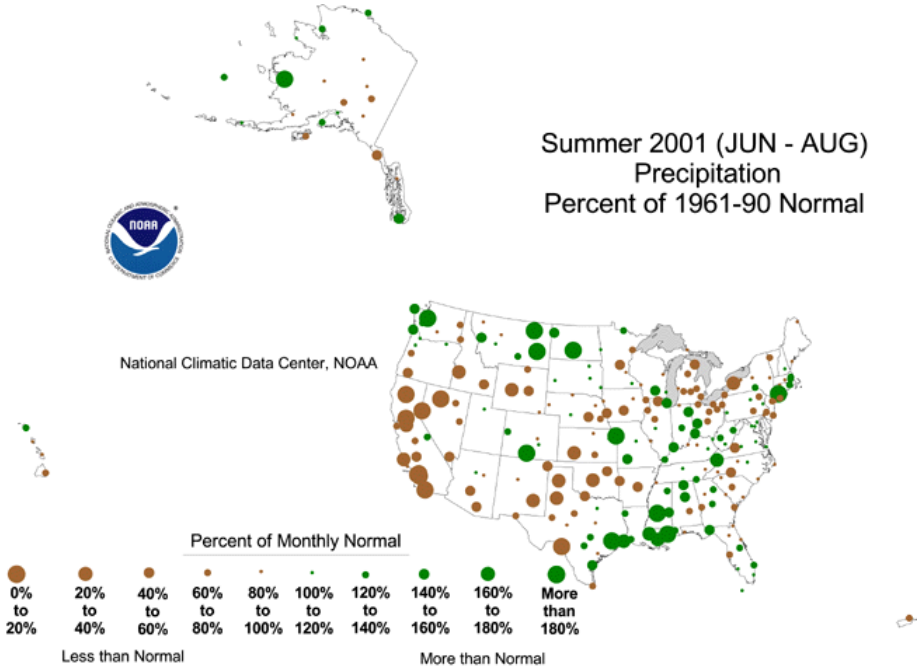


Figure 3-1b. Deviation from Normal Precipitation for Fall 2001.

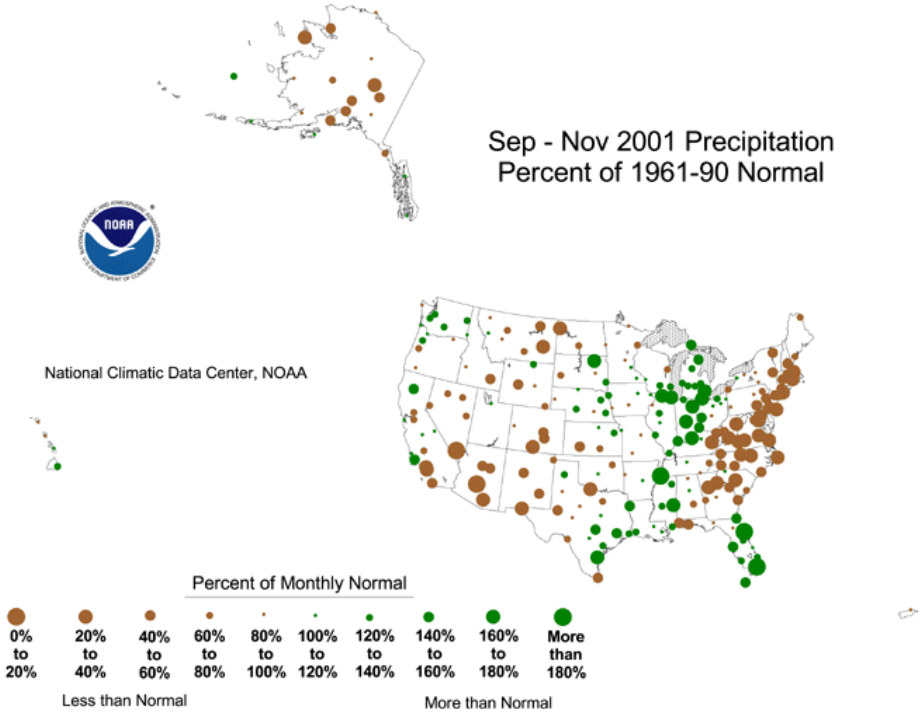


Figure 3-2a. Deviation from Normal Precipitation for Summer 2002.

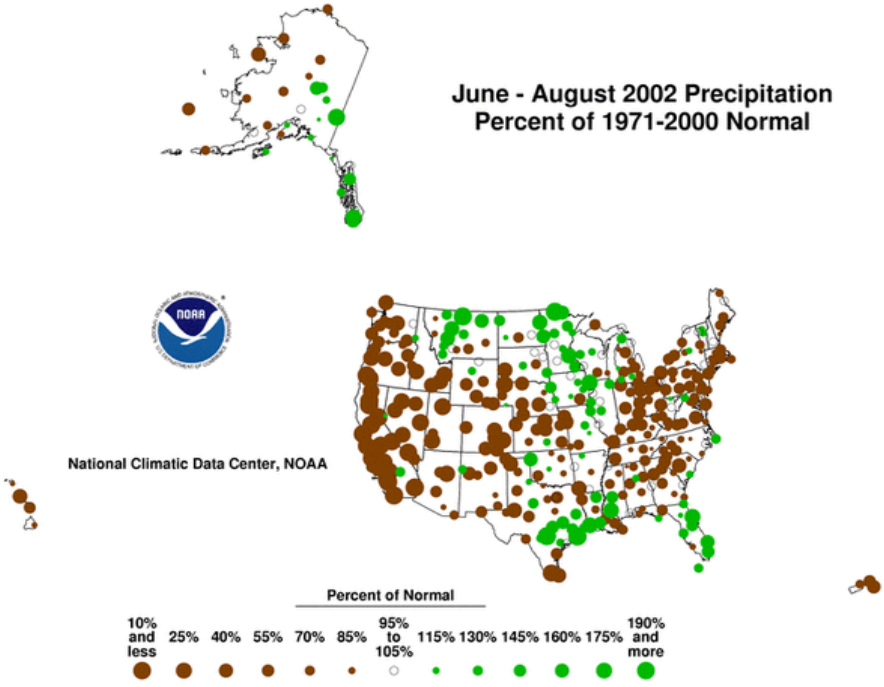


Figure 3-2b. Deviation from Normal Precipitation for Fall 2002.

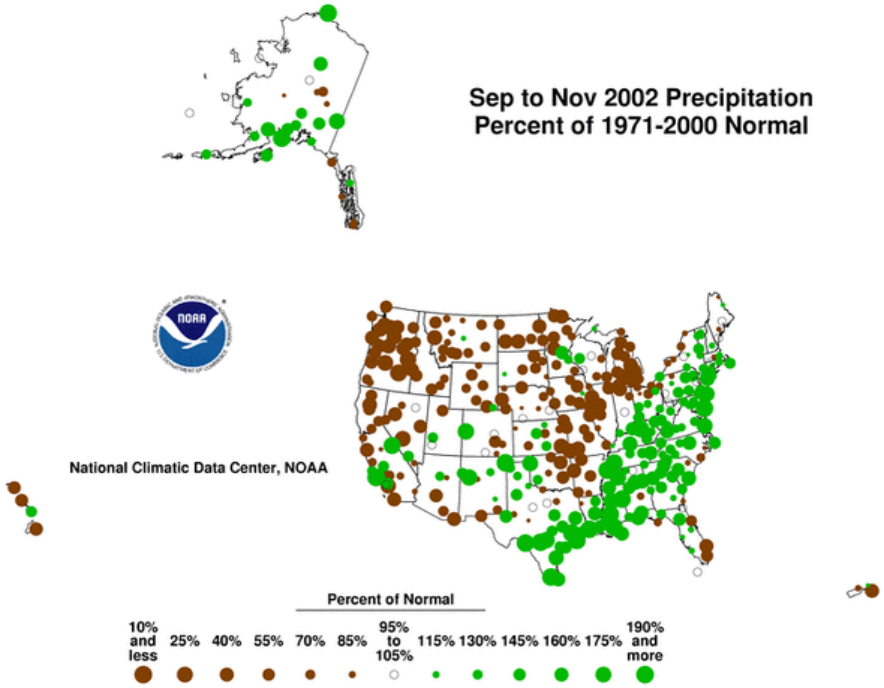


Figure 3-3. Deviation from Normal Temperature for Summer 2001.

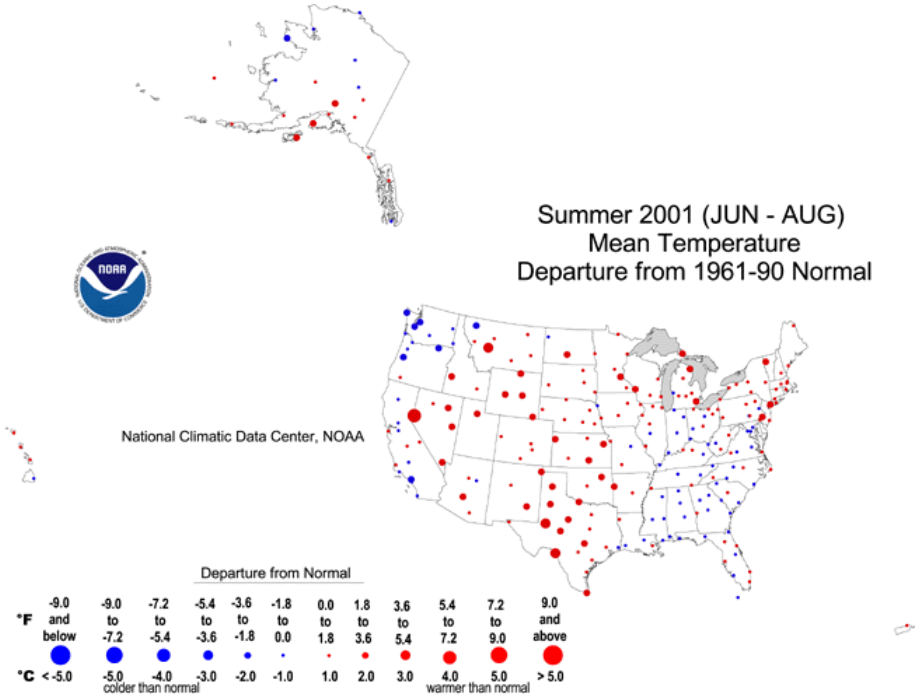
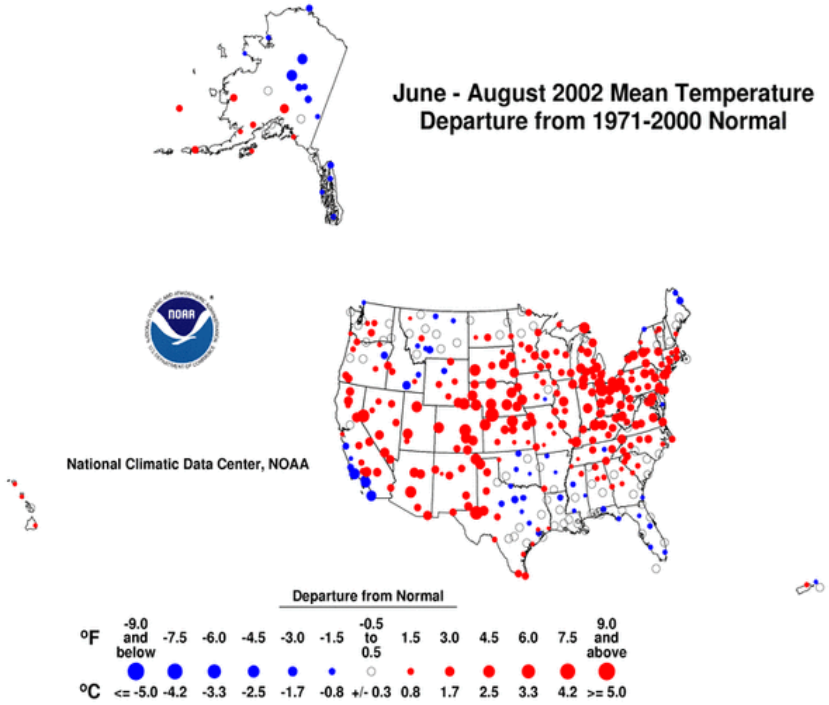


Figure 3-4. Deviation from Normal Temperature for Summer 2002.

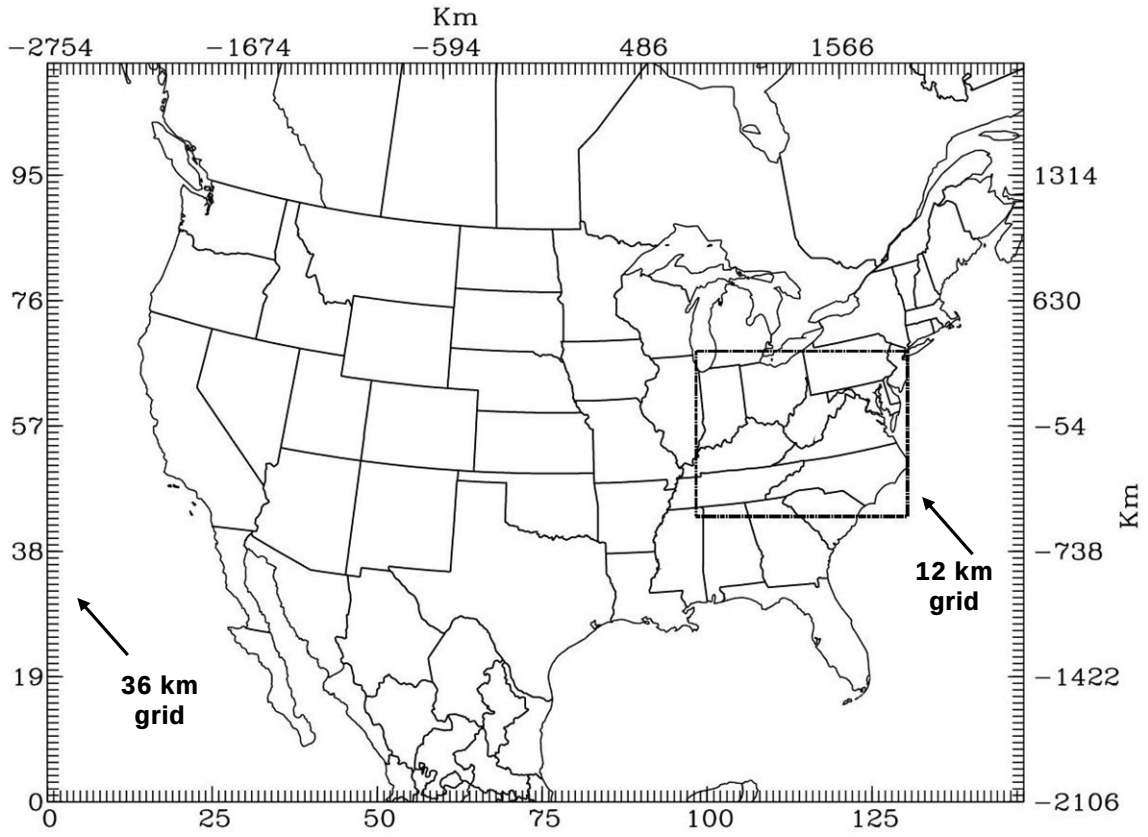


3.2. CMAQ Modeling Domain

3.2.1. Horizontal Extent and Grid Spacing

The CMAQ modeling domain is illustrated in Figure 3-5. The outer domain is the regional-scale modeling domain that has been established by EPA for regulatory applications (e.g. CAMR modeling). The outer grid encompasses the entire contiguous U.S. as well as portions of Canada and Mexico and, therefore, all or nearly all mercury emissions sources in North America. The horizontal resolution of the outer, coarse grid is 36 km. The inner grid focuses on Virginia and the surrounding states and has a horizontal grid resolution of 12 km.

Figure 3-5. CMAQ 36- and 12-km Nested-Grid Modeling Domain.



3.2.2. Vertical Structure

The CMAQ domain includes 14 vertical layers. CMAQ uses a sigma vertical coordinate system, which is a terrain-following vertical coordinate system with numerous numerical advantages. The vertical structure of the modeling domain is such that the highest resolution is achieved near the surface. The top of the modeling domain is approximately 17,000 m. The sigma layers and their approximate heights (under standard pressure conditions) are provided in Table 3-1.

Table 3-1. Vertical Levels that Define the CMAQ Modeling Domain.

Layer Number	Sigma	Height (m)
1	0.995	0
2	0.99	36
3	0.98	72
4	0.96	145
5	0.94	293
6	0.91	444
7	0.86	674
8	0.8	1074
9	0.74	1579
10	0.65	2115
11	0.55	2989
12	0.4	4078
13	0.2	6037
14	0	9733

3.3. AERMOD Spatial Configuration

3.3.1. Selection of Sources for Application of AERMOD

AERMOD was applied for the 15 sources in Virginia with the greatest mercury emissions and for the full annual simulation period. The sources reflect several different types of facilities and a variety of species distributions, stack parameters, locations relative to sensitive watershed areas, and designated potentials for future control.

3.3.2. Specification of Receptor Grids

The receptor area for each source was defined following EPA guidance and consists of a 10 by 10 grid with grid cells of 100 x 100 m near the source that increase to 200 x 200 m and then to 500 x 500 m. The receptor area extends approximately 3000 m (3 km) in any direction of the source.

3.4. Emissions Data and Databases

3.4.1. Baseline Emissions

The mercury emissions inventory incorporates the latest mercury emission data for point sources in Virginia (for 2002 and 2005). The mercury emissions inventory for point sources in Virginia were reviewed and updated as part of this study to ensure that the methods used to calculate the emissions are valid, the data are complete, and that the emissions totals, locations, and stack parameters are correct.

Baseline mercury emissions for all other areas and source categories were based on the latest version (version 3) of the 2002 National Emissions Inventory (NEI). Currently the NEI inventory does not include mercury emissions for motor vehicle or non-road sources.

We prepared the model-ready emissions for CMAQ using the SMOKE emissions processing program and applied our standard quality assurance procedures (as outlined in the quality assurance plan for the project) to the emissions processing.

CMAQ also requires hourly, gridded emissions for other criteria pollutants and related precursor emissions. For this study we used 36- and 12-km model-ready criteria-pollutant emissions prepared by EPA for the 2001 annual simulation period. The 36-km criteria pollutant emissions were used directly, since the VDEQ 36-km domain is the same as that used by EPA. The 12-km emissions for the VDEQ subdomain were extracted from a larger 12-km domain used by EPA. The criteria pollutant emissions were re-speciated for use with the CB05 chemical mechanism. We used SMOKE to merge the criteria pollutant and mercury emissions into a model-ready emissions inventory for CMAQ.

3.4.2. Future-Year Emissions

Future-year emission inventories were prepared for 2010, 2015, and 2018. Emissions projections were based on information available from EPA (e.g., CAMR) and from VDEQ (primarily through surveys). The future-year emission inventories were prepared using the SMOKE emissions processing system.

For all states, the future-year mercury emissions estimates take into account the provisions of CAMR. The CAMR, promulgated on May 18, 2005, includes two mechanisms to reduce mercury emissions from electric power plants. First, it sets standards of performance for new and existing coal-fired power plants. Second, it establishes a two-phase, national cap-and-trade program. In the initial phase of the cap-and-trade program, the national mercury emissions will be capped at 38 tons and emissions reductions will occur as a "co-benefit" of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions under the Clean Air Interstate Rule (CAIR) issued on March 10, 2005. In the second phase, due in 2018, coal-fired power plants will be subject to a second cap, which will reduce emissions to 15 tons upon full implementation.

For Virginia, HB1055 was also accounted for in the future emissions projections. To participate in the cap-and-trade program, states must submit to EPA a State Implementation Plan revision that describes how the state will meet its mercury reduction budget. States may adopt a "model rule" or a rule(s) with comparable provisions. Legislation enacted by Virginia in April 2006 authorized the Air Pollution Control Board to adopt and submit to EPA the model rule. As described below, the Virginia legislation also provided authority for state-specific rules to further control mercury emissions from sources regulated under CAMR. These are summarized by the following amendments to the Code of Virginia:

- § 10.1-1328 C—This section directs the Air Pollution Control Board to adopt and submit to EPA the CAMR "model rule" for participation in the federal mercury cap-and-trade trading program. The rule will include a set-aside of mercury allowances for new sources not to exceed 5 percent of the total state budget during the first five years and 2 percent thereafter.
- § 10.1-1328 D—This section is a state-specific (i.e., that exceeds the requirements of the CAMR rule) rule. Its requirements are similar to the CAMR cap-and-trade program, but it applies to additional (smaller) sources and includes additional restrictions on compliance options.
- § 10.1-1328 E—This section directs the Air Pollution Control Board to adopt regulations governing mercury emissions that meet, but do not exceed, the requirements and implementation timetables for (i) any coke oven batteries for which the EPA has promulgated standards under § 112(d) of the

Clean Air Act, and (ii) facilities subject to review under § 112(k) of the Clean Air Act and that receive scrap metal from persons subject to § 46.2-635 of the Code of Virginia.

- § 10.1-1328 F—This section is a state-specific rule that prohibits electric generating facilities in nonattainment areas from meeting mercury compliance obligations by purchasing credits from other facilities. An exception applies when the facility owner can demonstrate compliance using allowances at another of its facilities within 200 kilometers of the Virginia boarder.

These rules and provisions have been incorporated into the emissions estimates and the future-year emission inventories, staged them as appropriate, for each future year. The future-year emissions estimates also reflect the implementation timing and effects of the CAIR and CAMR emission reduction provisions (using the best available information at the time the work was conducted).

Preparation of the future-year mercury emissions included an analysis of expected emissions reductions, future-year trends for all source categories, and a comparison of Virginia emissions with neighboring states, regions, and national sources affecting Virginia.

The future-year criteria pollutant emissions inventories were based on EPA's 2010, 1015 and 2020 Clear Skies emission inventories (ref). The emissions for the 36-km domain were extracted directly from the inventories listed above. For the 12-km domain, the future-year emissions from the above inventories were allocated to the 12-km grid using spatial allocation factors. These factors were developed using the base-year (2001)12-km emission inventory. By applying these factors, the spatial distribution of emissions within each 36-km grid cell is the same for the base and future years but the amount of emissions reflects the future year. For all three future-years the criteria pollutant emissions were re-speciated for use with the CB05 chemical mechanism.

3.4.3. Emissions for AERMOD

Source-specific emissions estimates for input to AERMOD for both the baseline year and each future year were extracted from the CMAQ point-source emission inventory. Stack parameter, exit velocity, and stack diameter information for use by AERMOD was also extracted from the CMAQ emissions inventory.

3.5. Meteorological Data and Databases

As noted earlier, we made use of existing meteorological input files for this study. These were prepared by EPA for use in CMAQ modeling for the selected modeling domain using the MM5 meteorological model (EPA, 2005a; McNally, 2003). The MM5 outputs were postprocessed by EPA for input to CMAQ using the Meteorology-Chemistry Interface Processor (MCIP) program. The 2001 MM5-derived meteorological fields are available for both 36- and 12-km resolution. The 36-km meteorological fields were used directly, since the VDEQ 36-km domain is the same as that used by EPA. The 12-km meteorological fields for the VDEQ subdomain were extracted from a larger 12-km domain used by EPA.

The 2002 meteorological inputs used for sensitivity testing were also prepared by EPA (using MM5 and MCIP), for both 36- and 12-km resolution.

Corresponding meteorological inputs for AERMOD for 2001 were developed using observed data. For each source included in the AERMOD analysis, meteorological inputs were prepared using

available surface and upper-air meteorological data from nearby, geographically representative monitoring sites. The meteorological monitoring sites were paired with the source locations based on proximity, and similarities in geographical and land-use characteristics. Table 3-1 lists the AERMOD sources along with the matched surface and upper-air sites. The elevation of each location is given in the table. The distance between the facility and each of the paired meteorological monitoring sites is also listed.

Table 3-1. AERMOD Facilities and Paired Meteorological Monitoring Sites. Locations are in Virginia, Except Where Noted.

Facility Name	Facility Elevation (m)	Met Site Type	WBAN or CASTNet #	WBAN or CASTNet Name	Met Site Elevation (m)	Distance (km)
Dominion - Chesterfield Power Station	10.1	SFC	13740	Richmond	50	16.0
		UPR	93734	Sterling (Washington Dulles)	85	177.9
Chaparral Steel	50.3	SFC	13740	Richmond	50	38.7
		UPR	93734	Sterling (Washington Dulles)	85	199.9
Dominion - Bremo	67.1	SFC	93736	Charlottesville	190	49.2
		UPR	93734	Sterling (Washington Dulles)	85	158.0
American Electric Power-Clinch River	452.5	SFC	13877	Bristol-Johnson City-Kingsport, TN	465	53.4
		UPR	53829	Roanoke/Blacksburg	648	161.4
Dominion - Chesapeake Energy Center	4.0	SFC	13737	Norfolk	7	17.8
		UPR	93739	Wallops Island	13	147.8
Potomac River Generating Station	10.4	SFC	13743	Washington, DC	3	5.2
		UPR	93734	Sterling (Washington Dulles)	85	41.1
Dominion - Yorktown Power Station	4.0	SFC	93741	Newport News	13	9.7
		UPR	93739	Wallops Island	13	117.3
Jewel Coke Company LLP	365.9	SFC	13877	Bristol-Johnson City-Kingsport, TN	457	89.5
		UPR	53829	Roanoke/Blacksburg	648	144.6
Dominion-Possum Point Power Station	11.0	SFC	13773	Quantico	4	5.2
		UPR	93734	Sterling (Washington Dulles)	85	41.1
Stone Container Enterprises (Smurfit)	3.0	SFC	13740	Richmond	50	45.3
		UPR	93734	Sterling (Washington Dulles)	85	170.5

Stone Container Corporation - Hopewell	14.3	SFC	13740	Richmond	50	24.6
		UPR	93734	Sterling (Washington Dulles)	85	187.9
American Electric Power (Glen Lyn)	464.5	SFC	VPI120	Horton Station	920	27.4
		UPR	53829	Roanoke/Blacksburg	648	44.4
Intermet Foundry Archer Creek	167.6	SFC	13733	Lynchburg	287	16.2
		UPR	53829	Roanoke/Blacksburg	648	122.0
RES dba Steel Dynamics	301.8	SFC	13741	Roanoke	350	5.7
		UPR	53829	Roanoke/Blacksburg	648	37.3
Spruance Genco LLC	16.5	SFC	13740	Richmond	50	12.2
		UPR	93734	Sterling (Washington Dulles)	85	169.8

The meteorological inputs for AERMOD were generated using the AERMET program (EPA, 1998). For each location/site pair we needed to specify the roughness length, albedo and Bowen ratio based on the land-use characteristics of the area in which the surface meteorological monitoring site is located. This was accomplished by first assessing the land-use for each 100 by 100 m grid cell in a 3 km area surrounding the site. The land-use was plotted and divided in to sectors of similar land use based on visual inspection. For each sector the fractional land use was calculated. Each land-use value was assigned a value of roughness length, albedo and Bowen ratio based on tables provided in EPA (2007). (EPA. 2007 . "AERSURFACE User's Guide." Draft Version.) A weighted value for each parameter was calculated for each sector based on the fractional land use.

The remaining steps included: extraction of hourly surface and twice-daily upper-air data from the National Weather Surface (NWS) database, quality assurance of the data, merging of the surface and upper-air data, and application of AERMET to calculate the planetary boundary layer parameters required by AERMOD.

The meteorological inputs are contained in two files. The first file includes surface wind, temperature, pressure, relative humidity, and stability information as well as cloud cover and precipitation values. The second file contains information on the vertical structure of temperature and wind near the source location.

3.6. IC/BC, Land Use and Other Geophysical Data

For this study, we used existing initial condition, boundary condition, land-use and photolysis rate input files prepared by EPA for use in CMAQ modeling for the selected modeling domain and simulation period (EPA, 2005a). For mercury, the boundary conditions were extracted from the output of a global model (the CTM model).

3.7. Air Quality and Deposition Data

Air concentration and deposition data for the evaluation of model performance for both non-mercury and mercury species are described in Section 4.

4. Model Performance Evaluation

The evaluation of model performance for CMAQ and AERMOD is discussed in this section.

4.1. Overview of Model Performance

A typical application of any air quality and deposition modeling system consists of several simulations, including an initial simulation and a series of diagnostic and sensitivity simulations (designed to examine the effects of uncertainties in the inputs on the simulation results, identify deficiencies in the inputs, and investigate the sensitivity of the modeling system to changes in the inputs). For each simulation, model performance is primarily assessed through graphical and statistical comparison of the simulated pollutant concentrations and deposition amounts with observed data. The results of this comparison are used to guide the modeling analysis (through the determination of additional diagnostic and sensitivity simulations) and to assess whether the model is able to adequately replicate the air quality and deposition characteristics of the simulation period. Model performance evaluation tests and procedures and diagnostic and sensitivity analyses that may be performed to understand and improve model performance are discussed in this section.

EPA guidance (EPA, 2006a) stresses the need to evaluate a model relative to how it will be used in simulating the response to changes in emissions. In this study, we have used emissions contribution analysis together with comparisons with air quality and emissions trends to evaluate the reliability of the modeled response. Use of different models for regional and local scale mercury deposition has also helped us to evaluate the reasonableness of the responses and bound the response to the changes in mercury emissions.

The evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species. The emphasis of the model performance evaluation, however, was mercury deposition for Virginia and the mid-Atlantic region. Following EPA guidance for evaluating model performance, we examined 1) whether the CMAQ model is able to replicate observed (and estimated) mercury deposition data, and 2) whether the response of the model to changes in mercury emissions is reasonable.

For AERMOD, the evaluation of model performance was aimed at assessing the reasonableness of the simulated deposition amounts and spatial patterns, as well as the response of the model to changes in emissions.

4.2. Model Evaluation Datasets

4.2.1. Non-Mercury Species Concentrations and Deposition Data

The assessment of CMAQ model performance for non-mercury species considered air concentrations for ozone and fine particulate matter ($PM_{2.5}$) species, and deposition for selected PM species on a monthly and/or annual basis, depending on the pollutant.

Model performance for ozone was evaluated against observations available from the EPA Air Quality System (AQS) network. For the national-scale modeling domain, the number of sites ranges from approximately 500 to 1000, depending on the time of year. The sites are primarily located in urban areas. The daily maximum simulated ozone concentration for each monitor for each day of the annual simulation period was compared to the corresponding maximum observed concentration.

Measurements of $PM_{2.5}$ were obtained from the AQS network, which includes more than 200 sites, and the Interagency Monitoring of Protected Visual Environments (IMPROVE) network,

which samples approximately 100 Class I national parks and wilderness areas throughout the U.S. For $PM_{2.5}$ and its component species, daily average values were compared.

Observed wet deposition amounts of sulfate, nitrate, and ammonia from the National Acid Deposition Program (NADP) were used to assess the model's ability to simulate the deposition for each of these species. The NADP network includes more than 200, typically rural, sites. Monthly average values were compared.

4.2.2. Mercury Deposition Data

For mercury, the CMAQ wet deposition values were compared to data from the Mercury Deposition Network (MDN), as available from the National Acid Deposition Program (NADP). There are a total of 53 MDN monitors with complete data for 2001 in the full modeling domain.

Emphasis was given to the evaluation of model performance for the mid-Atlantic region. Mercury deposition data are available for MDN sites in several surrounding states, within and adjacent to the Mid-Atlantic region. The period of record for these sites varies, and there are several sites in Pennsylvania, North Carolina, and South Carolina that have data for 2001. Sites at the Allegheny Portage Railroad National Historic Site, Pennsylvania; Arendtsville, Pennsylvania; and Pettigrew State Park, North Carolina all have data for 2001 and are likely most representative, based on proximity and/or similar geographical features, to the areas of interest in Virginia. In particular, Pettigrew State Park, near the Albemarle Sound, may be representative of coastal Virginia.

Mercury wet deposition data for Virginia are available for three MDN monitoring sites, Shenandoah National Park (beginning in October 2002), Culpeper (beginning in November 2002) and Harcum (beginning in December 2004). The Culpeper site is located in central Virginia (near Richmond) and the Harcum site is located in coastal Virginia. Although there are no actual data for these sites for the 2001 simulation period, we used the data for 2003-2005 for sites in Virginia and throughout region to estimate deposition for 2001 at the Virginia monitoring sites. The estimated deposition values were used in the evaluation of model performance, primarily for CMAQ.

4.2.3. Estimated Mercury Deposition "Data"

We used the results from the CART analysis (which was conducted to support the development of the conceptual model) to estimate deposition for 2001 for the Virginia monitoring sites. Specifically, we classified each seven-day period in 2001 according to the observed meteorological conditions and determined the corresponding CART-based classification group. We assigned the daily average mercury deposition for the grouping (the daily average for all other periods in the classification group) to the 2001 weekly period (multiplying by 7 to get the weekly deposition amount). We did this for each period for the entire year of 2001 and then used the weekly mercury deposition values to estimate seasonal and annual deposition amounts. The key assumption here is that by matching the meteorological conditions for 2001 on a weekly basis to those for later years, observed mercury deposition for the later years can be used to estimate deposition for 2001. Applying this assumption on a weekly basis allowed us to account for the variable effects of meteorology throughout the year. We used a similar approach for the EPA OW, in order to estimate annual mercury deposition for a ten-year period (Douglas et al., 2003). EPA then used these values for water quality modeling and estimating fish tissue concentrations.

In order to confirm the reasonableness of these results, we also applied this same method for several additional sites with longer term records: including the Allegheny Portage Railroad National Historic Site, Arendtsville, and Pettigrew State Park (and these results were mixed). In addition, we compared ratios of the annual average deposition (for example, 2003/2001) for the nearby sites with observed data with those for the Virginia sites using the estimated data to ensure that the CART-derived estimated values are reasonable.

4.3. Model Performance Evaluation for CMAQ

The evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species. The non-mercury species include ozone, $PM_{2.5}$ and related species. For mercury, we compared the simulated total wet deposition with actual and estimated data for the MDN monitoring sites. We compared simulated and observed values of concentration and deposition for each site and the average over all sites within 1) the full domain, 2) the 12-km inner grid of the modeling domain, and 3) Virginia.

4.3.1. Statistical Performance Metrics

A variety of statistical measures were used to quantify model performance. These include

- Mean observed concentration or deposition = $1/N \sum O_I$
- Mean simulated concentration or deposition = $1/N \sum S_I$
- Ratio of means = $1/N \sum S_I / 1/N \sum O_I$
- Mean bias = $1/N \sum (S_I - O_I)$
- Mean fractional bias (expressed as percent) = $200 \cdot 1/N \sum (S_I - O_I)/ (S_I + O_I)$
- Mean error = $1/N \sum |SI - OI|$
- Mean fractional error (expressed as percent) = $200 \cdot 1/N \sum |S_I - O_I|/ (S_I + O_I)$
- Coefficient of determination (R^2) =
  $(\sum S_I O_I - \sum S_I \sum O_I/N)^2 /[(\sum O_I^2 - (\sum O_I)^2/N) \cdot (\sum S_I^2 - (\sum S_I)^2/N)]$

Where S is the simulated value, O is the observed value, and N is the number of simulation-observation pairs used in the calculation. Statistical measures were calculated on a monthly, seasonal and annual basis, based on data availability.

4.3.2. Graphical Analysis

Plots and graphics were also be used to assess the reasonableness of the results. Spatial plots of the simulated and observed values were used to qualitatively assess the ability of the model to emulate the spatial deposition patterns. Monthly time-series plots comparing these same values at the monitoring sites were used to determine whether the timing and magnitude of the simulated values matches the observations. Scatter plots were used to graphically compare the simulated and observed deposition values.

4.3.3. Diagnostic and Sensitivity Testing

To a large extent, model configuration for CMAQ was determined by the selection of the meteorological and emissions databases. Some additional testing was conducted to which of

the parameter settings are best suited for mercury deposition. We also explored how to maximize consistency between the AERMOD and CMAQ models.

Following the establishment of the modeling platform, we identified potential weaknesses in the model input fields and conducted some limited sensitivity simulations to examine the effects of these weaknesses or uncertainties. We examined the different estimates of boundary concentrations that are currently available (from the application of global models) and selected the mid range conditions. While no simulation tests with CMAQ were done, we tagged the boundary conditions using PPTM and were able to use the different global model estimates to estimate some bounds for the simulated global contribution. We also explored the sensitivity of the modeling results to the selection of the simulation period, by substituting the 2002 meteorological inputs and re-running CMAQ for a three-month (summer) period. This simulation allowed us to assess the importance of the meteorology in determining the amount of simulated mercury deposition and to ensure that the model responded in a reasonable way (based on our understanding of the meteorological differences) to changes in the meteorological conditions. In addition, we also used PPTM as a probing tool and examined the PPTM results to verify that the contributions from selected emission sources are commensurate with the locations and emissions of the sources as well as the prescribed meteorological conditions.

4.4. Model Performance Evaluation for AERMOD

For AERMOD, we conducted a limited performance evaluation to assess whether the model is able to simulate the deposition distributions and maximum values represented by the observed and estimated data. Sensitivity simulations were conducted to determine which of the parameter settings are best suited for mercury deposition and how to maximize consistency between the AERMOD and CMAQ models. With regard to model performance, we examined the response of the model for the sensitivity simulations to ensure that the model responds in a reasonable way (based on our current knowledge of near-source mercury deposition) to changes in the meteorological and emissions inputs.

4.5. Performance Goals and Benchmarks

In keeping with current EPA guidance on model performance evaluation for other pollutants, we used a “weight-of-evidence” approach to determine whether model performance for both CMAQ and AERMOD is good enough for use in future-year modeling and control measure assessment.

For CMAQ, this was based on the statistical performance measures, the response of the model to changes in the inputs, and the reasonableness of the PPTM contribution results.

For AERMOD, this was based on the comparison of simulated and estimated data—particularly the distribution and maximum values. We also compared the CMAQ and AERMOD results to assure that the simulated local contributions from AERMOD bound the CMAQ results, as they are more likely to represent the maximum impact from directly emitted divalent forms of mercury from a source.

4.6. Use of Model Performance Results to Guide the Interpretation and Use of Modeling Results

Information obtained as part of the model performance evaluation was used throughout the analysis to guide the interpretation and use of the future-year simulation results. For example,

although overall model performance for mercury deposition was reasonable for the mid-Atlantic sites, it varied from season to season. For some sites, this included overestimation of wet deposition during the winter months and underestimation during the summer months. Consequently, we examined the response of the model to changes in emissions (for the future-year scenarios) for each season as well as on an annual basis.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5. Assessment of Mercury Deposition

In this study, we used both the CMAQ and AERMOD models to examine the contributions of a variety of sources to mercury deposition to Virginia's "impaired" water bodies. The modeling analysis consisted of baseline modeling for 2001/2002 and future-year modeling for 2010, 2015, and 2018.

5.1. Baseline Modeling

5.1.1. CMAQ PPTM Scenarios

Several CMAQ/PPTM simulations were conducted using the baseline 2001/2002 emissions inventory. These simulations were designed to assess the contributions of various source sectors to mercury deposition to water bodies in Virginia.

The first scenario examined and quantified the contributions from mercury air emissions sources in 1) Virginia, 2) the mid-Atlantic region (or selected neighboring states), 3) all other U.S. states, 4) Canada and Mexico, 5) global emissions sources, and 6) natural emissions. We used CMAQ version 4.6 with PPTM. We assigned tags to each of the six regions/categories listed above. An initial/boundary condition tag was used to represent the global impact on deposition. This set of tags provides estimates of Virginia, regional, national, and global impacts on deposition for any location (grid cell or group of grid cells) within the state or the modeling domain.

The second scenario quantified the contributions from Electric Generating Unit (EGU) and non-EGU facilities in Virginia and the surrounding states. We tagged 1) all of Virginia's EGU sources and separately 2) all of the non-EGU sources in the state, 3) all EGU sources in the surrounding states (remainder of the 12-km grid), and 4) all non-EGU sources in the surrounding states. The results allow us to quantify and compare the contributions from these two source sectors to mercury deposition for any location (grid cell or group of grid cells) within the state or the modeling domain.

5.1.2. AERMOD Application

At the local scale, we applied the most recent version of the EPA Gaussian model AERMOD. The AERMOD modeling was performed for selected point sources in the Virginia emissions inventory (the top 15 emitters). We used AERMOD to estimate the maximum expected impact from each source based on the directly emitted mercury and to identify individual sources with a potentially significant local impact. AERMOD was applied separately for HG0, HG2 and HGP.

5.2. Future-year Modeling and Contribution Assessment

CMAQ was applied for 2010, 2015 and 2018, using emissions projected to these years. For 2010 and 2015, PPTM was not applied. For 2018, the same CMAQ/PPTM runs that were done for the baseline were conducted.

For each future year, we examined the simulated change in mercury deposition, overall and from each tagged (as possible) or modeled source or source category. The PPTM results were used to attribute the future-year reductions in mercury deposition for 2018 for each area of interest to the specific tagged sources or source categories.

AERMOD was also applied for 2010, 2015 and 2018 and the change in deposition relative to the base year was calculated.

5.3. Display and Analysis of the Modeling Results

Graphical and tabular summaries of the results were prepared. Plots of the CMAQ results were prepared for each CMAQ modeling domain and for each of the major water basins in the Commonwealth of Virginia. Tabular summaries of the overall and PPTM results were also assembled. Similarly, plots of the AERMOD results were prepared for each facility, showing the changes in deposition resulting from each future-year scenario. Analysis of the results focused on the effectiveness of the various measures and emissions changes in reducing future-year mercury deposition both statewide and within the key areas of interest. Given the uncertainties associated with mercury deposition modeling, we emphasize the relative changes in deposition associated with the emissions changes for each source and source category in our analysis of the results.

6. Procedural Requirements

Documents, technical memoranda, and databases developed in this study were submitted to VDEQ for review and distribution.

6.1. Reporting

In addition to this protocol document, other project documents include: 1) project work plan, 2) quality assurance plan, 3) memorandum summarizing the emissions data review, 4) draft and final versions of an emissions data analysis report, 5) draft and final versions of a conceptual model report, and 6) draft and final versions of a mercury deposition report.

The deposition modeling report contains an executive summary, technical details of all aspects of the modeling analysis (including input preparation, model performance evaluation, and the CMAQ and AERMOD results), a discussion of the uncertainties and limitations of the results, and information on how to access and utilize the modeling datasets.

6.2. Data Archival and Transfer of Modeling Files

All of the data, data files, and software required to corroborate the results and findings of the study areavailable from VDEQ. Files can made available by ftp methods (for the transfer of smaller files) and using portable disk drives (for the transfer of larger files and/or the complete database).


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7. References

Amar, P., D. Chock, A. Hansen, M. Moran, A. Russell, D. Steyn and W. Stockwell. 2005. "Second Peer Review of the CMAQ Model." Prepared for the Community Modeling and Analysis System Center, Carolina Environmental Program, Chapel Hill, North Carolina.

Brieman, L., J. H. Friedman, R. A. Olshen, and C. J. Stone. 1984. Classification and Regression Trees. Wadsworth, Belmont, California.

Bullock, O.R., D. Atkinson, T. Braverman, K. Civerolo, A. Dastoor, D. Davignon, C. Hogrefe, J. Ku, K. Loman, T. Myers, C. Seigneur, N. Selin, G. Sistla and K. Vijayaraghavan. 2008. The North American mercury model intercomparison study (NAMMIS). (*Parts 1 and 2 submitted to the Journal of Geophysical Research.*)

Bullock, O.R., Brehme, K.A. 2002. Atmospheric mercury simulation using the CMAQ model: formulation description and analysis of wet deposition results. *Atmospheric Environment* 36, 2135–2146.

Byun, D. W. and J. K. S. Ching. 1999. "Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System." U.S. EPA Office of Research and Development, Washington, D.C. (EPA/600/R-99/030).

Douglas, S., B. Hudischewskyj, and T. Myers. 2003. "CART Analysis of Wet and Dry Mercury Deposition for Three Locations in Wisconsin." Prepared for the U.S. Environmental Protection Agency, Office of Water, Washington, D.C. ICF International, San Rafael, California (03-015).

Douglas, S., T. Myers, and Y. Wei. 2006. "Implementation of Mercury Tagging in the Community Multi-scale Air Quality Model." Prepared for the U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. ICF International, San Rafael, California (06-051).

EPA. 1998. "User's Guide for the AERMOD Meteorological Preprocessor (AERMET)." EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA. 2004. "User's Guide for the AMS/EPA Regulatory Model—AERMOD." EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC (EPA-454/B-03-001).

EPA. 2005a. Technical Support Document for the Final Clean Air Mercury Rule: Air Quality Modeling, EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, March 2005. (http://www.epa.gov/ttn/atw/utility/aqm_oar-2002-0056-6130.pdf)

EPA. 2005b. Emissions Inventory and Emissions Processing for the Clean Air Mercury Rule (CAMR). EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, March 2005. (http://www.epa.gov/ttn/atw/utility/emiss_inv_oar-2002-0056-6129.pdf).

EPA. 2006a. "Guidance on the Use of Models and Other Analyses for Demonstrating Attainment of Air Quality Goals for Ozone, $PM_{2.5}$, and Regional Haze," Draft 3.2, EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina (September 2006).

EPA. 2006b. "Addendum User's Guide for the AERMOD Meteorological Preprocessor (AERMET)." EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Myers, T., Wei, B. Hudischewskyj, J. Haney, and S. Douglas. 2006. "Model-Based Analysis and Tracking of Airborne Mercury Emissions that May Contribute to Water Quality Impacts." Prepared for the U.S. Environmental Protection Agency, Office of Water, Washington, D.C. ICF International, San Rafael, California (06-077).

McNally, D. 2003. "Annual Application of MM5 for Calendar Year 2001." Prepared for the U.S. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Steinberg, D., and P. Colla. 1997. CART—Classification and Regression Trees. Salford Systems, San Diego, CA.

Appendix B: Conceptual Model Report

Virginia Department of Environmental Quality (VDEQ)

Conceptual Description of Mercury Deposition for Monitored Areas in Virginia

Technical Report

February 13, 2008

07-034

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Conceptual Description of Mercury Deposition for Monitored Areas in Virginia

Technical Report

February 13, 2008

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1. Overview of Mercury Deposition

This document provides a conceptual description of mercury deposition for several locations in Virginia and the surrounding states. It includes a summary of observed mercury deposition data and trends, an analysis of the relationships between mercury deposition and meteorology, an overview of mercury emissions, and an examination of available mercury modeling results. The key questions to be addressed in the conceptual description include:

1. Is mercury deposition primarily a local issue, or are regional, national, and global factors important?
2. Are there any characteristic temporal (seasonal) patterns of mercury deposition?
3. Are there any characteristic spatial patterns of mercury deposition?
4. What are the specific meteorological parameters that influence mercury deposition in Virginia, and how important are each of these parameters?
5. Are there discernable trends in mercury deposition, and have recent changes in deposition been accompanied by changes in emissions or primarily driven by meteorological variability?
6. What is the relative importance of wet versus dry deposition, and the various mercury species?

Before addressing these issues for Virginia, we begin with a brief review of the science of mercury deposition including a discussion of the sources of airborne mercury, mercury chemistry, global and regional transport, mercury deposition mechanisms, and effects.

1.1. Sources of Airborne Mercury

Mercury in the atmosphere can be attributed to both natural and anthropogenic sources. The global cycle of mercury must also account for deposition of mercury to the earth's surface through a variety of wet and dry deposition processes and re-emission of mercury that has been previously deposited to the earth's surface back into the atmosphere.

Certain soils, rocks, and other geologic structures naturally contain mercury and therefore represent natural or geogenic sources of mercury emissions. Volcanic activity is thought to be an important but variable source of naturally occurring airborne mercury (Niagru and Becker, 2003). Within North America, most natural mercury emissions are associated with land types found in the western part of the continent. In addition to the land masses, the oceans are also a source of natural mercury emissions. Emissions fluxes from the ocean are thought to be greatest near the equator and to decrease toward the poles (Seigneur et al., 2003; Kim and Fitzgerald, 1986).

Anthropogenic sources of mercury include coal-fired power plants and other industrial coal-burning facilities, municipal, medical, industrial and hazardous waste incinerators, chlor-alkali and other chemical manufacturing plants, taconite and other metallurgical processing facilities, pulp and paper manufacturing facilities, mining operations, cement plants, mobile sources, and a wide variety of other industrial and residential sources (EPA, 2005a).

Re-emission of both natural and anthropogenic emissions from both land and water areas is an important part of the global mercury budget. Over land, prescribed burning and wild fires can increase the rate of re-emission.

Currently, it is estimated that global mercury emissions are equally apportioned among natural emissions, direct anthropogenic emissions, and re-emission of previously deposited natural and anthropogenic emissions (Valente et al., 2007).

1.2. Mercury Chemistry

Airborne mercury (Hg) is comprised of three forms: elemental mercury (Hg(0)), reactive gaseous mercury (RGM), and particulate mercury (Hg(p)). RGM is known to be comprised almost entirely of divalent mercury (Hg^{2+} or Hg(II)), since mercury compounds at other valence states tend to be chemically unstable in the atmosphere (Bullock et al., 2007). Hg(p) is also primarily comprised of divalent mercury, but may also include elemental mercury.

Elemental mercury is the dominant atmospheric species and comprises about 99 percent of the total mercury in the atmosphere. Hg(0) is characterized by low reactivity and low solubility in water. The dry deposition velocity is believed to be relatively low. Hg(0) has a long atmospheric lifetime (perhaps on the order of months to years) and is therefore dispersed and transported/circulated globally.

RGM represents less than one percent of atmospheric mercury. It is highly reactive and highly soluble. It can be actively removed from the atmosphere through both wet and dry deposition processes. As a result, the atmospheric lifetime of RGM is expected to be on the order of one day to one week. Based on these properties, RGM likely contributes to mercury deposition near the source location (locally or regionally).

Hg(p) also represents less than one percent of atmospheric mercury. It is moderately reactive and highly soluble in water. It is likely removed from the atmosphere primarily through wet deposition, since the dry deposition velocity of Hg(p) is expected to be low (based on that for similar fine particles). The atmospheric lifetime of Hg(p) is estimated to be on the order of one day to one week, or longer in the absence of precipitation. Based on these properties, Hg(p) also likely contributes to mercury deposition near the source location (locally or regionally).

Chemical transformations transfer mercury mass from one of these states to another. Several gas phase and aqueous phase reactions and equilibrium processes are expected to be important in the transformation of mercury (Seigneur et al., 2003):

Equilibrium processes

$Hg(0)\ (g) \leftrightarrow Hg(0)\ (aq)$

$HgCl_{2\ (g)} \leftrightarrow HgCl_2\ (aq)$

$Hg(OH)_2\ (g) \leftrightarrow Hg(OH)_2\ (aq)$

$HgCl_2\ (aq) \leftrightarrow Hg^{2+} + 2Cl^-$

$Hg(OH)_2\ (aq) \leftrightarrow Hg^{2+} + 2OH^-$

$Hg^{2+} + SO_3^{2-} \leftrightarrow HgSO_3$

$HGSO_3 + SO_3^{2-} \leftrightarrow Hg(SO_3)_2^{2-}$

$Hg(II)\ (aq) \leftrightarrow Hg(II)\ (p)$

Gas phase transformations

$Hg(0)\ (g) + O_3\ (g) \rightarrow Hg(II)\ (g)$

$Hg(0)\ (g) + HCl\ (g) \rightarrow HgCl_2\ (g)$

$Hg(0)\ (g) + Cl_2\ (g) \rightarrow Hg\ Cl_2\ (g)$

$Hg(0)\ (g) + H_2O_2\ (g) \rightarrow Hg(OH)_2\ (g)$

$Hg(0)\ (g) + OH\ (g) \rightarrow Hg(OH)_2\ (g)$

Aqueous phase transformations

$Hg(0)\ (aq) + O_3\ (aq) \rightarrow Hg^{2+}$

$HgSO_3\ (aq) \rightarrow Hg(0)\ (aq)$

$Hg(II)\ (aq) + HO_2\ (aq) \rightarrow Hg(0)\ (aq)$

$Hg(0)\ (aq) + HOCl\ (aq) \rightarrow Hg^{2+}$

$Hg(0)\ (as) + OCl^- \rightarrow Hg^{2+}$

Aqueous phase reactions occur primarily in clouds and fog. The chlorine pathway is considered to be active only at night. In the above formulae Hg(II) (g) refers to divalent gaseous mercury (or RGM) and Hg (II) (p) refers to divalent particulate mercury (or Hg(p)). Hg(p) is assumed to be adsorbed onto fine particles (such as soot particles).

1.3. Global and Regional Transport

Various atmospheric processes influence the dispersion, advection, and transport of mercury. With an atmospheric lifetime that may be on the order of months to years, Hg(0) is dispersed and transported globally by atmospheric circulation systems and regionally by synoptic scale weather systems. Similarly, with atmospheric lifetimes on the order of a week, RGM and Hg(p) may also be subject to regional-scale transport. The global and regional transport of mercury is an important consideration in any analysis of mercury deposition. Recent modeling studies (e.g., Myers et al., 2006) have indicated that for most areas in the U.S., global background may account for as much as 25 to 50 percent or more of mercury deposition, with the greatest percent contribution from global background occurring along the west coast. According to these modeling studies, the contribution from upwind sources (the regional transport component) increases from west to east across the U.S., consistent with the presence of anthropogenic emissions sources, prevailing wind conditions, and the movement of synoptic scale weather systems (primarily from west to east).

1.4. Deposition Mechanisms

Various atmospheric processes also influence the wet and dry deposition of mercury onto land and water surfaces.

Wet deposition is the scavenging of gasses and particulates from the atmosphere by precipitation, and their subsequent deposition (via precipitation) to the surface. Dry deposition occurs upon contact with the surface and the deposition flux is proportional to the concentration of mercury in the atmosphere as well as the adsorption properties of the species and the uptake properties of the surface.

As noted earlier Hg(0) is not very soluble in water. In addition, dry deposition of Hg(0) is not expected to be rapid. RGM and HG(p) are highly soluble and therefore subject to wet deposition. Dry deposition of both RGM and Hg(p) is also expected, and determining their respective dry deposition velocities is an area of ongoing research.

A majority of measurements of mercury deposition are limited to wet deposition. Recent modeling studies (e.g., Myers, 2006) indicate that for most areas in the U.S. on an annual basis both wet and dry depositions are important to total mercury deposition. For many areas, the simulated annual wet and dry deposition amounts are about equal.

Once deposition occurs, mercury can be re-emitted from both land and water surfaces (e.g., Sofiev and Galperin (2000)). Prescribed burning and wild fires may account for some of the re-emissions. Other natural processes, including microbial activity, may also account for some of the re-emission (Syrakov, 1998). Re-emission of mercury is mainly in the form of Hg(0) (Schluter, 2000)

1.5. Impacts of Mercury Deposition on Aquatic Ecosystems

In the U.S., more than 8,500 individual bodies of water have been identified as mercury impaired and the primary source of mercury to these water bodies is believed to be atmospheric deposition. Mercury deposition affects the viability of aquatic ecosystems in a number of different ways. The sustainability of marine life, recreational and commercial fishing, and human health can be directly or indirectly affected by mercury deposition and the build up of mercury in lakes, streams, rivers, and wetland areas. In certain bodies of water such as those with low dissolved oxygen, high organic matter content, and low acidity, mercury deposition can lead to the formation and build up of the highly bio-accumulative form of mercury (methyl mercury).

Human exposure to mercury is most commonly associated with the consumption of contaminated fish. Due to measured high levels of mercury in fish, at least 44 U.S. states have, in recent years, issued fish consumption advisories. These advisories cover more than 2000 individual bodies of water and may suggest limits on the consumption of certain types of fish or recommend limiting or not eating fish from certain bodies of water because of unsafe levels of mercury contamination.

Within Virginia, fish consumption advisories have been issued for several bodies of water for which atmospheric deposition is thought to be the primary source of mercury. These are primarily located along the coastal plain, and have characteristics that are consistent with mercury methylation and bioaccumulation of mercury in fish. The “mercury sensitive waters” include: Lake Gordonsville (in Louisa Co.), Lake Whitehurst (in Norfolk), Lake Trashmore (in Virginia Beach), a portion of the Mattaponi River, a portion of Herring Creek, a portion of the Pamunkey River, Chickahominy Lake (in Charles City Co.), Harrison Lake (in Charles City Co.), portions of the Blackwater River, a portion of the Dismal Swamp Canal, and Dragon Run Swamp.

Other areas suspected of being “mercury sensitive waters” and undergoing monitoring in 2006-2007 include additional portions of the Blackwater River, the Nottoway River, and the Meherrin River.

2. Summary of Observed Mercury Deposition for Virginia and Surrounding States

In this section, we summarize the availability and characteristics of the observed mercury wet deposition data for monitoring sites located in Virginia and several surrounding states.

2.1. Site-Specific Mercury Deposition Amounts, Characteristics and Trends

Mercury wet deposition data are available for three Mercury Deposition Network (MDN) sites in Virginia: Culpeper, Shenandoah National Park, and Harcum (NADP, 2007). The period of record for the MDN data is late 2002 through 2006 for Culpeper, late 2002 to the present for Shenandoah, and approximately 2005 to the present for the Harcum site. The Culpeper site is located in north central Virginia. The Shenandoah site is a high elevation monitoring site located within the national park (in northwestern Virginia), while the Harcum site is located along the southern portion of the inner coast of the Chesapeake Bay. Each measurement of wet deposition represents an approximate seven-day period. Annual mercury wet deposition for these sites is summarized in Table 2-1. Figure 2-1a shows the location of these sites as well as other selected MDN sites in neighboring states. Figure 2-1b highlights the Virginia MDN sites and also shows the locations of nearby surface and upper-air meteorological monitoring sites that will be referred to later in the report.

Table 2-1. Summary of Annual Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

Site Name (MDN ID)	Annual Observed Mercury Wet Deposition (ng m^{-2})		
	2003	2004	2005
Culpeper (VA08)	13,097	7,784	8,811
Shenandoah National Park (VA28)	11,922	9,727	7,074
Harcum (VA98)	—	—	8,218

Figure 2-1a. Locations of MDN Monitoring Sites in Virginia and Neighboring States.

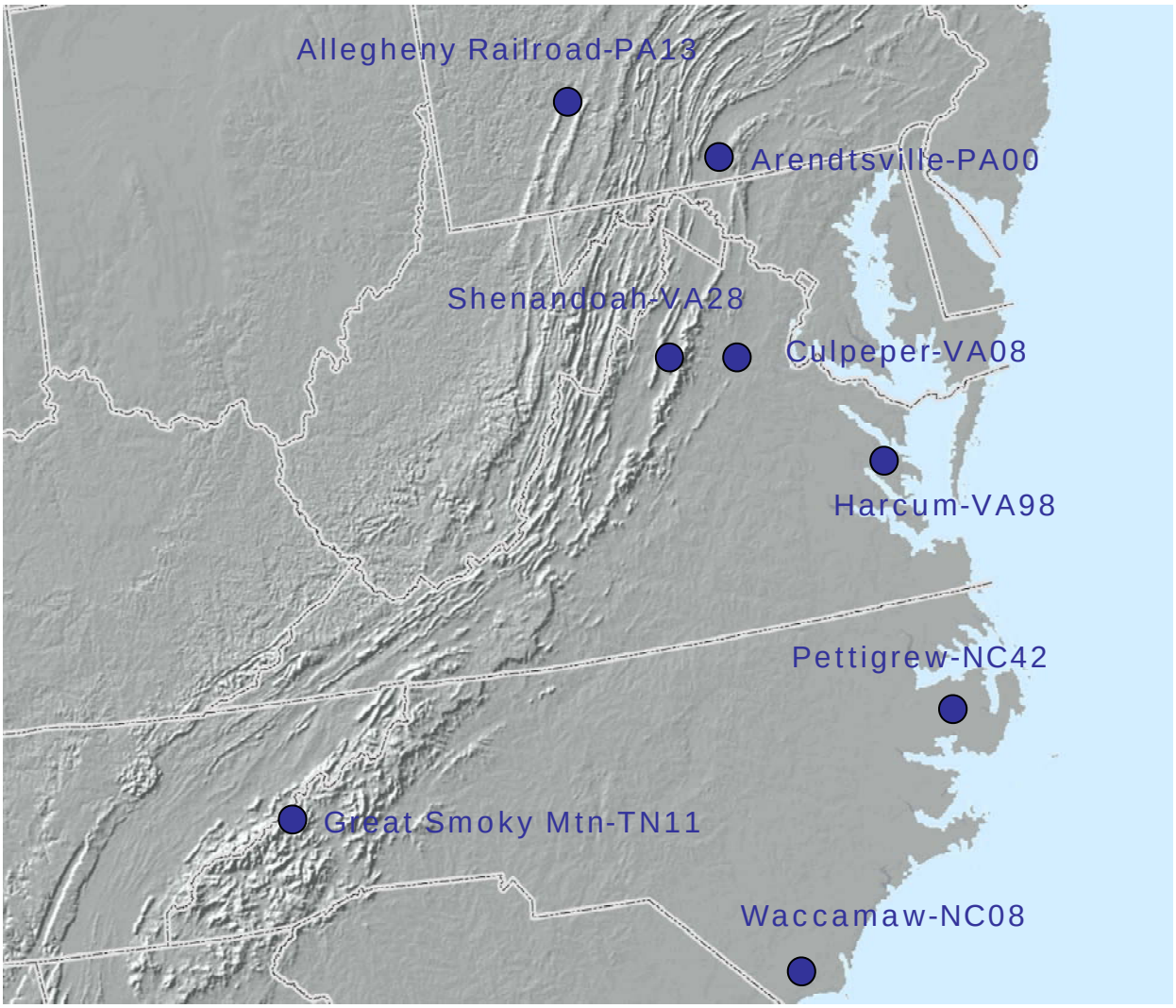
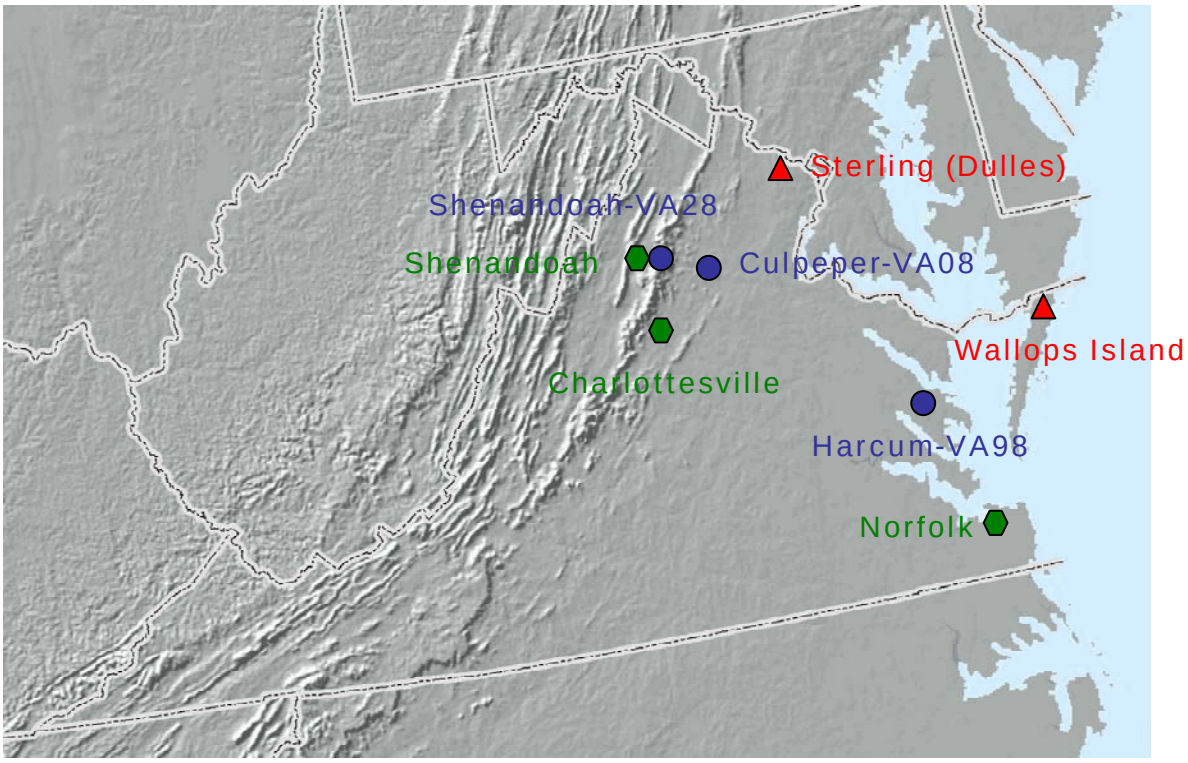


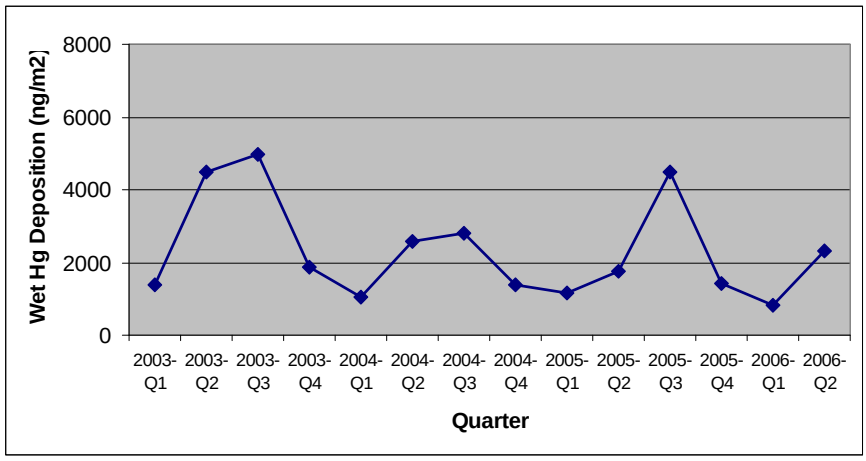
Figure 2-1b. Locations of MDN Monitoring Sites (Blue) and Nearby Surface (Green) and Upper-Air (Red) Meteorological Monitoring Sites in Virginia.



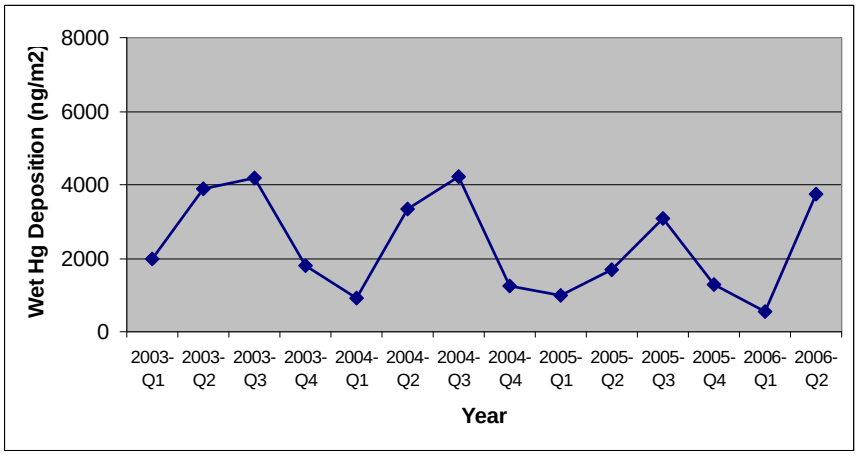
Within each calendar year, there are variations in deposition by week, month, and quarter, primarily in accordance with variations in rainfall amount. Figure 2-2, which displays quarterly deposition amounts, suggests that mercury deposition (and thus rainfall amounts) appear to have an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively).

Figure 2-2. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

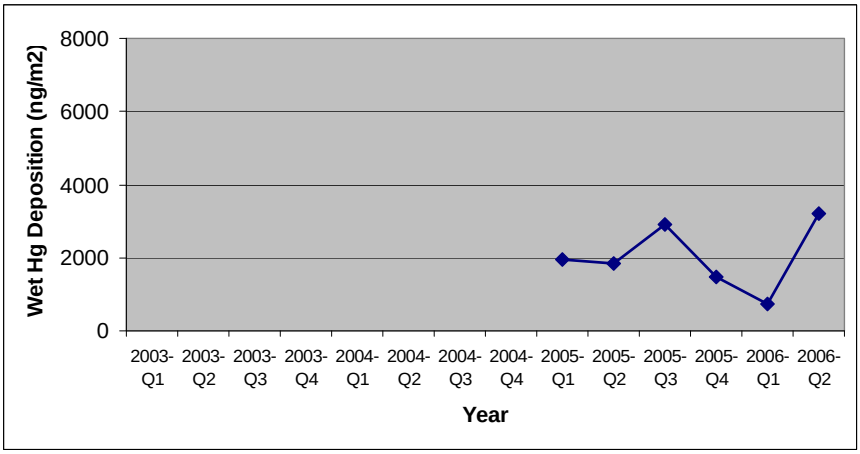
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)

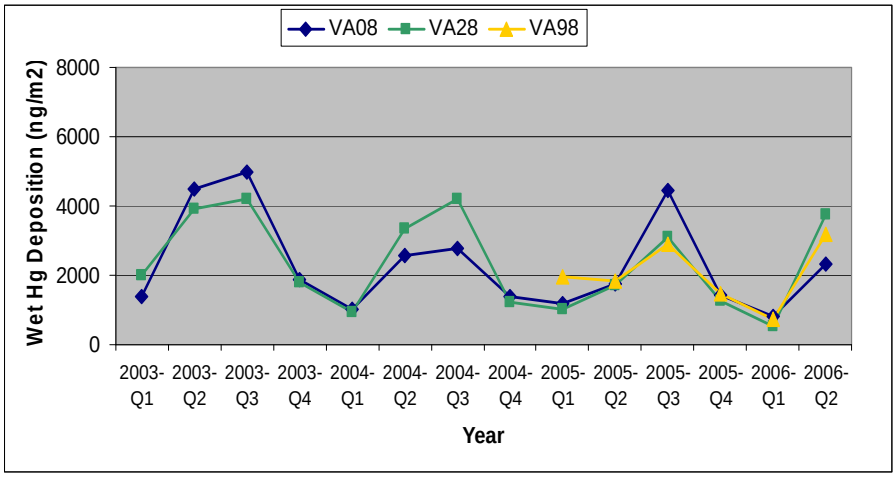


(c) Harcum (VA98)



When plotted together (Figure 2-3), the annual cycle shows up clearly and we see that the deposition amounts are generally similar among the three sites but that there are some differences.

Figure 2-3. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for the Three MDN Monitoring Sites in Virginia.



With only three full calendar years of data, it is difficult to assess annual variations and trends. Therefore, we also obtained and examined data for several other MDN sites located in neighboring states. For each site, the site ID, site name, location, elevation, and period for which data are currently available are listed in Table 2-2.

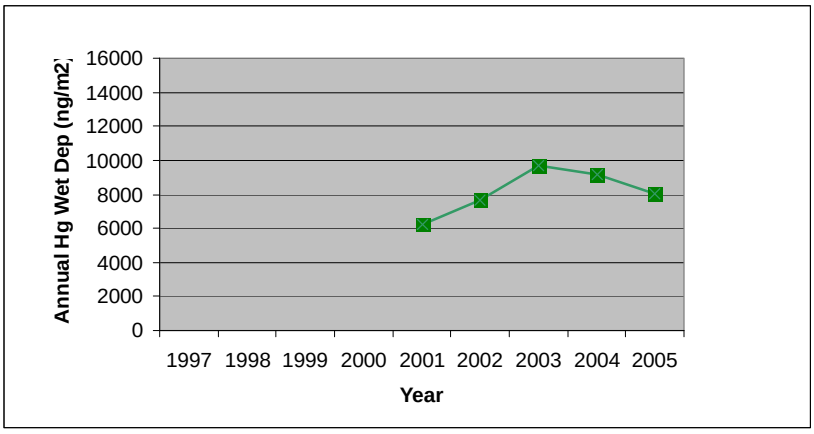
Table 2-2. List of MDN Monitoring Sites in Virginia and Several Surrounding States.

Site ID	Site Name	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Period of Record
VA08	Culpeper	38.42	-78.10	163	11/19/02 - 6/30/06
VA28	Shenandoah National Park	38.52	-78.44	1074	10/22/02 - 6/30/06
VA98	Harcum	37.53	-76.49	13	12/17/04 - 6/30/06
NC08	Waccamaw State Park	34.26	-78.48	10	7/1/96 - 6/30/06
NC42	Pettigrew State Park	35.74	-76.51	2	7/1/96 - 6/30/06
PA00	Arendtsville	39.92	-77.31	269	11/14/00 - 6/30/06
PA13	Allegheny Portage Railroad National Historic Site	40.46	-78.56	739	1/9/97 - 6/30/06
TN11	Great Smoky Mountains National Park	35.66	-83.59	640	1/30/02 - 6/30/06

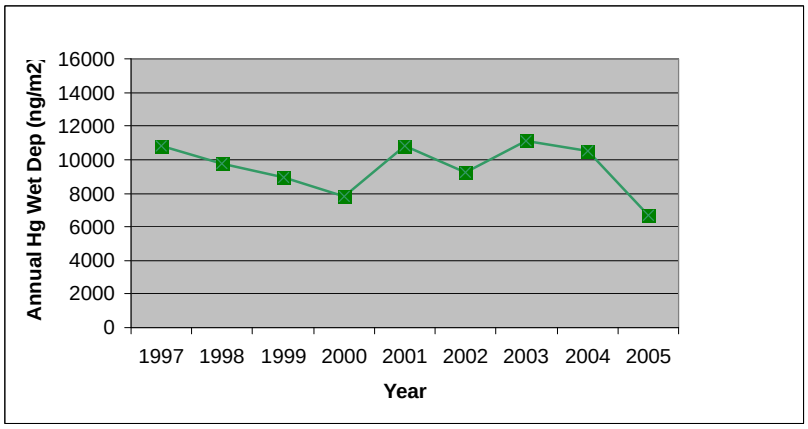
In addition to having longer data records, the sites in Arendtsville, Pennsylvania (near Gettysburg, along the PA/MD border), Allegheny Portage Railroad National Historic Park in the southern Allegheny Mountains of Pennsylvania, and Pettigrew State Park in coastal, northeastern North Carolina also have some geographical similarities (with respect to location, elevation, and proximity to the coastline) to the three Virginia sites (Culpeper, Shenandoah, and Harcum, respectively). The observed annual variations in mercury wet deposition for these three neighboring sites are displayed in Figure 2-4.

Figure 2-4. Annual Observed Mercury Wet Deposition (ng m^{-2}) for Selected MDN Monitoring Sites in Pennsylvania and North Carolina.

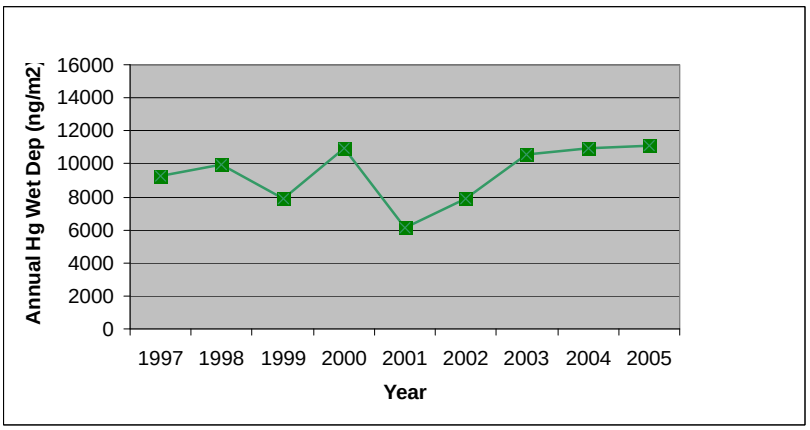
(a) Arendtsville, PA (PA00)



(b) Allegheny Portage Railroad National Historic Site, PA (PA13)



(c) Pettigrew State Park, NC (NC42)

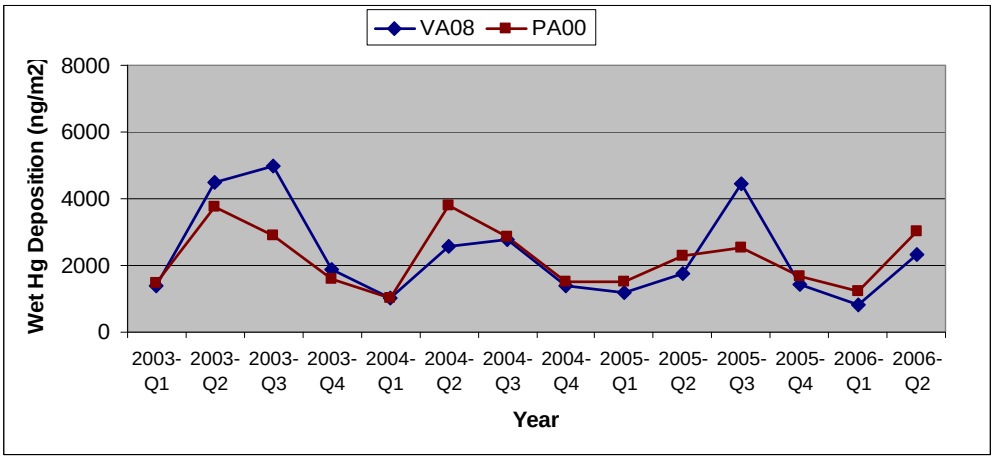


For all three neighboring sites, there is significant year-to-year variation in mercury wet deposition and this most likely reflects year-to-year variability in the meteorological conditions, particularly rainfall. The data do not reveal an obvious trend; however, more analysis of the meteorology and emissions is needed to ascertain any underlying trend in the data.

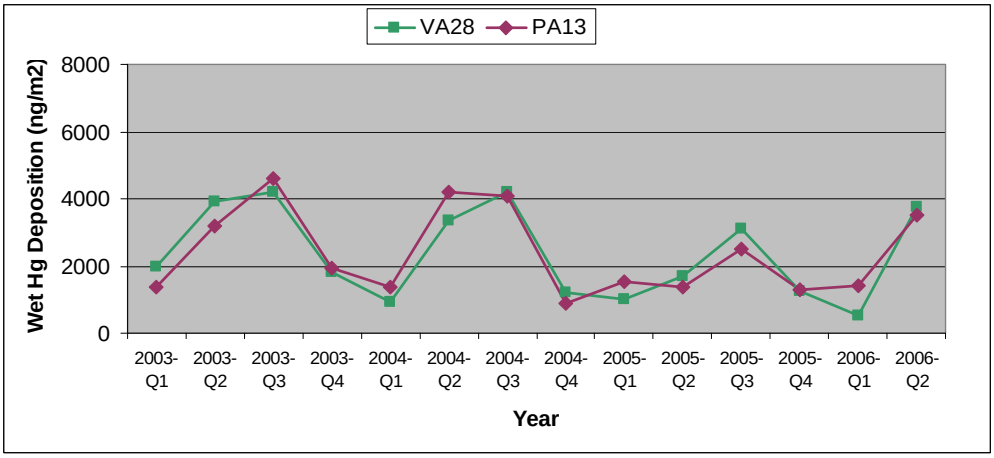
The corresponding quarterly deposition amounts are compared with the quarterly deposition amounts for the Virginia sites that are best matched to these sites in Figure 2-5.

Figure 2-5. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia and Selected Sites in Pennsylvania and North Carolina.

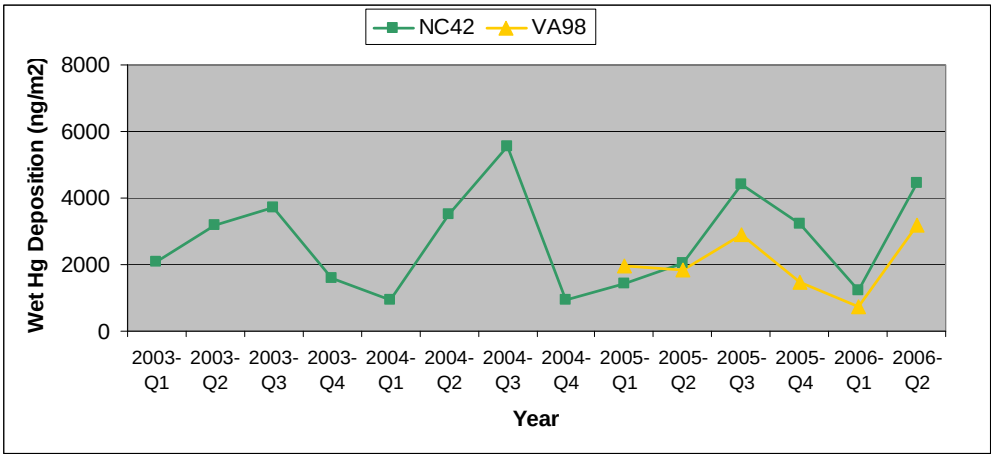
(a) Culpeper (VA08) and Arendtsville, PA (PA00)



(b) Shenandoah National Park (VA28) and Allegheny Portage Railroad National Historic Site, PA (PA13)



(c) Harcum (VA98) and Pettigrew State Park, NC (NC42)



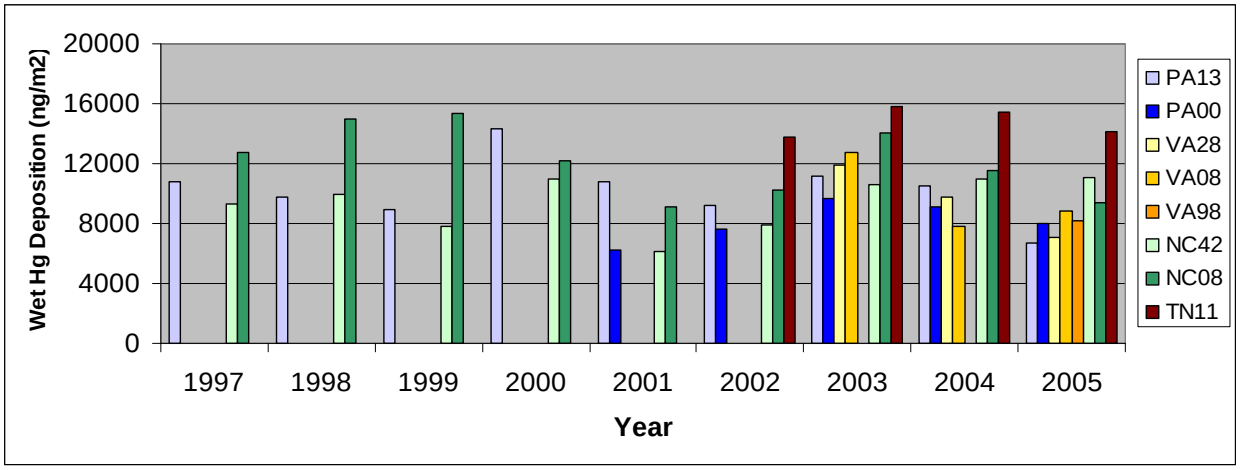
Culpeper has higher deposition than Arendtsville for two of the Q3 periods (2003 and 2005), while Arendtsville is higher for the 2004 Q2 period (Figure 2-4a). Otherwise, deposition at the two sites is similar. The deposition data for the two higher elevation sites (Figure 2-4b) is very similar. Along the coast, Harcum is characterized by lower deposition than Pettigrew State Park (Figure 2-4c).

2.2. Spatial Variations in Mercury Deposition

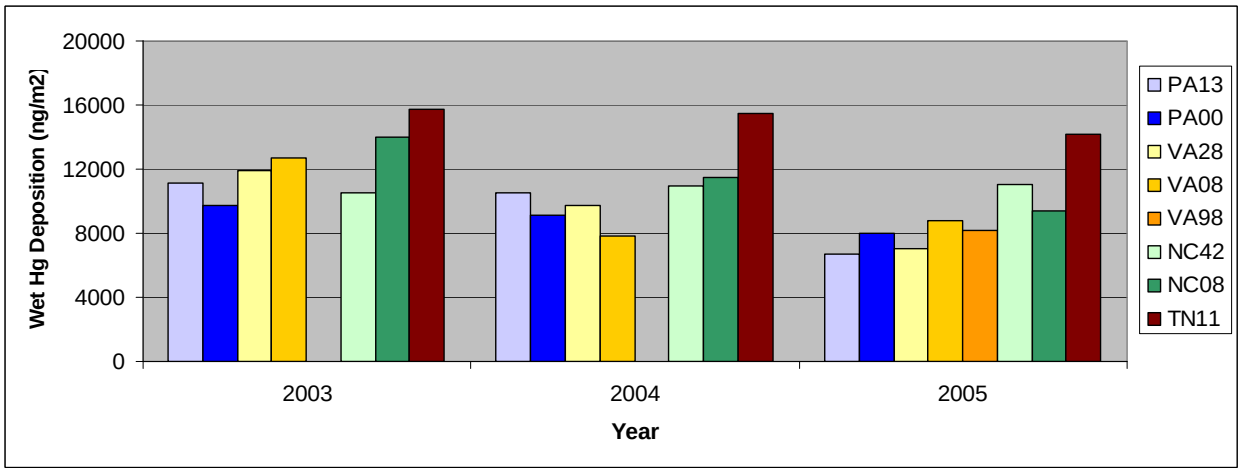
Spatial and temporal variations for all eight sites included in this analysis are further displayed in Figure 2-6. Figure 2-6a shows annual mercury wet deposition data for all sites for 1997-2005, as available. Figure 2-6b focuses on 2003 to 2005, when data are available for Virginia.

Figure 2-6. Annual Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia and Neighboring States.

(a) 1997-2005



(b) 2003-2005



This display indicates that annual deposition amounts for sites in Pennsylvania and Virginia are similar for 2003 to 2005. Sites in North Carolina tend to have higher deposition amounts than sites in Virginia, with some exceptions. Deposition at the Great Smoky Mountains site in Tennessee is consistently higher than that at the other sites.

The mercury deposition data are coupled with meteorological and emissions data and examined further in the following sections.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3. Meteorological Influences

In this section, we examine the relationships between meteorological conditions and mercury wet deposition for monitoring sites in Virginia. Scavenging by precipitation is an important removal mechanism for mercury in the atmosphere. Thus, mercury wet deposition is clearly linked with precipitation. This analysis examines whether observed mercury wet deposition is more influenced by the amount or duration of precipitation (or both) and whether deposition is also influenced by other meteorological factors.

3.1. Overview of Meteorological Factors Influencing Mercury Deposition

As noted above, precipitation is an important mechanism for wet mercury deposition. All of the factors that contribute to precipitation events are therefore potentially important to mercury deposition. These include upper-level synoptic-scale airflow and pressure patterns that guide the movement of regional-scale weather patterns and features, including low pressure systems, associated frontal systems, and possibly other precipitation generating events (e.g., tropical storms and hurricanes), and cause precipitation to occur over Virginia. They also include local meteorological factors such as temperature, humidity, stability, and wind speed that control the development and severity of small-scale precipitation events, such as thunderstorms.

Wind directions, both near the surface and aloft, may influence the regional and local transport of mercury emissions from source regions or individual sources for subsequent deposition at the monitoring sites (and to bodies of water) in Virginia.

Although not considered in this analysis, dry deposition of mercury will be influenced by several meteorological factors including the stability of the atmosphere and the wind speed. These factors influence the near surface concentration of airborne mercury, determine the turbulence characteristics of the atmosphere, and consequently determine dry deposition velocities.

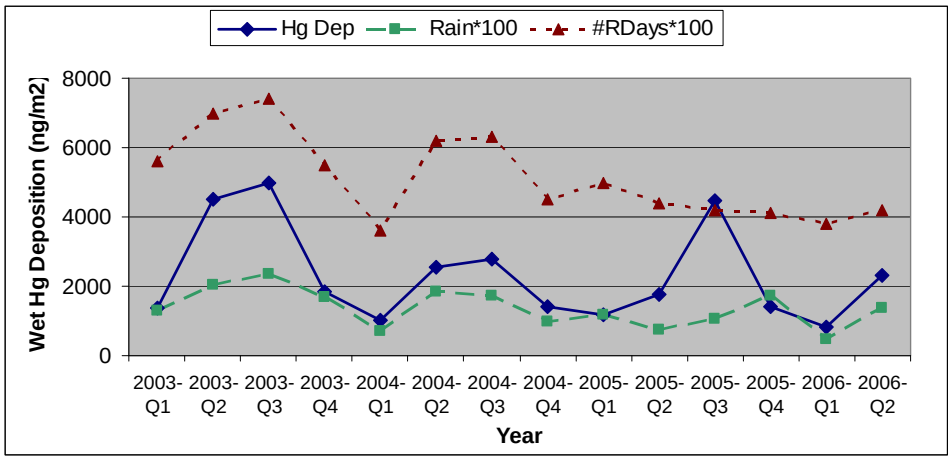
3.2. Precipitation Effects

Figure 3-1 compares quarterly mercury wet deposition with rainfall amount and number of days with measurable rainfall for the three MDN sites in Virginia. Precipitation data from nearby Class I National Weather Service (NWS) meteorological monitoring sites with complete data for the analysis period were used for this comparison. For the Culpeper site, the matched meteorological monitoring site is in Charlottesville, VA (about 44 km away). For the Harcum site, the matched meteorological monitoring site is in Norfolk, VA (about 69 km away). For Shenandoah, precipitation is measured at the MDN site. (Refer to Figure 2-1b.)

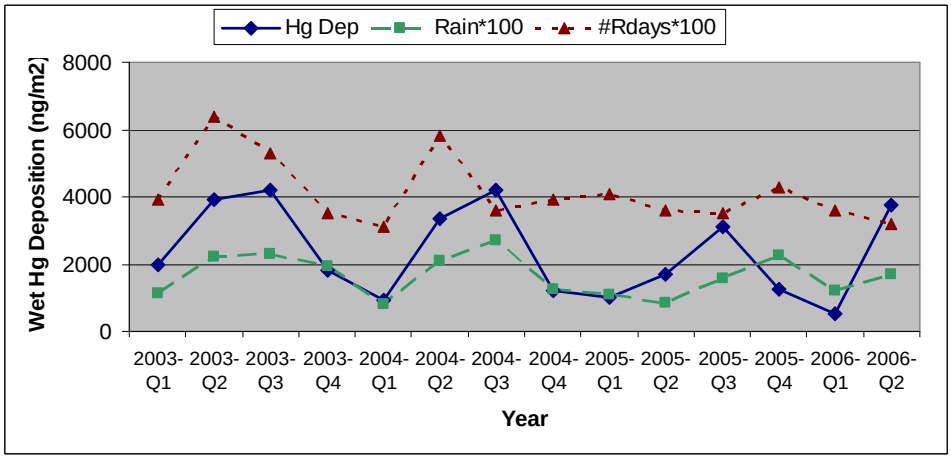
For all three site pairs, there appears to be a relationship between rainfall amount and mercury deposition, although mercury deposition is not fully explained by rainfall amount. Similarly, the number of rain days also appears to be well correlated with the deposition amount for all three sites, especially during 2005-2006. Note that for Culpeper and Harcum, the distance between the MDN and meteorological monitoring sites might contribute to the differences in timing between deposition and rainfall (especially in the event of localized rainfall that affects one but not both of the locations). Nevertheless, the agreement between mercury deposition and precipitation is no better for Shenandoah than for the other two sites. This simple analysis indicates that mercury deposition is affected by the amount and frequency of precipitation, but that there are also other factors that influence mercury deposition. These are explored further in the following sections.

Figure 3-1. Quarterly Observed Mercury Wet Deposition (ng m^{-2}), Total Rainfall (Scaled to Inches x 100), and Number of Days with Rainfall (Scaled by 100).

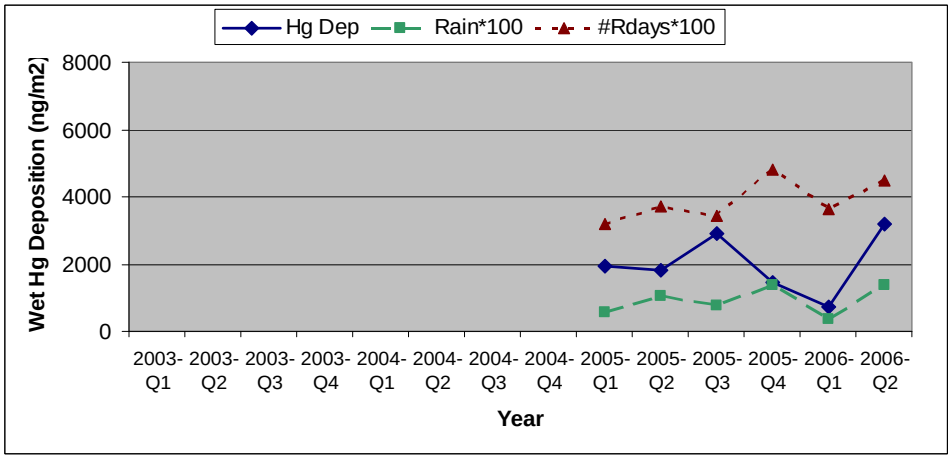
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



(c) Harcum (VA98)



3.3. Regional-Scale Wind Patterns

As noted earlier, wind directions, both near the surface and aloft, may influence the regional and local transport of mercury emissions from source regions or individual sources for subsequent deposition at the monitoring sites (and to bodies of water) in Virginia.

Plots comparing the frequency of wind directions and speeds for all periods versus high mercury deposition periods are provided in Figure 3-2 through 3-10. The high mercury deposition periods are defined separately for each site and include the top 20 percent of the periods with the highest mercury deposition totals. The MDN sites were matched with surface and upper-air meteorological monitoring sites, based on location and data completeness. For the Culpeper site, the matched surface meteorological monitoring site is in Charlottesville, VA (about 44 km away) and the upper-air monitoring site is in Sterling, VA (Dulles Airport) (about 83 km away). For Shenandoah, surface winds are monitored at the location of the MDN site and the nearest upper-air site is Dulles Airport (about 98 km away). For the Harcum site, the selected surface meteorological monitoring site is in Norfolk, VA (about 69 km away) and the nearest upper-air site is at Wallops Island, VA (about 99 km away). (Refer to Figure 2-1b).

The upper-air data are from National Weather Service (NWS) radiosonde monitoring sites, and are available twice per day, at approximately 0700 and 1900 EST. In the plots, we examine data for 850 mb, which is approximately 1500 m above ground level (agl). The upper-air wind data are used here to represent the regional-scale wind patterns. The surface wind data are intended to represent local wind information.

We present the wind data as wind rose diagrams. In these diagrams, wind direction is defined as the direction from which the wind is blowing. The length of the bar within that wind-direction sector indicates the frequency of occurrence of a particular wind direction. The shading indicates the distribution of wind speeds. We specifically examine the distribution of wind direction for all periods and, separately, for high mercury wet deposition periods. Distinguishing features in the wind plots for the high deposition periods, when contrasted to those for all periods, may help to define the wind and/or transport patterns associated with high deposition events. Our qualitative discussion of differences between the plots is not intended to imply that the differences are significant. They are simply provided to advise the reader of our observations.

The 850 mb morning wind distributions for Dulles Airport for all periods and high mercury deposition periods for Culpeper are presented in Figure 3-2. Winds at this level are most frequently from the west to northwest. A comparison of the wind diagrams for the morning sounding time for all days and days within the high deposition periods reveals that the distributions are similar but that there are some differences. For example, there is a slightly greater tendency for easterly winds and a slightly lesser tendency for northerly winds during the high deposition periods.

The 850 mb evening wind distributions for Dulles Airport for all periods and high mercury deposition periods for Culpeper are presented in Figure 3-3. The wind diagrams for the evening period show a greater tendency for both southwesterly and northerly winds during the high deposition periods.

The surface wind distributions for Charlottesville for all periods and high mercury deposition periods for Culpeper are presented in Figure 3-4. Winds at the surface are most frequently from the south to southwest. The wind diagrams for both sets of days are similar, but there are some differences.

The 850 mb morning wind distributions for Dulles Airport for all periods and high mercury deposition periods for Shenandoah are presented in Figure 3-5. Winds at this level are most frequently from the west to northwest. A comparison of the wind diagrams for the morning sounding time for all days and days within the high deposition periods reveals that the distributions are similar but that there are some differences. For example, the wind diagrams show a slightly greater tendency for northeasterly winds and a slightly lesser tendency for northwesterly to northerly winds during the high deposition periods. Winds from the southwest are also slightly less frequent.

The 850 mb evening wind distributions for Dulles Airport for all periods and high mercury deposition periods for Shenandoah are presented in Figure 3-6. As for the morning period, the wind diagrams for the evening period show a slightly greater tendency for northeasterly winds and a slightly lesser tendency for northwesterly to northerly winds during the high deposition periods.

The surface wind distributions for all periods and high mercury deposition periods for Shenandoah are presented in Figure 3-7. Winds at the surface are most frequently from the west to northwest at this high elevation site. The wind diagrams show a greater tendency for westerly winds during the high deposition periods.

The 850 mb morning wind distributions for Wallops Island for all periods and high mercury deposition periods for Harcum are presented in Figure 3-8. Winds at this level and time are most frequently from the southwest to northwest. Comparison of the wind diagrams reveals a different distribution during the high deposition periods that includes a greater predominance of winds from the northwest.

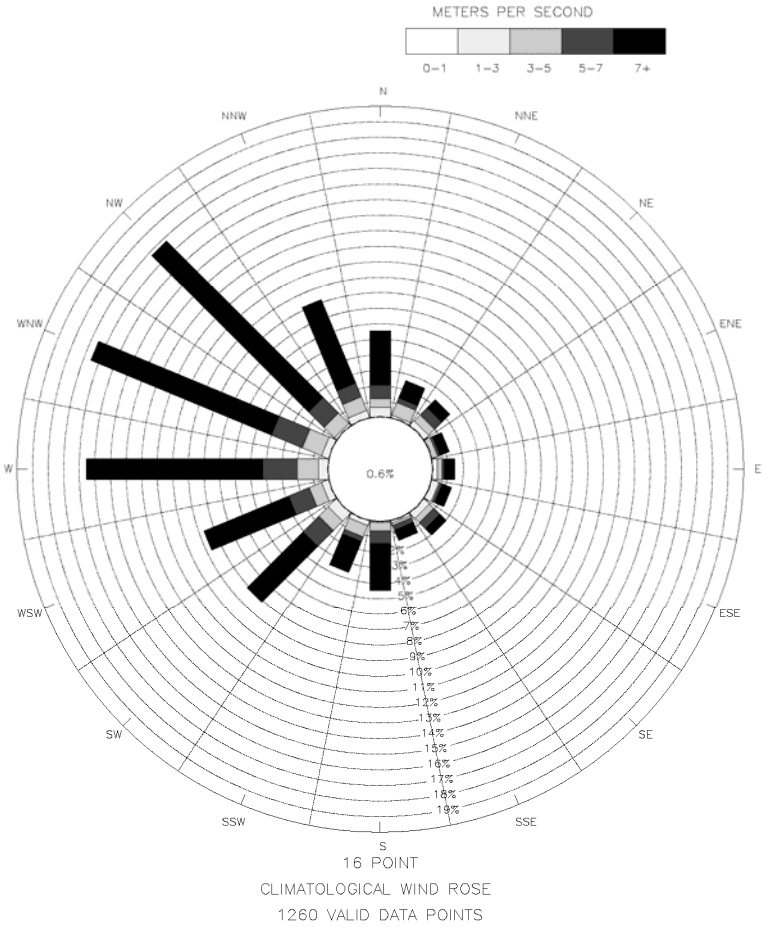
The 850 mb evening wind distributions for Wallops Island for all periods and high mercury deposition periods for Harcum are presented in Figure 3-9. Winds are predominantly from the west to northwest, with some periods of southerly to southwesterly winds. The wind diagrams for the evening period show a slightly greater tendency for southerly winds during the high deposition periods.

The surface wind distributions for Norfolk for all periods and high mercury deposition periods for Harcum are presented in Figure 3-10. The wind rose for the surface indicates a broad range of wind directions, with a greater frequency of winds from the northeast and south-southwest, compared to other directions. For the higher deposition periods, the predominance of these directions is less pronounced and there is an increase in the frequency of winds from the south-southeast.

For all three sites, the wind rose diagrams show that wind directions are slightly different during high deposition periods compared to all periods. This could be an indication of regional or local transport of mercury emissions from the indicated directions (very generally from the east or northeast for Culpeper and Shenandoah, and from the south or southwest for Harcum).

Figure 3-2. Distribution of Wind Speed and Direction at the 850 mb Level for the Sterling, VA (Dulles Airport) Sounding for 0700 EST.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Culpeper (VA08)

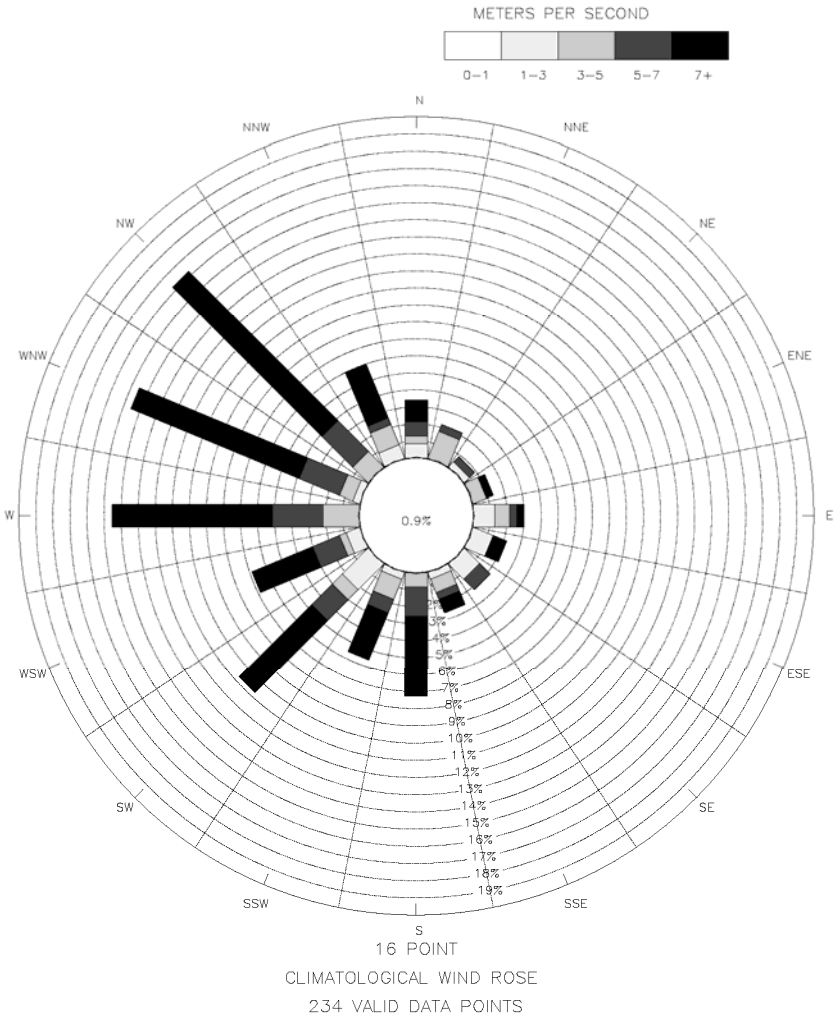
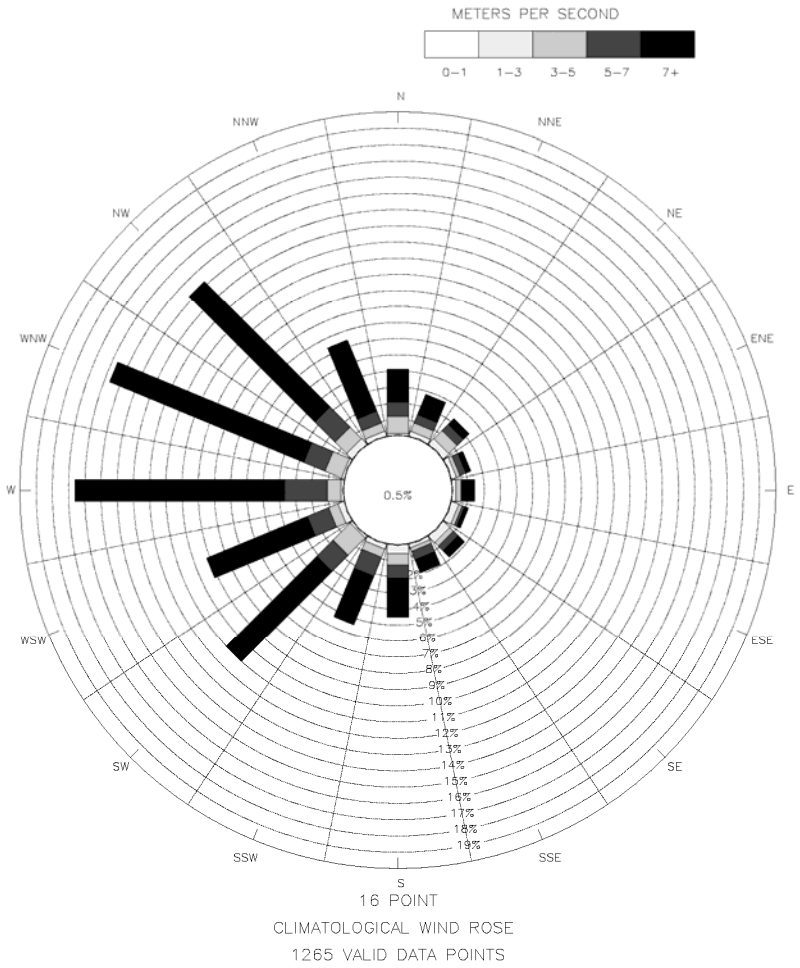


Figure 3-3. Distribution of Wind Speed and Direction at the 850 mb Level for the Sterling, VA (Dulles Airport) Sounding for 1900 EST.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Culpeper (VA08)

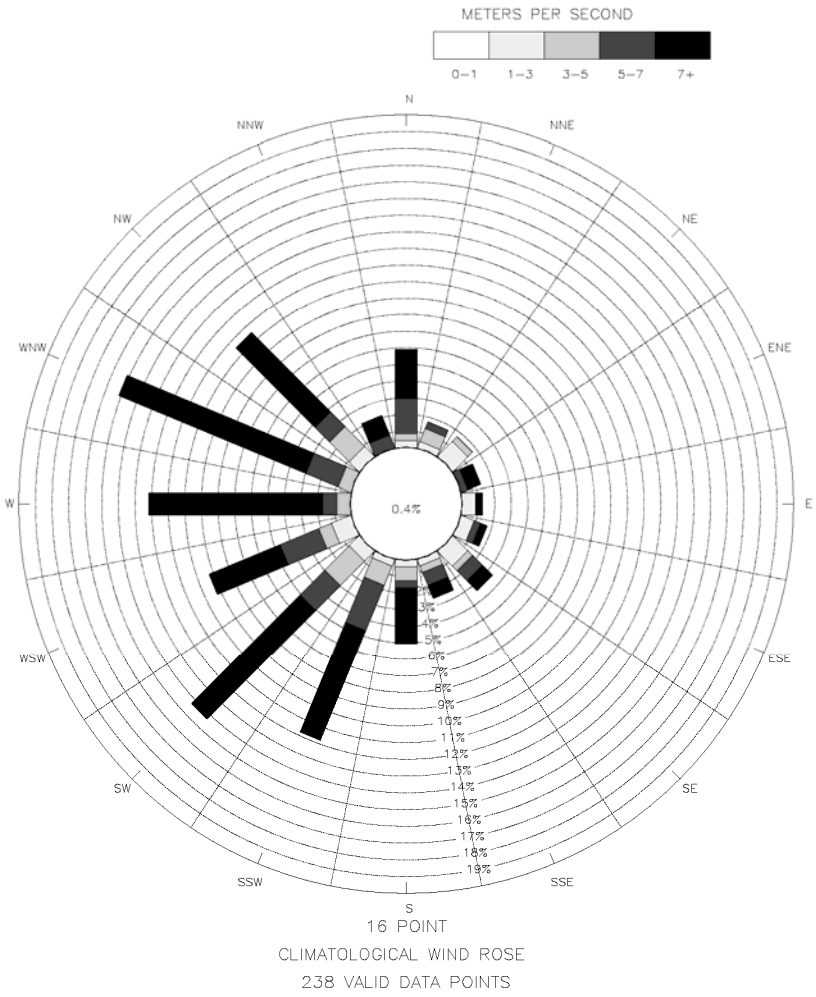
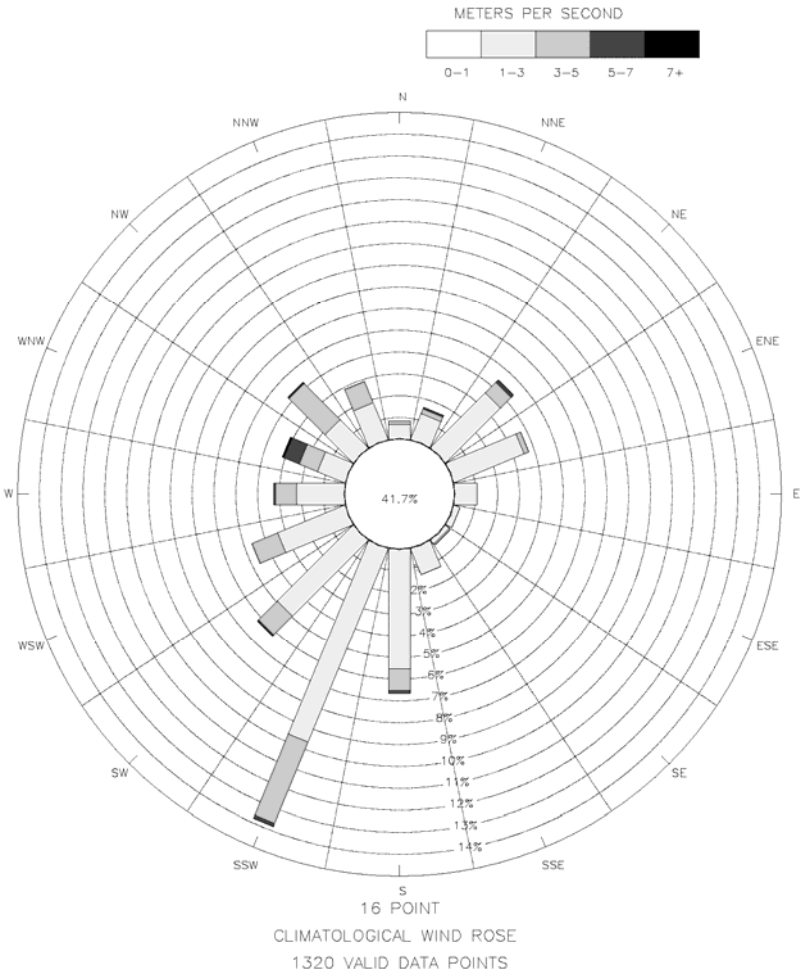


Figure 3-4. Distribution of Surface Wind Speed and Direction for Charlottesville, VA.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Culpeper (VA08)

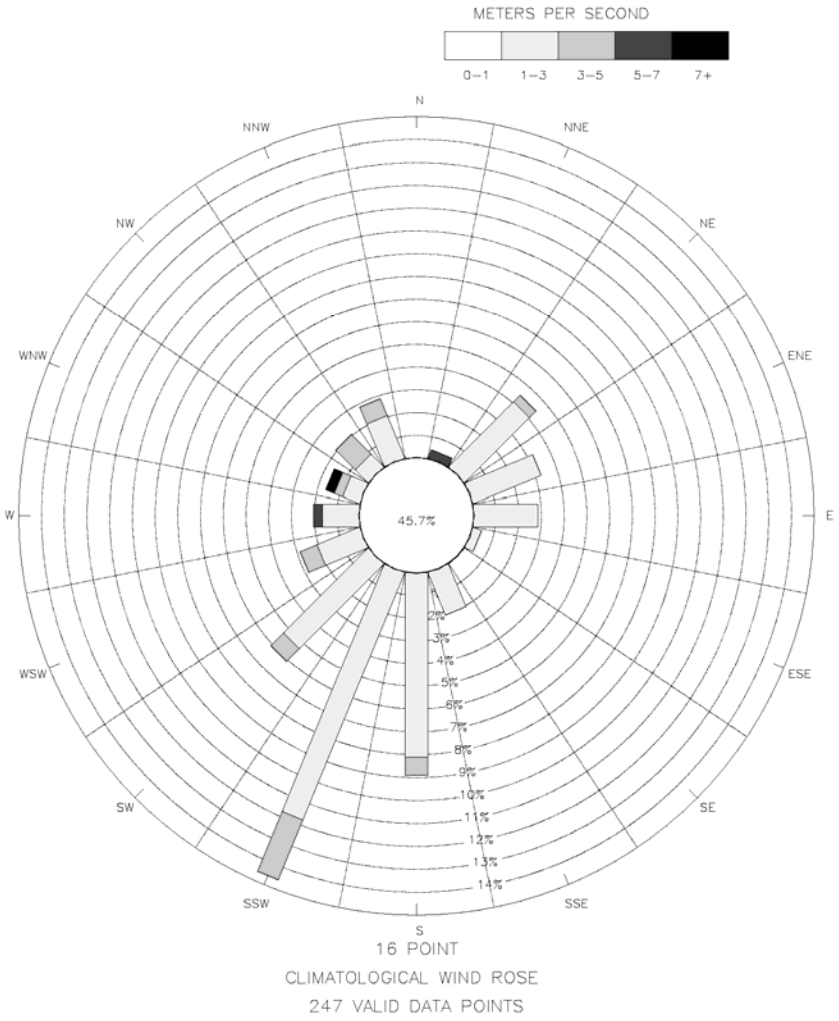
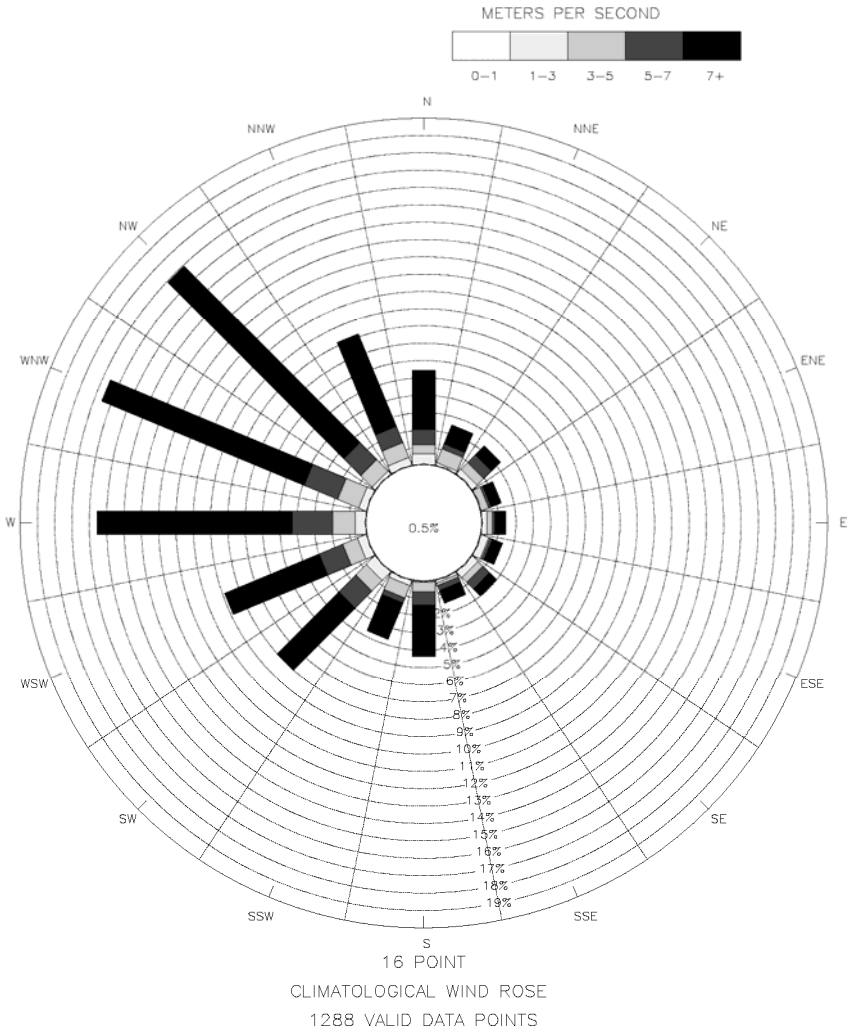


Figure 3-5. Distribution of Wind Speed and Direction at the 850 mb Level for the Sterling, VA (Dulles Airport) Sounding for 0700 EST.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Shenandoah National Park (VA28)

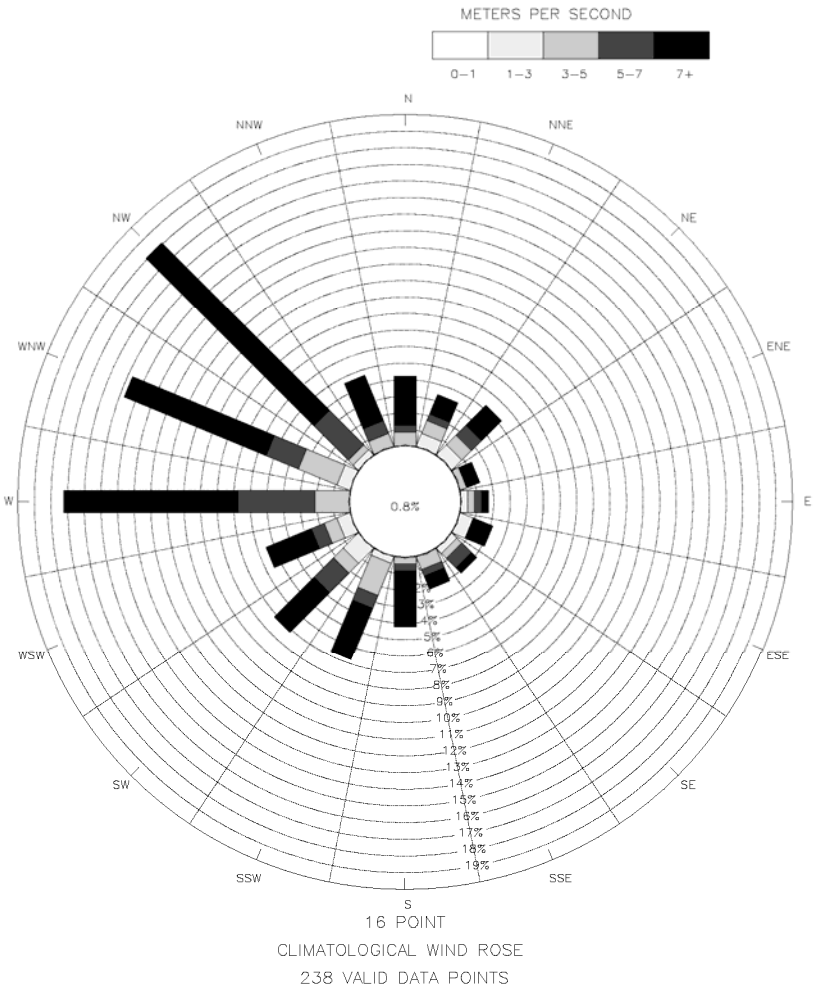
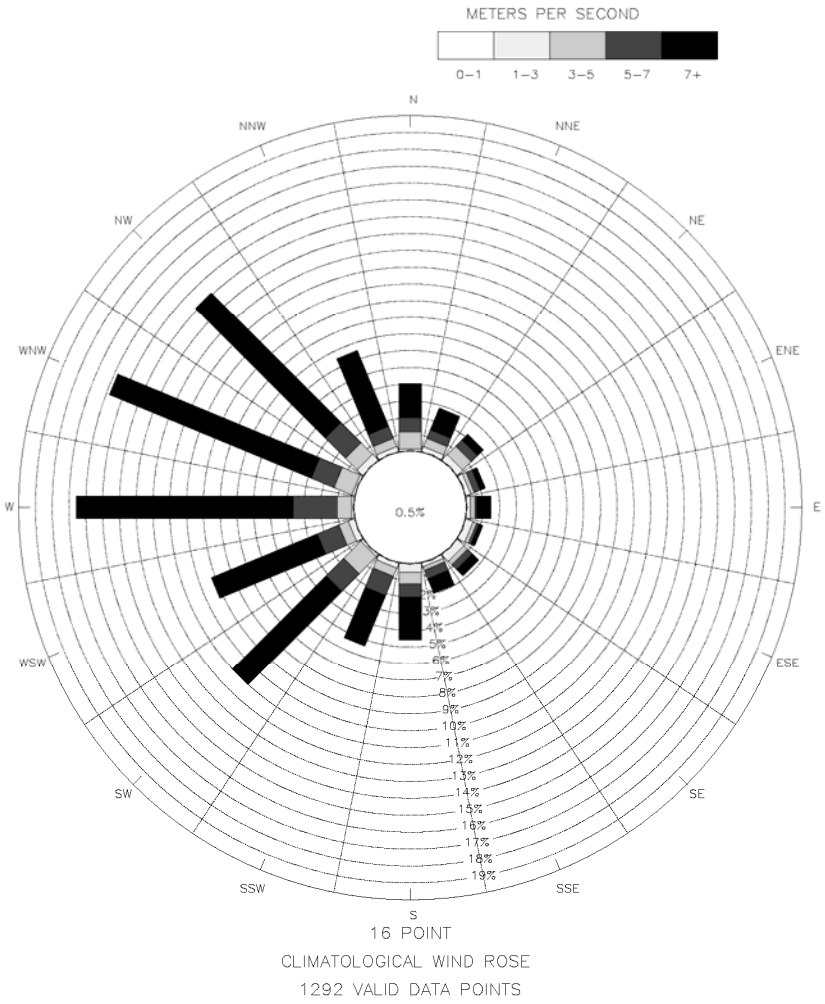


Figure 3-6. Distribution of Wind Speed and Direction at the 850 mb Level for the Sterling, VA (Dulles Airport) Sounding for 1900 EST.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Shenandoah National Park (VA28)

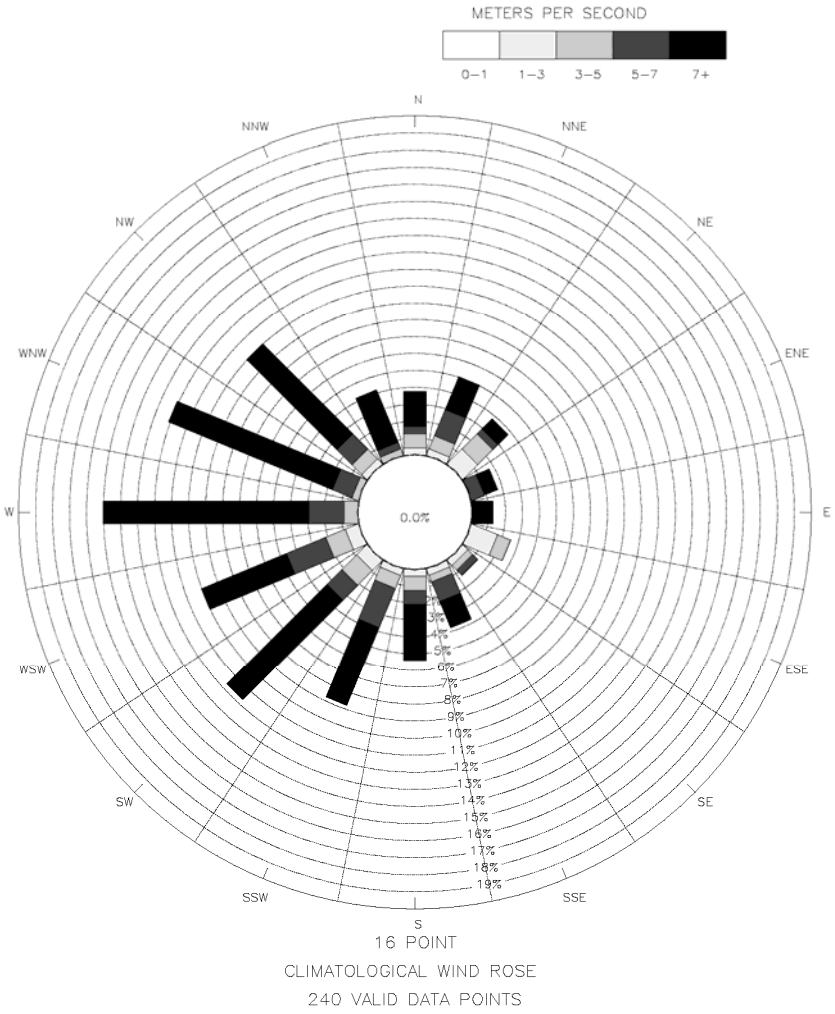
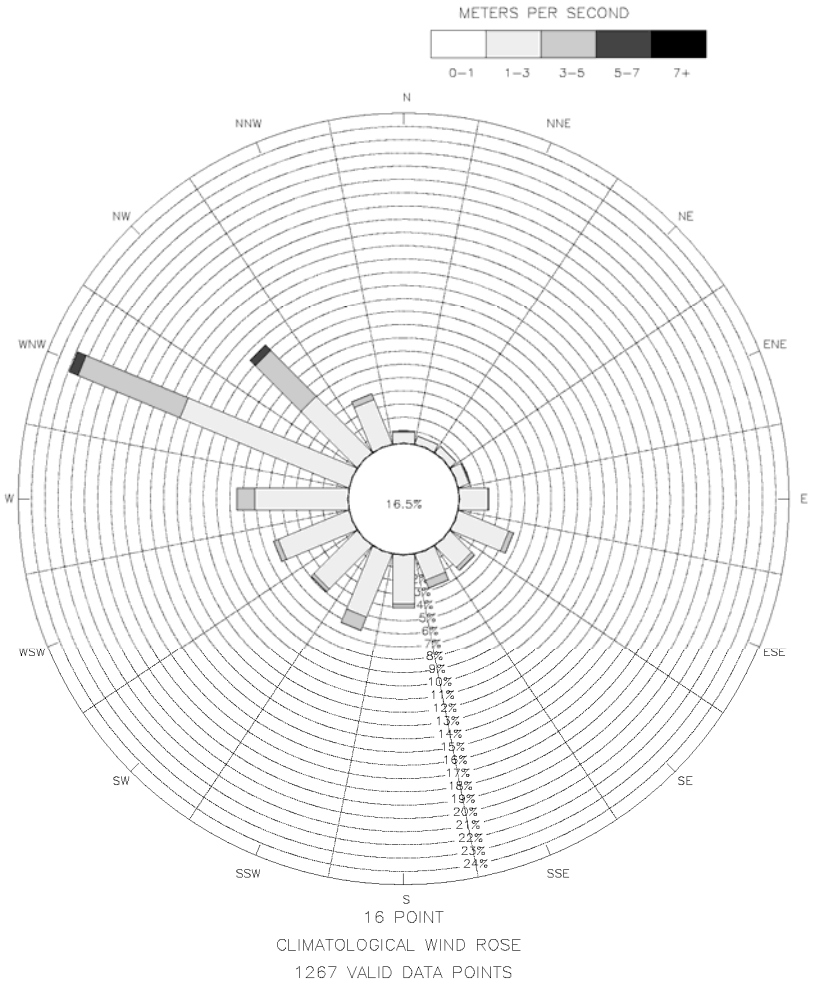


Figure 3-7. Distribution of Surface Wind Speed and Direction for Shenandoah National Park (Big Meadows).

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Shenandoah National Park (VA28)

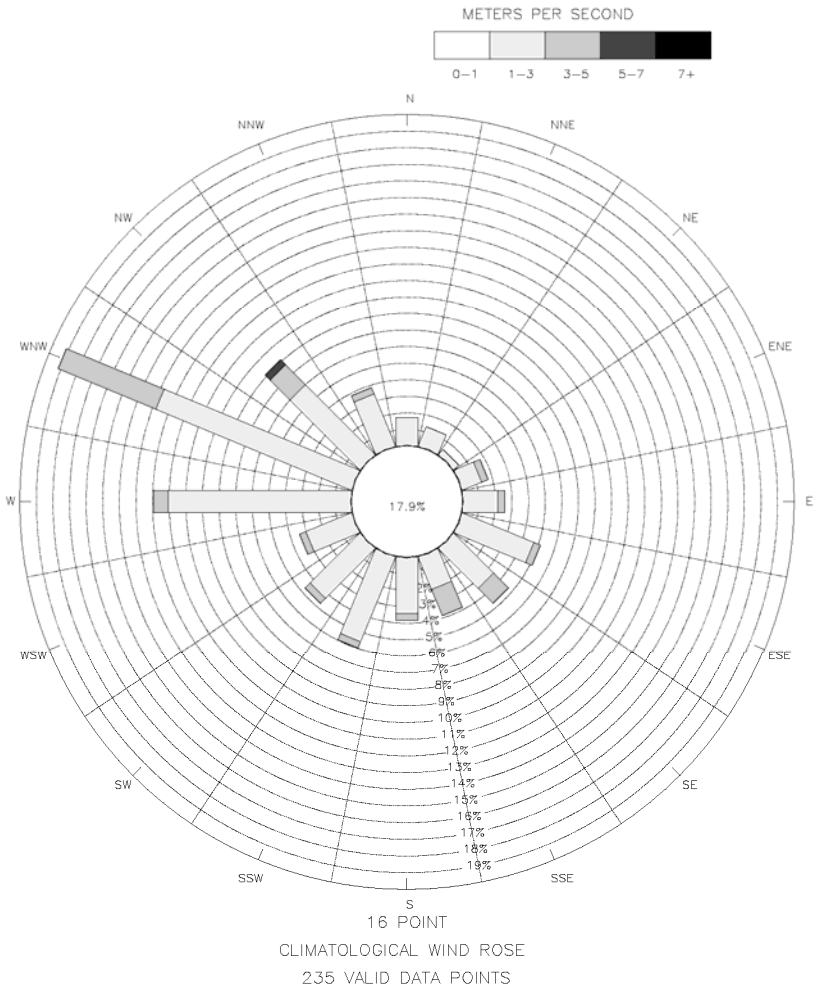
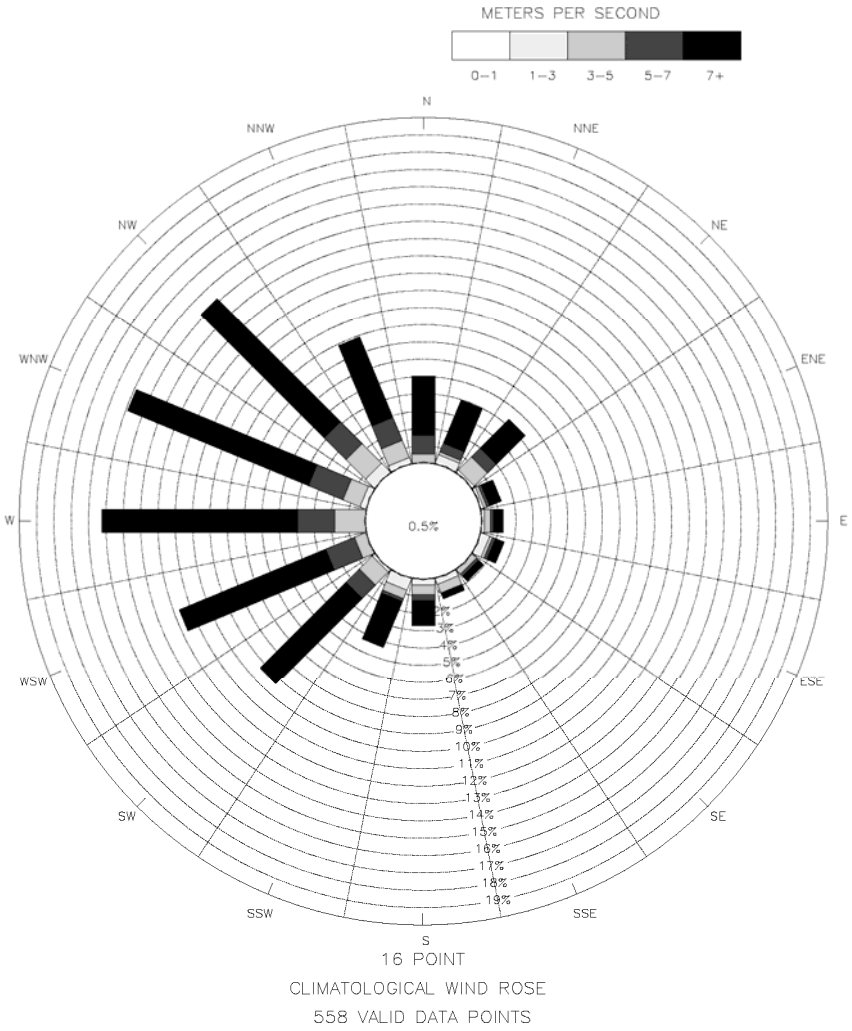


Figure 3-8. Distribution of Wind Speed and Direction at the 850 mb Level for the Wallops Island, VA Sounding for 0700 EST.

(a) All Periods (December 2004 to June 2006)



(b) High Mercury Deposition Periods for Harcum (VA98)

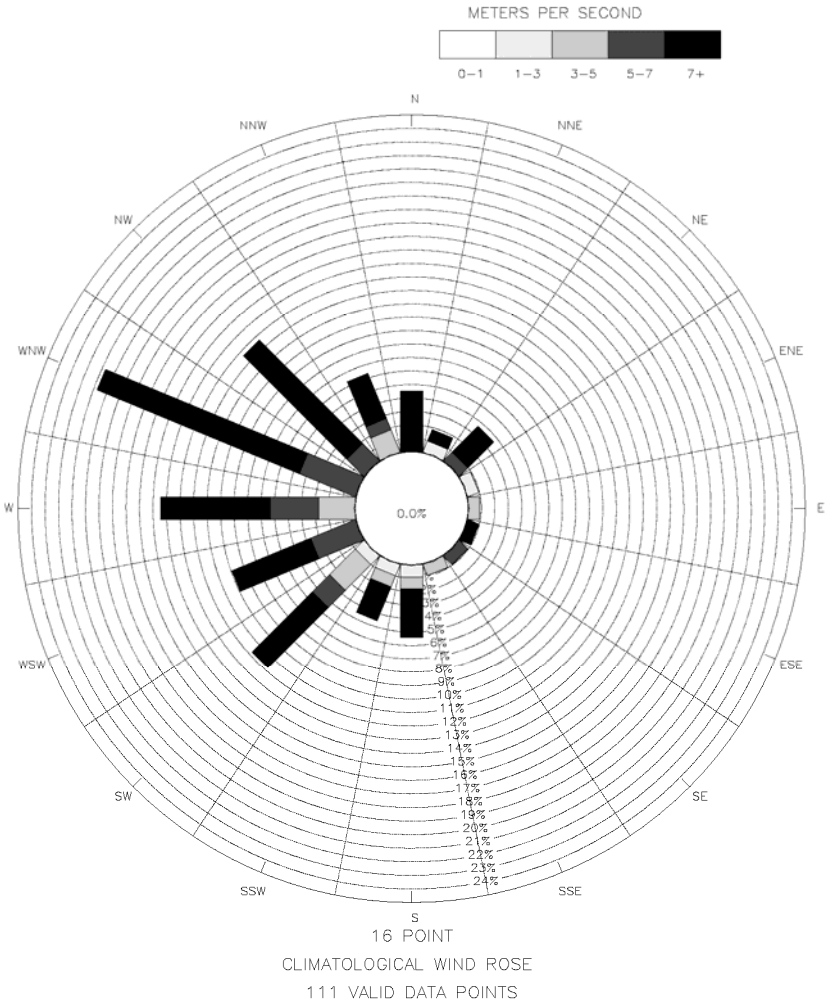
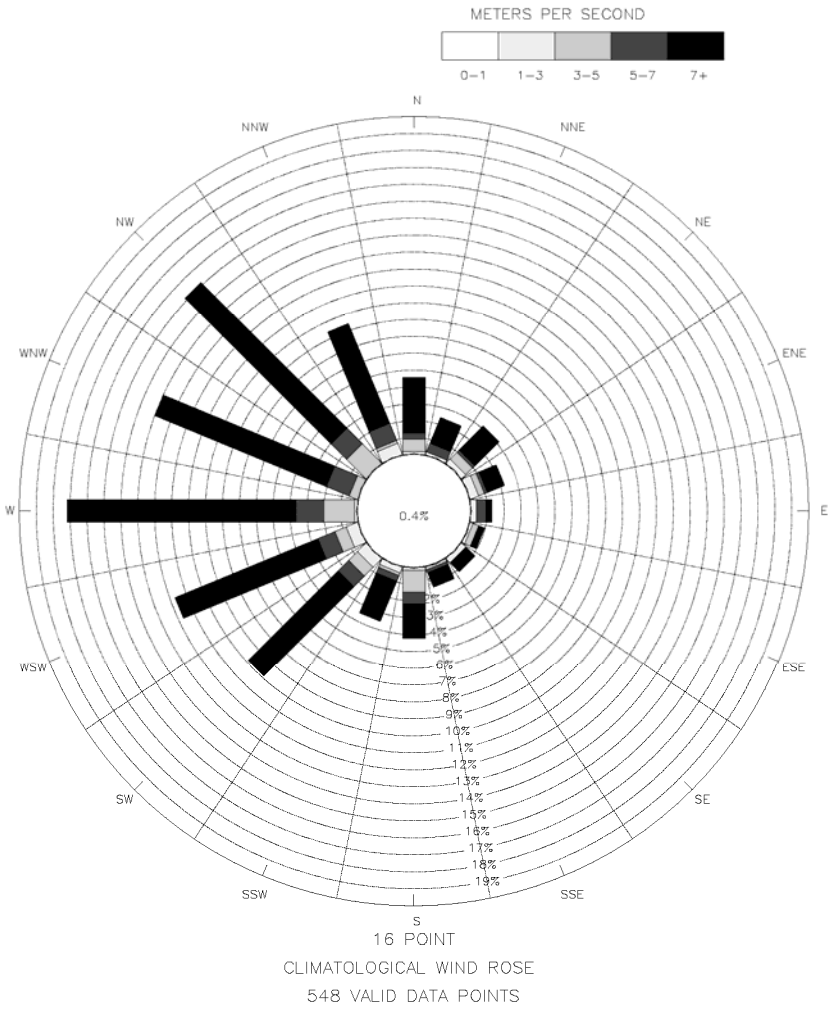


Figure 3-9. Distribution of Wind Speed and Direction at the 850 mb Level for the Wallops Island, VA Sounding for 1900 EST.

(a) All Periods (December 2004 to June 2006)



(b) High Mercury Deposition Periods for Harcum (VA98)

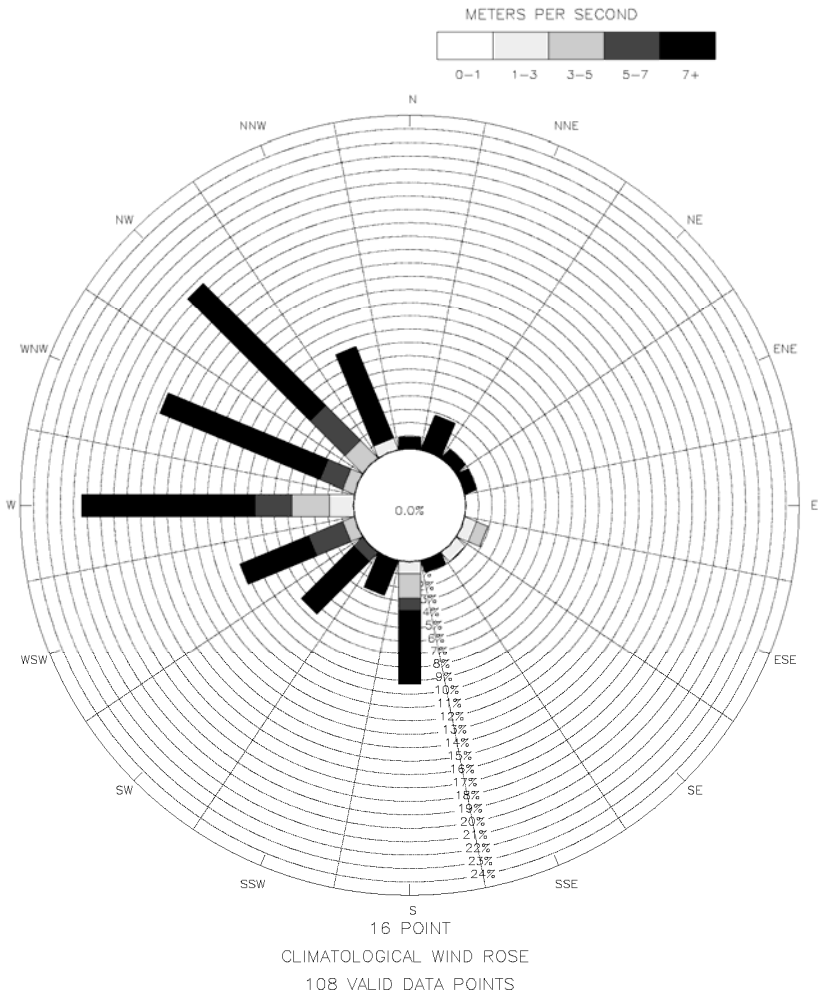
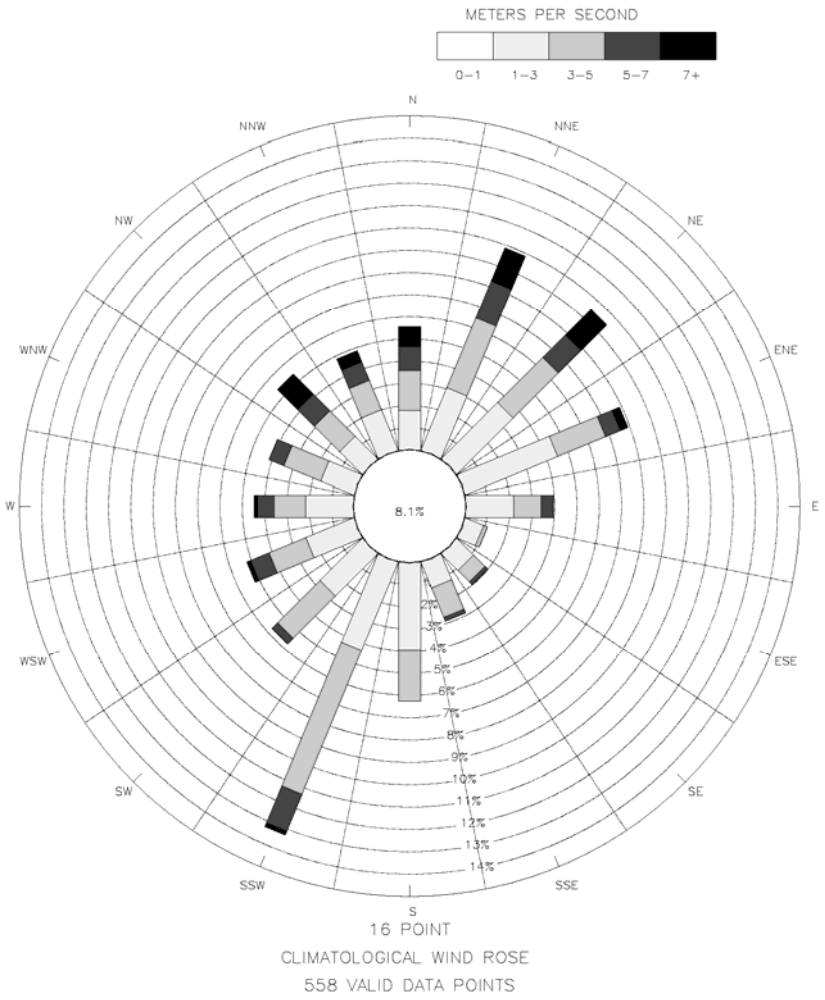
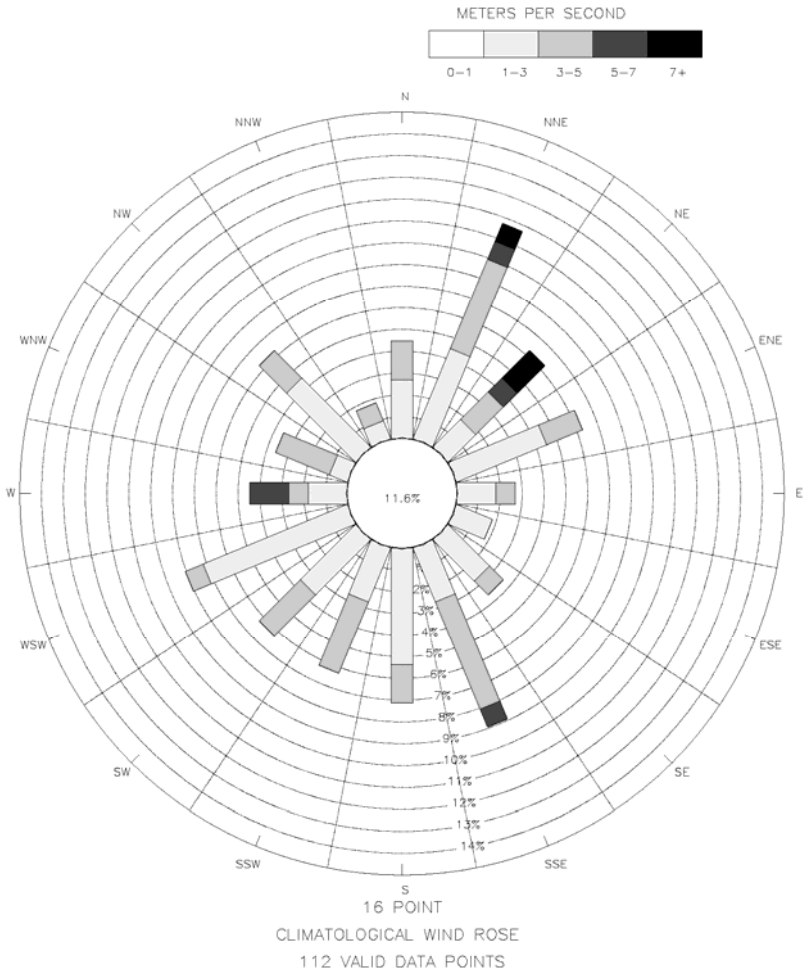


Figure 3-10. Distribution of Surface Wind Speed and Direction for Norfolk, VA.

(a) All Periods (December 2004 to June 2006)



(b) High Mercury Deposition Periods for Harcum (VA98)



3.4. Other Meteorological Factors

The factors that influence mercury wet deposition at the Virginia sites were further examined using correlation analysis and Classification and Regression Tree (CART) analysis.

3.4.1. Correlation Analysis

To further examine possible relationships between observed mercury wet deposition and meteorology, we calculated the correlation between deposition amount and various parameters. For this analysis, the correlation (R) is defined as the sample covariance between the two datasets divided by the product of the standard deviations for each dataset, which is equivalent to:

$$R = \left(n\left(\sum XY\right) - \left(\sum X\right)\left(\sum Y\right)\right) \Big/ \sqrt{\left(n\sum X^2 - \left(\sum X\right)^2\right)\left(n\sum Y^2 - \left(\sum Y\right)^2\right)},$$

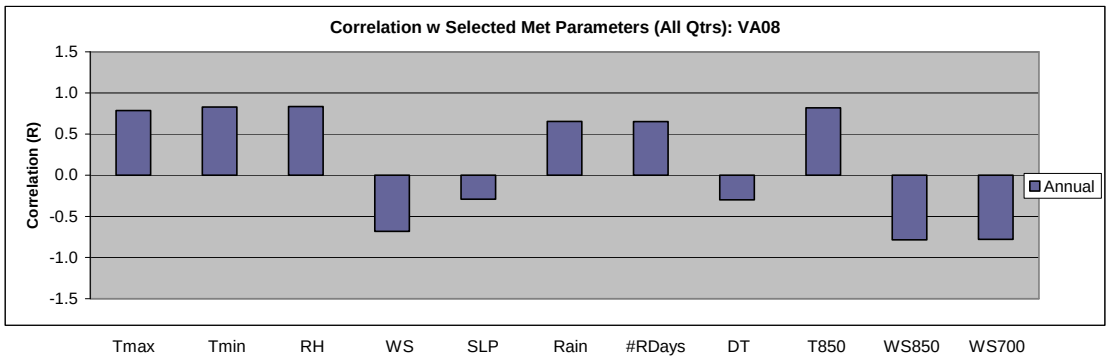
where the two datasets *X* and *Y* each have *n* data points.

The same pairings of MDN and meteorological monitoring sites as discussed above were used for the correlation analysis.

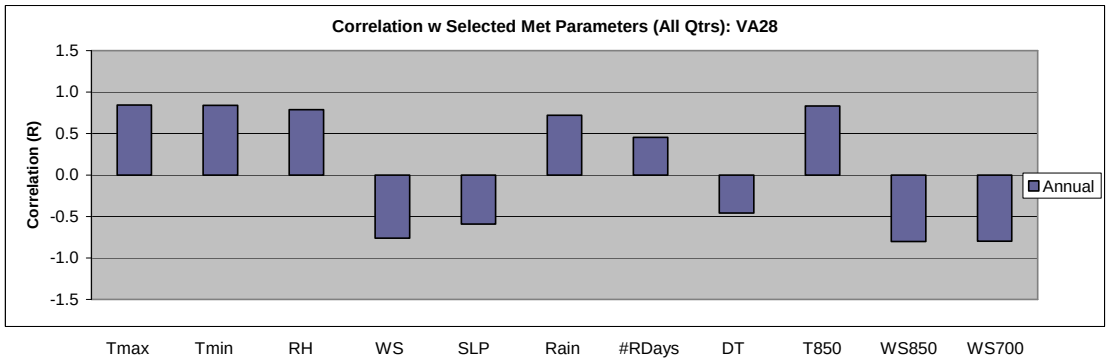
Figure 3-11 shows the R values for mercury wet deposition and the following parameters: maximum temperature (Tmax), minimum temperature (Tmin), relative humidity (RH), surface wind speed (WS), sea level pressure (SLP), rainfall total (Rain), number of days with measurable rainfall (#RDays), temperature gradient between the 900 mb level and the surface (DT), temperature at the 850 mb level (T850), wind speed at 850 mb level (WS850), and wind speed at the 700 mb level (WS700).

Figure 3-11. Correlation Between Annual Mercury Wet Deposition and Selected Meteorological Parameters.

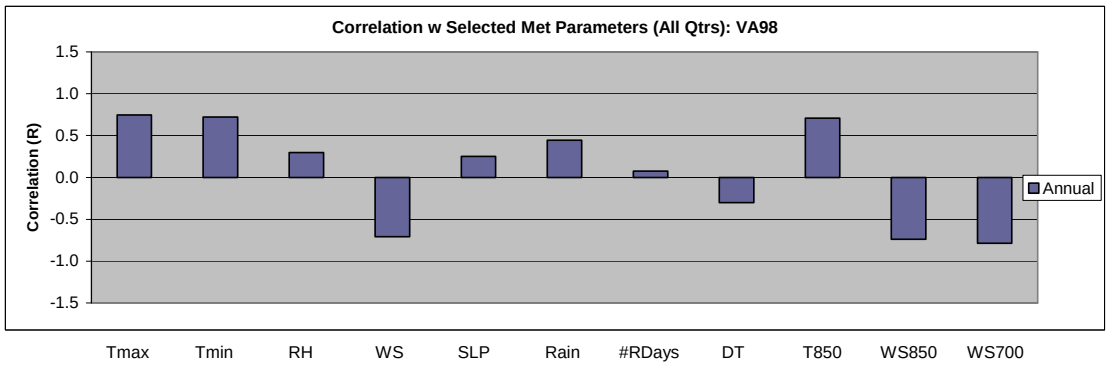
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



(c) Harcum (VA98)



The direction and approximate magnitude of the correlations is very similar among the three sites. For all three sites, there is a positive correlation between rainfall, temperature, and relative humidity such that the greater the values of these parameters, the greater the deposition. High temperatures, high relative humidity, and rainfall are all greatest during the summer months so these correlations are consistent with the quarterly distributions of deposition shown in Section 1 of the report. There is a negative correlation between wind speed and stability which indicates that higher deposition is associated with lower wind speeds and unstable conditions. Again these are representative of summertime conditions (and in the case of stability, rainfall events) and consistent with the timing of the higher observed deposition amounts.

Interestingly, no single parameter (such as rainfall) stands out as being very highly correlated with mercury wet deposition. This indicates that while rainfall is important, other meteorological factors may influence deposition amounts. This is explored further in the next section.

3.4.2. CART Analysis

CART analysis was used to obtain information on the key meteorological factors that influence mercury wet deposition at each of the three MDN monitoring sites.

Overview of CART

The Classification and Regression Tree (CART) analysis technique (Breiman et al., 1984; Steinberg and Colla, 1997) is a statistical analysis technique and was used in this study to classify the mercury deposition periods based on deposition amount and meteorological conditions. The CART analysis software was used to separate the periods into different groups (classification "bins"), such that periods placed within the same bin exhibit similar meteorological features and are characterized by similar average daily mercury wet deposition amounts. For example, one bin may include high deposition periods associated with significant rainfall, instability, and low wind speeds; while another may include high deposition periods with moderate rainfall, northeasterly winds, and higher wind speeds, with transport indicated. Each bin is assigned to a pre-defined classification category. The classification parameter (which is used to define the classification categories) is average daily deposition amount. Since the length of the mercury deposition periods varies, average daily deposition, rather than total deposition for the period, was used as the classification parameter. The remaining parameters (for separating the periods into bins) include a variety of meteorological parameters. CART assumes a causal relationship between the meteorological input parameters and mercury wet deposition (the classification parameter).

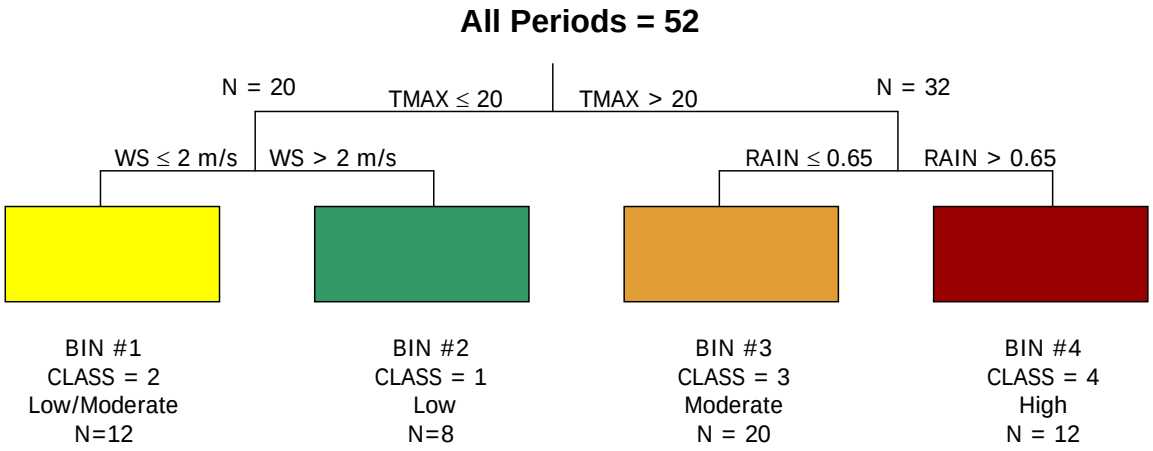
The results of the CART analysis take the form of an upside-down "tree," with branches representing different values of the input parameters leading to bins representing different values of the classification parameter (in this case, mercury wet deposition). Each bin corresponds to a particular range of mercury deposition and a particular set of meteorological conditions. By examining the parameters associated with each classification category, and specifically the parameters and parameter values used to segregate the periods into the various classification bins, the analyst can gain insight into the key differences between high and low deposition periods as well as the mechanisms contributing to high-deposition events.

CART keeps track of the frequency with which each parameter is used in constructing the classification tree and uses this information to rank the various input parameters in terms of relative importance. This information can then be used to infer the relative importance of each parameter to mercury wet deposition.

Each value of the classification parameter may be represented by more than one bin, allowing for the possibility that different combinations of the independent input parameters can be associated with a single value of the classification parameter. By segregating the data values into the classification bins, CART also provides information regarding the frequency of occurrence of the conditions associated with each classification bin (or group of periods). In this manner, the likely recurrence rate for a particular type of period and the associated prevailing conditions are obtained.

A simple example of a CART classification tree diagram is provided in Figure 3-12. In this example, 52 periods are grouped into four classification bins that correspond to different levels of mercury deposition. The bins are distinguished by three independent input parameters: maximum temperature, wind speed, and rainfall amount. In this example, Bin #4 includes 12 periods that are classified as belonging to the highest deposition category (Class 4). Periods with average daily maximum temperatures greater than 20°C and average daily rainfall amounts greater than 0.65 inches are placed in this bin. Bins 1, 2, and 3 are comprised of periods with different deposition and meteorological characteristics.

Figure 3-12. Simple CART Classification Tree Diagram, with Splits on Maximum Temperature (TMAX), Wind Speed (WS), and Precipitation Amount (RAIN).



Note that this is a very simple example of a CART tree. For the VDEQ CART analyses, the CART trees have approximately 15 to 35 bins and include multiple bins for each classification category.

CART Application Procedures

CART was applied separately for each of the three MDN monitoring sites in Virginia as well as five monitoring sites in the surrounding states. The classification parameter is average daily wet mercury deposition. Five deposition ranges, corresponding to Categories 1 to 5, were used for classification. The first category was defined by zero deposition and the remaining four categories were defined by the 20, 50, 80 percentile values of the average daily deposition amount for each site. The categories are therefore defined by the following mercury wet deposition amounts and ranges:

Category 1: No deposition

Category 2: Greater than 0 but less than or equal to the 20 percentile value of deposition

Category 3: Greater than the 20 percentile value but less than or equal to the 50 percentile value

Category 4: Greater than the 50 percentile value but less than or equal to the 80 percentile value

Category 5: Greater than the 80 percentile value

Surface meteorological parameters are used to characterize the local meteorological conditions for the days corresponding to the MDN observation period. Note that most periods include seven days, but this did vary from site to site and throughout the year. The surface meteorological inputs for CART are listed below.

- Average of the daily maximum temperatures (ºC)
- Average of the daily minimum temperatures (ºC)
- Average of the daily (24-hr) average relative humidity values (%)
- Average of the daily (24-hr) average surface wind speed (ms^{-1})
- Average of the daily (24-hr) average surface pressure (mb)
- Predominant surface wind direction (northeast, southeast, southwest, or northwest quadrant), if applicable. Otherwise, calm or variable winds.
- Percent of days with a potential for recirculation[1] (%)
- Average daily rainfall (in)
- Percent of days with measurable rainfall (%)
- Maximum 24-hr rainfall (in).

Upper-air meteorological parameters are used to characterize the regional-scale meteorological conditions. The upper-air parameters are as follows:

- Average of the daily 900 mb to surface am temperature difference (°C)
- Average of the daily 850 mb am temperatures (°C)
- Average of all 850 mb wind speeds for the periods (morning and evening) (ms^{-1})
- Predominant 850 mb wind direction (considering both morning and evening) (northeast, southeast, southwest, or northwest quadrant), if applicable. Otherwise, calm or variable winds.
- Average of all 700 mb wind speeds for the periods (morning and evening) (ms^{-1})
- Predominant 700 mb wind direction (considering both morning and evening) from the (northeast, southeast, southwest, or northwest quadrant), if applicable. Otherwise, calm or variable winds.

[1] Recirculation potential index is defined as: 24-hour average vector wind speed/24-hour average scalar wind speed. This is an indicator of wind persistence. If the value is 1, this indicates that the wind was blowing from the same direction during the entire period. A value of 0 indicates that the wind direction was from one direction for half the time and from the opposite direction the other half of the time. Thus a low value indicates the potential for recirculation.

- Percent of pairs of consecutive days with potential for recirculation aloft (calculated using the daily average wind speed and wind direction (average of morning and evening) and consecutive pairs of days e.g., day1/day2, day2/day3, day3/day4).

The MDN and meteorological site groupings are as follows:

MDN Site = Culpeper (VA08), Surface meteorology = Charlottesville, Upper-air meteorology = Dulles Airport

MDN Site = Shenandoah National Park (VA28), Surface meteorology = Shenandoah, Upper-air meteorology = Dulles Airport

MDN Site = Harcum (VA98), Surface meteorology = Norfolk, Upper-air meteorology = Wallops Island and Dulles Airport

MDN Site = Pettigrew State Park (NC42), Surface meteorology = Elizabeth City, NC, Upper-air meteorology = Morehead City/Newport

MDN Site = Waccamaw (NC08), Surface meteorology = Wilmington, NC, Upper-air meteorology = Morehead City/Newport

MDN Site = Arendtsville (PA00), Surface meteorology = Arendtsville, Upper-air meteorology = Dulles Airport

MDN Site = Allegheny Railroad NHS (PA13), Surface meteorology = Altoona, PA, Upper-air meteorology = Dulles Airport

MDN Site = Great Smoky Mountains National Park (TN11), Surface meteorology = Great Smoky Mountains NP, Upper-air meteorology = Roanoke/Blacksburg

CART Analysis Results

CART was applied separately for each site. In presenting the results, we focus on the Virginia MDN sites and examine classification accuracy, average values of the input parameters by category and by bin, and parameter importance.

CLASSIFICATION ACCURACY

As a first step in reviewing and using the CART results we examined classification accuracy – or the ability of CART to assign each period to the correct deposition category using only the meteorological information. Overall classification accuracy is approximately 80 percent for all three sites, with 80 to 93 percent of the high deposition periods correctly classified. The classification results are presented in Table 3-1. The numbers in the table are the number of cases included in the CART analysis.

Table 3-1. Summary of CART classification accuracy. Units are number of classification periods.

(a) Culpeper (VA08)

CART Category (Right)	1	2	3	4	5
Actual Category (Below)					
1	26	0	1	1	0
2	3	25	1	2	0
3	1	5	37	3	1
4	2	1	6	35	4
5	0	0	2	1	27

(b) Shenandoah National Park (VA28)

CART Category (Right)	1	2	3	4	5
Actual Category (Below)					
1	20	0	0	0	0
2	2	24	4	1	0
3	2	3	29	13	2
4	0	0	2	43	3
5	0	0	0	6	26

(c) Harcum (VA98)

CART Category (Right)	1	2	3	4	5
Actual Category (Below)					
1	9	0	1	0	0
2	0	7	2	4	0
3	0	0	18	1	0
4	0	1	4	14	0
5	0	0	0	1	13

Misclassification can occur due to a number of reasons including: monitoring network limitations (the deposition and meteorological monitoring sites are typically not collocated), use of discrete classification categories (periods with deposition values near the category boundaries may be misplaced into a lower or higher category, but in this case the deposition difference is only

slight), the complexity of the inter-variable relationships, the completeness of the dataset with respect to defining these relationships, and data errors or missing data.

For Culpeper and Shenandoah, CART trees with approximately 25-35 bins were selected to optimize classification accuracy and physical reasonableness. Fewer bins (approximately 15) were selected for Harcum due to the smaller dataset. The majority of the high deposition periods were grouped into one to four key bins.

Comparisons of average values of the CART input parameters by classification category and bin provide the basis for identifying those factors that potentially contribute to the differences in mercury deposition and distinguish each category and bin. The relative importance of each parameter in constructing the CART classification trees (information that is provided by CART) allows us to assess the importance of the meteorological factors in determining deposition amount.

SUMMARY OF RESULTS FOR CULPEPER

Mean values for wet deposition and each meteorological parameter are summarized in Table 3-2 for the five categories of mercury wet deposition (defined by no deposition (Category 1) and the 0 to 20, 20 to 50, 50 to 80, and greater than 80 percentile values of average daily wet deposition (Categories 2 through 5)).

Table 3-2. Summary of Average Input Parameters for Each CART Classification Category: Culpeper, VA (VA08)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Category 1	Category 2	Category 3	Category 4	Category 5
Hg wet deposition (ng/m2)	0.0	3.8	13.7	32.3	79.7
Surface Meteorological Parameters					
Maximum surface temperature (°C)	18.4	13.4	15.2	20.7	23.5
Minimum surface temperature (°C)	6.5	2.3	5.2	10.0	13.8
Relative humidity (%)	58.2	59.4	66.5	69.1	75.3
Surface wind speed (ms^{-1})	1.9	2.2	1.9	1.8	1.6
Surface wind direction (deg)	217	180	211	180	180
% of days with recirculation likely	9.3	10.5	11.0	12.0	9.4
Sea level pressure (mb)	1018	1018	1017	1016	1015
Rainfall amount (in)	0.0	0.1	0.1	0.2	0.3
% of days with measurable rain	32.9	43.7	46.1	60.6	65.0
Daily maximum rainfall amount (in)	0.1	0.3	0.6	0.9	1.2
Upper-Air Meteorological Parameters					
850 mb temperature (AM) (°C)	4.2	1.0	3.7	8.2	11.3
900 mb to sfc temp gradient (AM) (°C)	0.1	0.5	0.2	0.2	-0.6
850 mb wind speed (ms^{-1})	10.3	11.5	11.6	9.4	9.1
700 mb wind speed (ms^{-1})	14.2	15.8	15.8	12.8	12.1
850 mb wind direction (deg)	279	279	277	275	265
700 mb wind direction (deg)	283	276	271	274	270
% of days with recirculation likely	3.4	1.2	2.4	3.2	6.1

A column-by-column comparison of the values in Table 3-2 reveals some clear tendencies in several of the meteorological parameters.

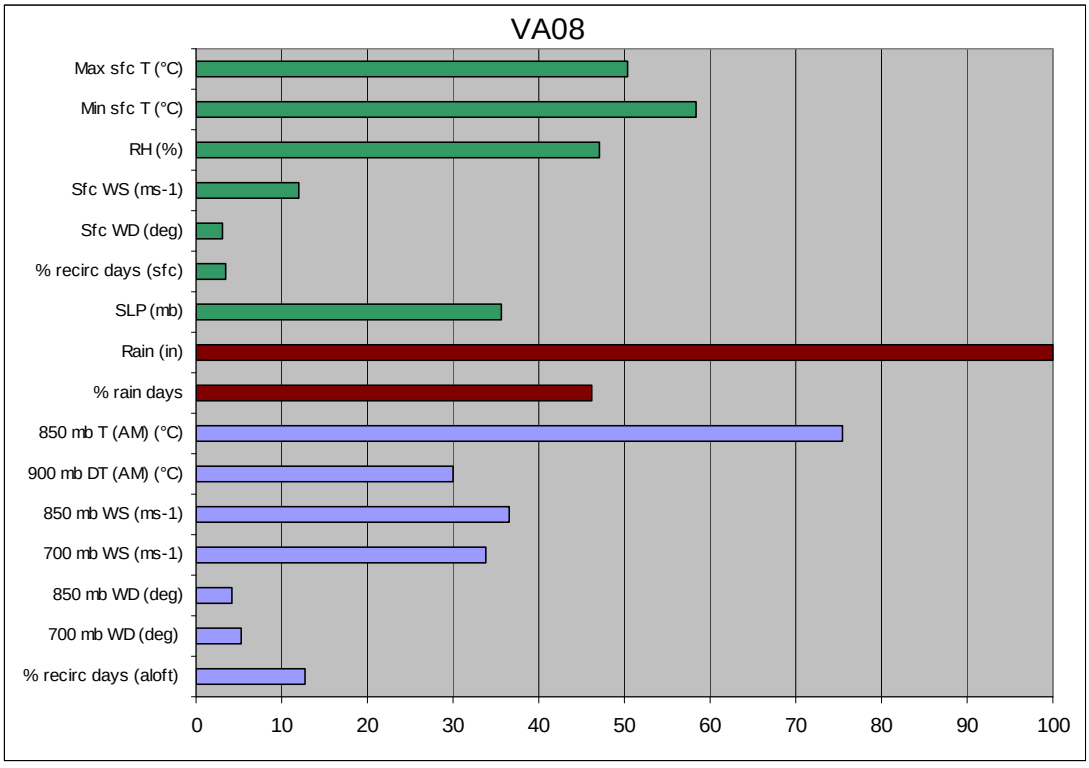
Mercury wet deposition at the Culpeper site is associated with high temperatures, high relative humidity, and rainfall. All three of the rainfall parameters increase steadily with increasing wet deposition. Surface wind speeds decrease with increasing deposition, but for all categories the surface wind directions are southerly to southwesterly.

The upper-air meteorological parameters (based here on Dulles Airport) indicate that higher mercury wet deposition occurs with higher 850 mb temperatures. Conditions within the atmospheric boundary layer are less stable, compared to the other categories.

As for the surface, lower wind speeds aloft are aligned with higher deposition amounts. Average wind directions aloft shift slightly from northwesterly to westerly for the higher deposition periods. Recirculation aloft is more likely during high deposition periods, compared to the other periods.

Key classification parameters for CART include the precipitation parameters, 850 mb temperature, surface temperature parameters, and relative humidity. The relative importance of each parameter, on a scale of 0 to 100, is displayed in Figure 3-13.

Figure 3-13. Relative Importance of the Meteorological Parameters from the Culpeper CART Analysis.



The information in Table 3-2 provides a general overview of how average conditions vary across (and potentially lead to) different mercury deposition amounts for the Culpeper site. Within the high deposition categories, there are other key differences among the parameters that result in different types of high deposition events. We have used the CART results to examine these differences.

Only certain of the CART bins are assigned to Category 5, and contain the majority of the 20 percent highest deposition periods. Of these, we identified those bins with the most number of correctly classified high deposition periods as key bins. Table 3-3 considers the input parameter values for the key high-deposition bins for Culpeper.

Table 3-3. Summary of Average Input Parameters for CART High Deposition Bins: Culpeper, VA (VA08)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Bin 20	Bin 26	Bin 29	Bin 32
No. of observation periods	9	4	8	10
Hg wet deposition (ng/m2)	45.1	48.1	77.1	103.6
Surface Meteorological Parameters				
Maximum surface temperature (°C)	16.8	8.7	26.2	30.2
Minimum surface temperature (°C)	6.3	0.0	17.0	20.5
Relative humidity (%)	71.2	62.3	83.3	77.9
Surface wind speed (ms^{-1})	2.0	2.5	1.2	1.2
Surface wind direction (deg)	236	180	180	180
% of days with recirculation likely	11.1	11.3	12.5	7.9
Sea level pressure (mb)	1013	1017	1015	1016
Rainfall amount (in)	0.3	0.3	0.3	0.3
% of days with measurable rain	63.9	66.9	72.8	63.1
Daily maximum rainfall amount (in)	1.4	1.3	1.4	1.3
Upper-Air Meteorological Parameters				
850 mb temperature (AM) (°C)	5.1	1.3	13.3	16.7
900 mb to sfc temp gradient (AM) (°C)	0.8	2.2	-1.9	-1.4
850 mb wind speed (ms^{-1})	10.6	16.1	7.2	6.7
700 mb wind speed (ms^{-1})	14.3	22.1	9.8	8.7
850 mb wind direction (deg)	275	288	297	270
700 mb wind direction (deg)	275	270	297	279
% of days with recirculation likely	2.8	0.0	8.8	8.7

Bins 20, 26, 29 and 32 are all Category 5 bins. While many of the characteristics are similar, there are some differences. These provide possible insight into the factors influencing the deposition periods within each bin.

Bins 20 and 26 are distinguished from the other high deposition bins by lower deposition amounts, lower temperatures, and higher wind speeds. Rainfall amounts are similar to those for the other high deposition periods. Thus these high deposition periods correspond to cooler season events. Differences in temperature, wind speed, surface wind direction, and stability

also distinguish periods in Bin 20 from those in Bin 26. Periods in Bin 26 have lower temperatures, higher wind speeds, and greater stability. Average surface winds are from the southwest for Bin 20 and from the south for Bin 26.

For Bin 29, higher deposition amounts are coupled with high relative humidity and the greatest percentage of days with measurable rainfall among the key Category 5 bins. Periods within this bin are also the least stable. The humidity and instability suggest that the rainfall is associated with local thunderstorm activity.

On average, the periods in Bin 32 have the highest wet deposition amounts, as well as the highest temperatures and lowest wind speeds among the key high-deposition bins.

SUMMARY OF RESULTS FOR SHENANDOAH

Mean values for wet deposition and each meteorological parameter are summarized in Table 3-4 for the five categories of mercury wet deposition (defined by no deposition (Category 1) and the 0 to 20, 20 to 50, 50 to 80, and greater than 80 percentile values of average daily wet deposition (Categories 2 through 5)).

Table 3-4. Summary of Average Input Parameters for Each CART Classification Category: Shenandoah National Park (VA28)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Category 1	Category 2	Category 3	Category 4	Category 5
Hg wet deposition (ng/m2)	0.0	4.0	14.9	32.5	85.4
Surface Meteorological Parameters					
Maximum surface temperature (°C)	9.8	4.9	10.7	13.0	16.3
Minimum surface temperature (°C)	2.5	-2.1	4.2	6.3	9.9
Relative humidity (%)	68.3	68.5	76.4	77.4	81.8
Surface wind speed (ms^{-1})	2.2	2.7	2.4	2.3	2.2
Surface wind direction (deg)	277	270	268	254	258
% of days with recirculation likely	10.4	6.9	10.5	10.8	9.5
Sea level pressure (mb)	1019	1018	1016	1016	1015
Rainfall amount (in)	0.0	0.0	0.1	0.2	0.4
% of days with measurable rain	13.8	31.0	39.5	45.2	53.0
Daily maximum rainfall amount (in)	0.1	0.3	0.6	1.1	1.5
Upper-Air Meteorological Parameters					
850 mb temperature (AM) (°C)	3.6	-0.1	5.7	7.8	10.6
900 mb to sfc temp gradient (AM) (°C)	0.9	0.5	0.0	0.2	-0.6
850 mb wind speed (ms^{-1})	10.0	12.1	10.5	9.9	9.4
700 mb wind speed (ms^{-1})	14.2	16.9	14.4	13.3	12.1
850 mb wind direction (deg)	277	270	268	254	258
700 mb wind direction (deg)	280	276	275	270	272
% of days with recirculation likely	3.3	1.2	4.1	2.6	3.5

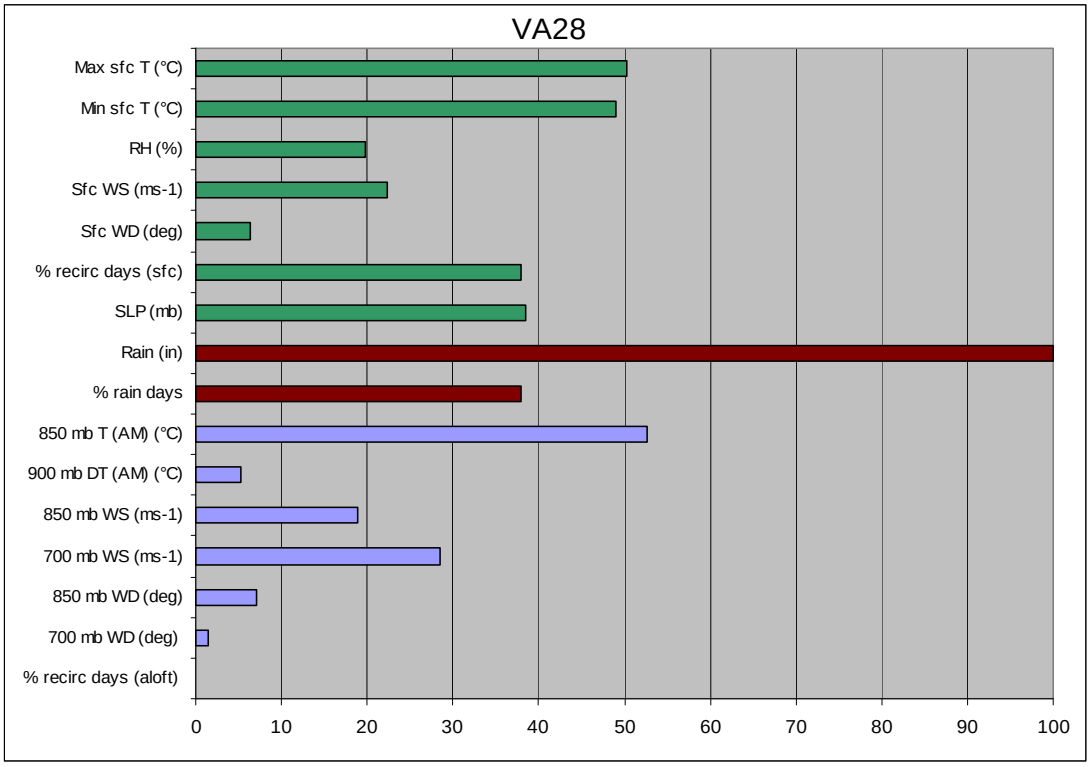
Mercury wet deposition at the Shenandoah site is associated with higher temperatures, high relative humidity, and rainfall. All three of the rainfall parameters increase steadily with increasing wet deposition. Surface wind speeds decrease with increasing deposition, and surface wind directions back slightly from west-northwesterly to west-southwesterly.

The upper-air meteorological parameters (based here on Dulles Airport) indicate that higher mercury wet deposition occurs with higher 850 mb temperatures. Conditions within the atmospheric boundary layer are less stable, compared to the other categories.

Lower wind speeds aloft are also associated with higher deposition amounts. Average wind directions at 850 mb also shift slightly from west-northwesterly to west-southwesterly for the higher deposition periods.

Key classification parameters for CART include the precipitation and temperature parameters; pressure, recirculation (near the surface), and wind speed (near the surface and aloft) are also relatively important. The relative importance of each parameter, on a scale of 0 to 100, is displayed in Figure 3-14.

Figure 3-14. Relative Importance of the Meteorological Parameters from the Shenandoah National Park CART Analysis.



Within the high deposition categories, there are other key differences among the parameters that result in different types of high deposition events. We have used the CART results to examine these differences.

Of the CART bins assigned to Category 5, two contain the majority of the 20 percent highest deposition periods. Table 3-5 considers the input parameter values for the key high-deposition bins.

Table 3-5. Summary of Average Input Parameters for CART High Deposition Bins: Shenandoah National Park, VA (VA28)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Bin 23	Bin 27
No. of observation periods	7	23
Hg wet deposition (ng/m2)	41.2	95.0
Surface Meteorological Parameters		
Maximum surface temperature (°C)	8.4	19.5
Minimum surface temperature (°C)	0.5	13.8
Relative humidity (%)	72.9	85.4
Surface wind speed (ms^{-1})	3.0	1.9
Surface wind direction (deg)	90	270
% of days with recirculation likely	7.1	9.8
Sea level pressure (mb)	1016	1015
Rainfall amount (in)	0.3	0.4
% of days with measurable rain	43.6	57.7
Daily maximum rainfall amount (in)	1.6	1.5
Upper-Air Meteorological Parameters		
850 mb temperature (AM) (°C)	3.9	13.6
900 mb to sfc temp gradient (AM) (°C)	1.8	-1.0
850 mb wind speed (ms^{-1})	12.9	8.2
700 mb wind speed (ms^{-1})	16.4	10.3
850 mb wind direction (deg)	90	270
700 mb wind direction (deg)	0	270
% of days with recirculation likely	0.0	5.0

Bins 23 and 27 appear to contain cooler and warmer season deposition events, respectively. A key difference is that the periods in Bin 27 have higher average deposition amounts. The bins are further distinguished from one another by differences in temperature, relative humidity, wind speed, wind direction, and stability. Rainfall amounts are similar, but the Bin 27 periods have a greater percentage of days with measurable precipitation. For Bin 23, average winds (for both the surface and aloft) are from the north or east, compared to the west for Bin 27.

SUMMARY OF RESULTS FOR HARCUM

Mean values for wet deposition and each meteorological parameter are summarized in Table 3-6 for the five categories of mercury wet deposition (defined by no deposition (Category 1) and the 0 to 20, 20 to 50, 50 to 80, and greater than 80 percentile values of average daily wet deposition (Categories 2 through 5)).

Table 3-6. Summary of Average Input Parameters for Each CART Classification Category: Harcum, VA (VA98)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Category 1	Category 2	Category 3	Category 4	Category 5
Hg wet deposition (ng/m2)	0.0	2.3	11.4	27.1	69.0
Surface Meteorological Parameters					
Maximum surface temperature (°C)	20.2	16.1	17.2	18.6	22.8
Minimum surface temperature (°C)	12.0	8.1	9.1	11.2	14.4
Relative humidity (%)	61.7	67.6	64.2	69.2	67.9
Surface wind speed (ms^{-1})	4.5	4.3	4.8	4.3	3.8
Surface wind direction (deg)	207	63	0	45	180
% of days with recirculation likely	7.7	21.8	17.3	13.1	21.4
Sea level pressure (mb)	1015	1014	1014	1010	1013
Rainfall amount (in)	0.0	0.1	0.1	0.1	0.1
% of days with measurable rain	18.8	33.8	30.2	44.4	58.0
Daily maximum rainfall amount (in)	0.1	0.4	0.4	0.9	0.6
Upper-Air Meteorological Parameters					
850 mb temperature (AM) (°C)	7.3	4.2	4.4	5.8	8.4
900 mb to sfc temp gradient (AM) (°C)	-0.7	-1.3	0.7	-0.9	-1.4
850 mb wind speed (ms^{-1})	10.3	11.7	11.6	10.2	10.2
700 mb wind speed (ms^{-1})	13.1	16.3	15.9	13.7	13.4
850 mb wind direction (deg)	307	283	281	283	266
700 mb wind direction (deg)	284	270	284	270	270
% of days with recirculation likely	2.5	1.0	0.6	4.6	2.7

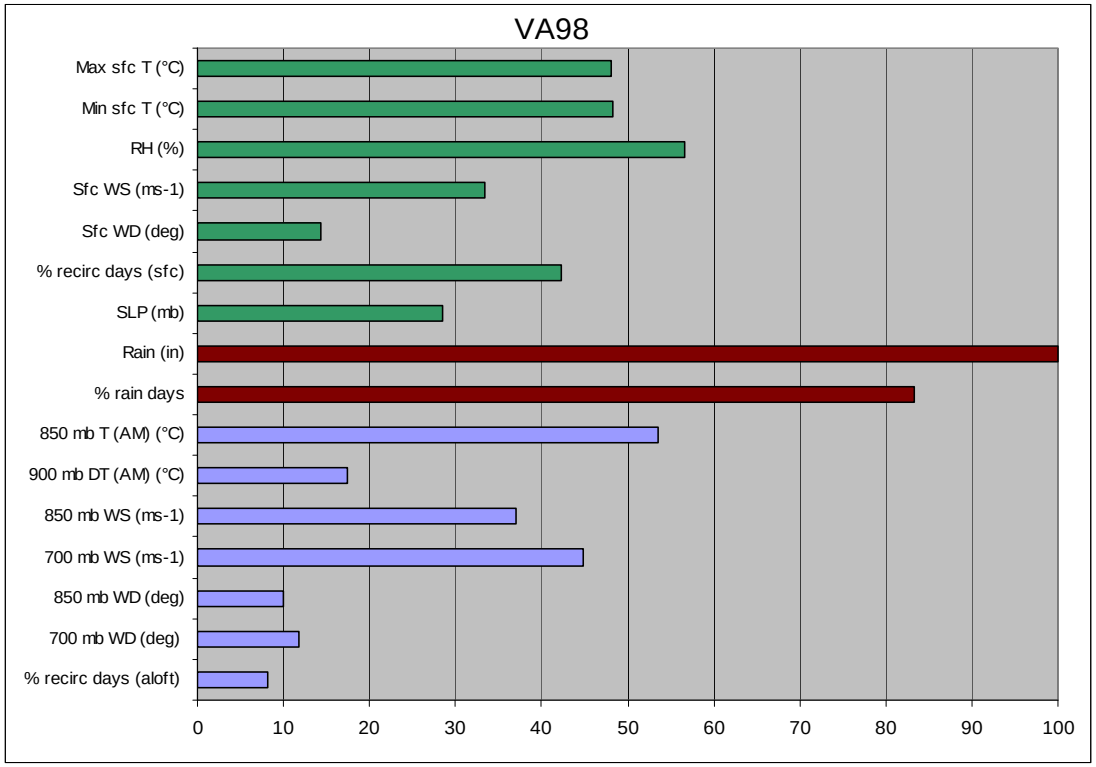
Mercury wet deposition at the Harcum site is generally associated with higher temperatures and lower wind speeds. The number of rain days increases with increasing wet deposition, but the other two rainfall parameters do not follow the pattern of deposition as clearly. Considering the non-zero deposition periods, surface wind directions veer from northerly/northeasterly to southerly with increasing deposition.

The upper-air meteorological parameters (based here on Wallops Island) indicate that higher mercury wet deposition occurs with slightly higher 850 mb temperatures and slightly lower wind speeds. Average wind directions at 850 mb also shift slightly from west-northwesterly to westerly for the higher deposition periods.

It is also interesting to note the differences in average wind direction between the surface and the 850 mb level. This could be due to the influence of the Chesapeake Bay on surface wind directions.

Key classification parameters for CART include the precipitation parameters, relative humidity and temperature parameters. Recirculation (near the surface) is indicated to be relatively important and suggests some influence from the sea- or bay breeze. Wind speed aloft is also relatively important for the Harcum CART analysis. The relative importance of each parameter, on a scale of 0 to 100, is displayed in Figure 3-15.

Figure 3-15. Relative Importance of the Meteorological Parameters from the Harcum CART Analysis.



All but two of the 14 highest deposition periods are assigned to Bin 13 and the average values closely match those for all Category 5 periods, as presented in Table 3-6. Due to the limited period of record for the Harcum site, CART was not able to identify multiple high-deposition regimes.

3.5. Effects of Meteorology on Mercury Trends

Variations in meteorology contribute to the observed variations in quarterly and annual mercury wet deposition. These variations in meteorology may make if difficult to identify trends in the data that are due to changes in emissions. In this section, we examine "meteorologically adjusted" annual mercury deposition values for the two MDN sites in Virginia with multiple complete years of data (Culpeper and Shenandoah) as well as several sites in neighboring states. The meteorologically adjusted deposition values are then compared with emissions estimates for an analysis of recent trends.

In developing the "meteorologically adjusted" deposition values, our objective was to create a deposition metric that is not sensitive to yearly meteorological variation. This exercise relies on results of the Classification and Regression Tree (CART) analysis, as discussed earlier in this section.

CART was used to classify the mercury deposition periods according to deposition amount and meteorological conditions. While the category of a bin reflects the amount of mercury wet deposition associated with the bin's meteorological conditions, the number of periods and days in a bin represents the frequency with which those conditions occur. Since the bins are determined

using a multi-year period, individual years may be normalized such that the different sets of meteorological conditions are represented no more or less than they are on average over all years in the period. This is the basis for our creation of meteorologically adjusted design values.

The specific steps include:

Step 1: Determine the average number of days per bin and per year to include in the normalized year (accounting for differences in the number of days per deposition measurement period).

Step 2. For each bin, calculate the daily average deposition amount represented by each bin, for each year included in the analysis and for all years. Use only days from correctly classified deposition periods in the calculation.

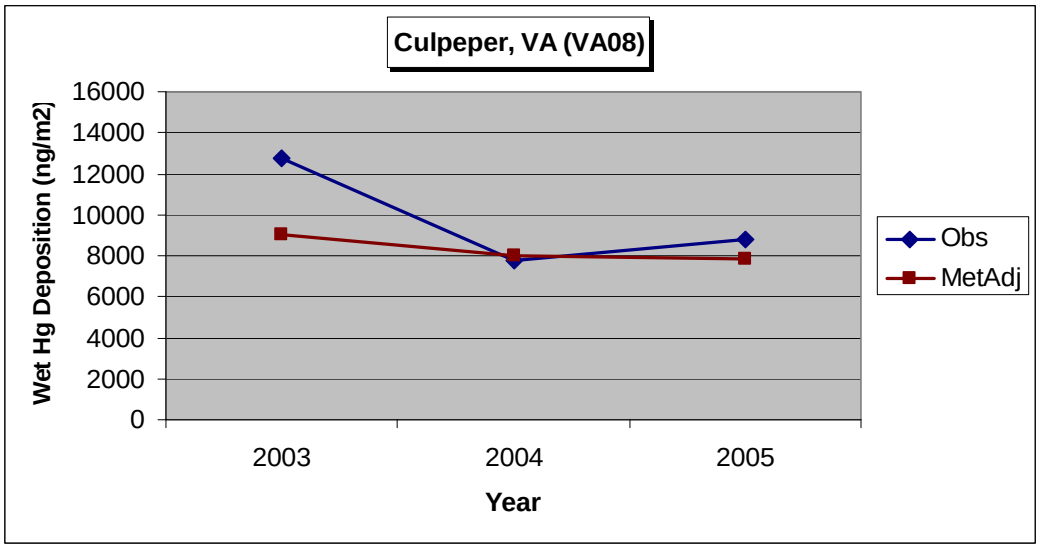
Step 3: If a bin is not represented in a given year, assign the overall average value to that bin.

Step 4: For each bin and each year, calculate the adjusted deposition amount. This is equal to the average number of days per bin per year (from Step 1) multiplied by the average deposition amount for each bin (from Steps 2 and 3).

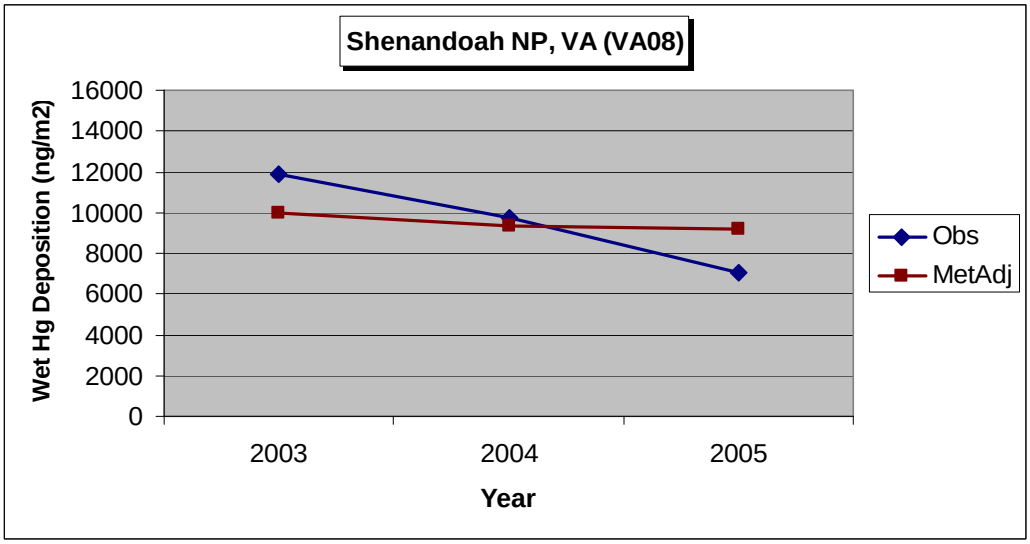
The resulting meteorologically adjusted deposition values for the Culpeper (VA08) and Shenandoah National Park (VA28) sites are illustrated in Figure 3-16.

Figure 3-16. Actual & Meteorologically-Adjusted Annual Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)

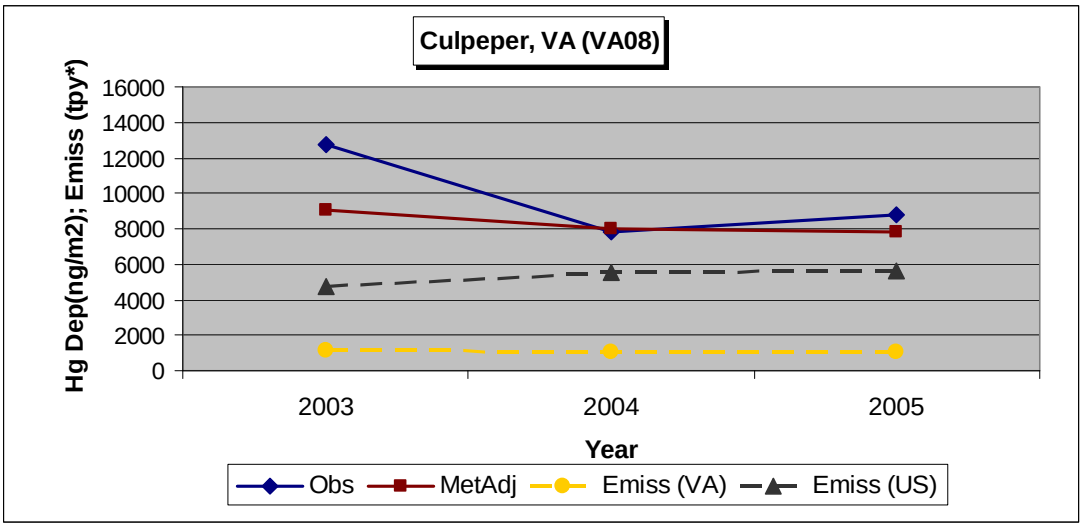


The meteorologically adjusted deposition amounts exhibit less variation among the years and indicate a slight downward trend in mercury deposition during this three-year period.

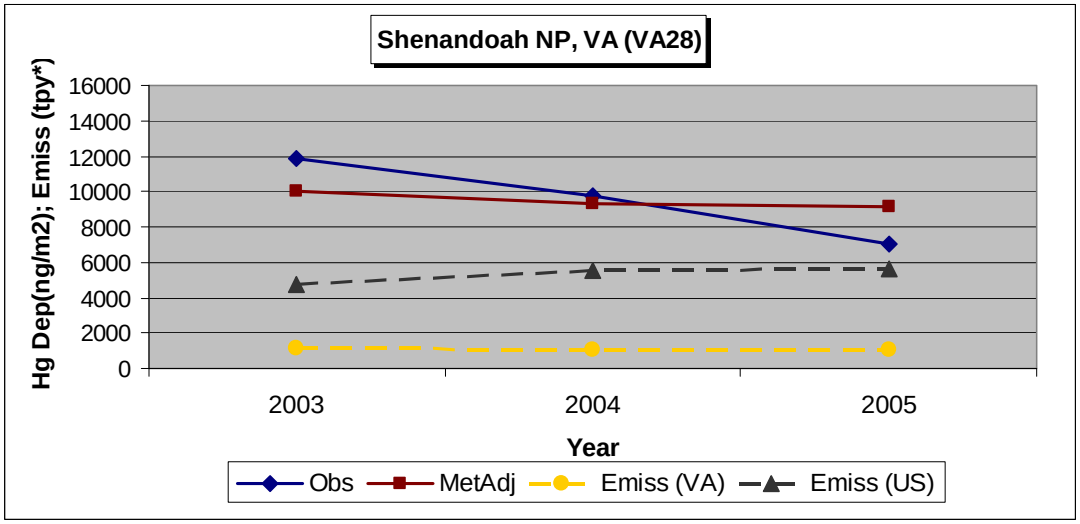
The meteorologically adjusted values are consistent with mercury emissions data from the EPA Toxics Release Inventory (TRI) (EPA, 2007). Figure 3-17 show the observed and meteorologically adjusted deposition values along with the TRI emissions for Virginia and the entire U.S. Note that for plotting purposes, the emissions totals for Virginia (tons per year (tpy)) have been multiplied by 1000 and the emissions totals (tpy) for the U.S. have been multiplied by 50.

Figure 3-17. Actual & Meteorologically-Adjusted Annual Mercury Wet Deposition (ng m-2) for MDN Monitoring Sites in Virginia Plotted Together with TRI Annual Mercury Emissions Totals (scaled tpy) for Virginia and the Entire U.S.

(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



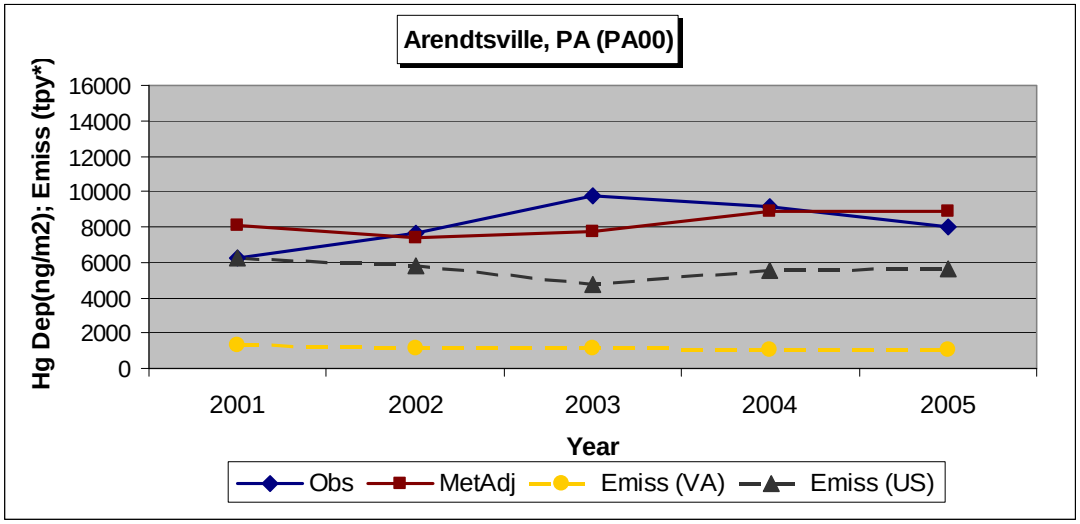
The meteorologically adjusted deposition values (for both sites) and the emissions for Virginia decrease slightly during the three-year period. The tendencies exhibited by the meteorological adjusted values are consistent with the emissions (much more so than the observed tendencies).

Meteorologically adjusted deposition values for those sites with longer periods of record that provided the best match to the Virginia sites Arendtsville (PA00), Allegheny Railroad NHS (PA13), and Pettigrew State Park (NC42) are plotted in Figure 3-18. Note that for plotting purposes, the emissions total for Virginia (tpy) has been multiplied by 1000 and the emissions totals (tpy) for the

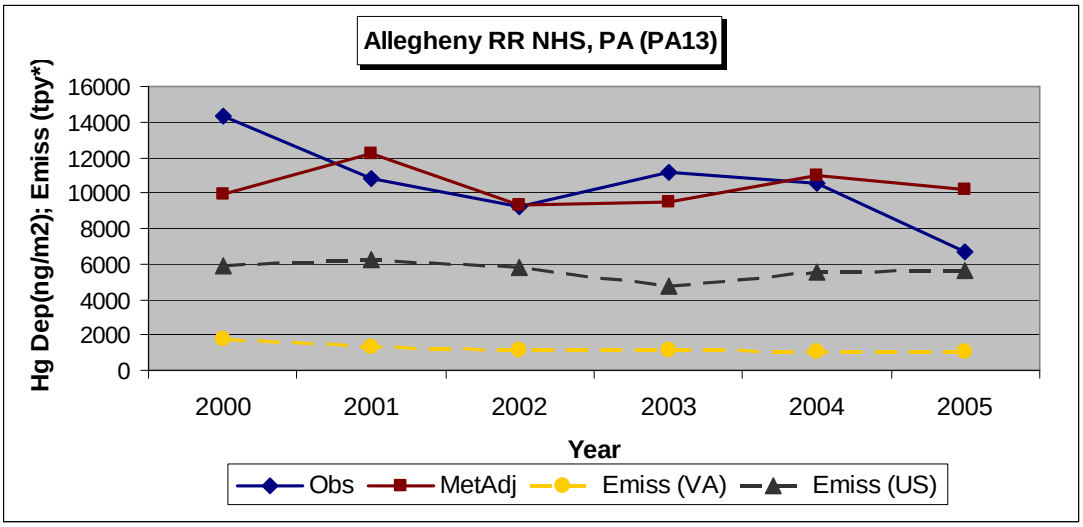
U.S. have been multiplied by 50. Also note that the emissions data are available beginning for 2000, so all plots begin in 2000 or later, based on MDN data availability.

Figure 3-18. Actual & Meteorologically-Adjusted Annual Mercury Wet Deposition (ng m-2) for Geographically Similar MDN Monitoring Sites in Surrounding States Plotted Together with TRI Annual Mercury Emissions Totals (tpy) for Virginia and the Entire U.S.

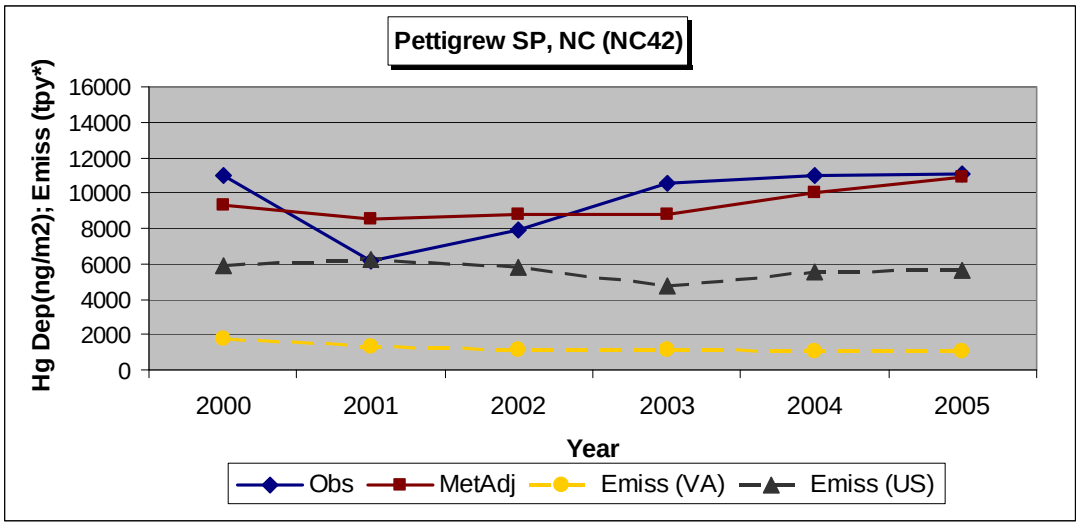
(a) Arendtsville (PA00)



(b) Allegheny Portage Railroad NHS (PA13)



(c) Pettigrew State Park (NC42)



The meteorologically adjusted deposition values for the three additional sites, also exhibit less variation among the years. For these sites, the trend for 2003 to 2005 is slightly upward, in contrast to that calculated for the Virginia sites. The meteorologically adjusted deposition values appear to track the U.S. emissions totals quite well.

4. Emissions Related Influences

Global, national, regional, and local sources of air mercury emissions contribute to mercury deposition. Understanding these contributions is an important step toward identifying measures that will effectively reduce mercury deposition and environmental mercury levels.

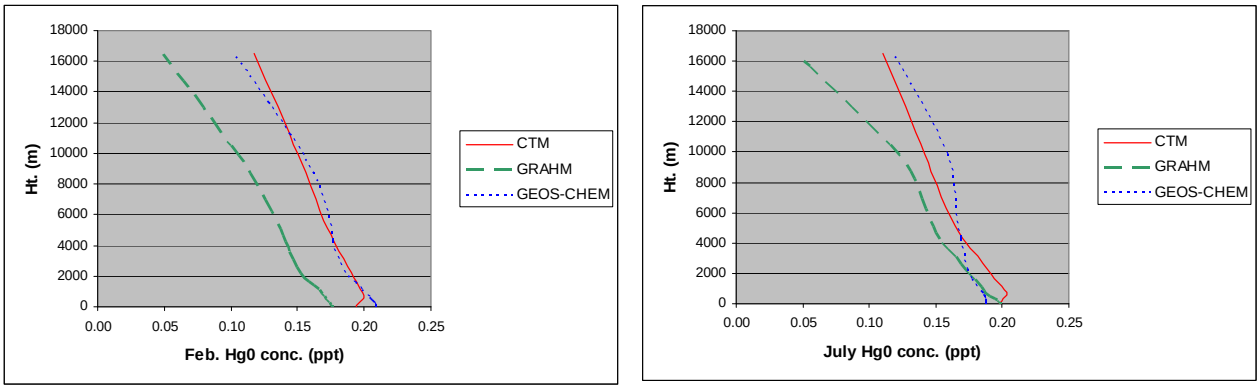
4.1. Global Background

It is expected that global background concentrations of mercury are high enough to influence the magnitude of mercury deposition within the U.S. The magnitude of global background concentrations is not, however, well known. In particular, the concentrations of the oxidized forms of mercury are very uncertain. Recent modeling studies have estimated that background concentrations of elemental mercury are about 1.6 nanograms per cubic meter (ng m^{-3}) (Pai et al., 1999; Myers et al., 2003). Support for this estimate can be found in experimental studies (e.g., Blanchard et al., 2002).

As part of the North American Mercury Model Inter-comparison Study (NAMMIS), several global simulation models were used to estimate global background concentrations of elemental, divalent gaseous, and particulate mercury to be used as boundary conditions for modeling of the continental U.S. (Bullock et al., 2006). These included the Chemical Transport Model (CTM), the Global/Regional Atmospheric Heavy Metals model (GRAHM), and the GEOS-Chem model.

A summary and comparison of the boundary concentrations of Hg(0) derived from the three global models is presented in Figure 4-1 (from Myers et al., 2006). The concentrations depicted in the plots represent the average concentration around the perimeter of the U.S. Each data point represents the average for one layer of a regional model, averaged over all grid cells that comprise the perimeter of a modeling domain that encompasses the continental U.S. and portions of Canada and Mexico. The boundary conditions are compared for February and July in order to examine the temporal variation of concentrations. The units are parts per trillion (ppt). At standard temperature and pressure conditions (STP), 0.2 ppt is approximately 1.8 ng m^{-3} of mercury. Differences among the global models reflect the uncertainty in global background estimates. The plots also show that the concentrations vary in the vertical and with time of year.

Figure 4-1. Comparison of CTM, GRAHM, and GEOS-CHEM Derived Boundary Concentrations (ppt) for a Modeling Domain Encompassing the U.S. for HG(0): February and July 2001.



4.2. National, Regional, and Local Emissions

Mercury in the atmosphere can be attributed to both natural and anthropogenic sources. Natural sources of mercury include soils, rocks, volcanoes, and the oceans. Within the U.S., most natural mercury emissions are associated with land types found in the western part of the continent. Prescribed burning and wild fires, which occur in many different areas throughout the U.S., can cause re-emission of natural and previously deposited emissions into the atmosphere.

Anthropogenic sources of mercury include coal-fired power plants and other industrial coal-burning facilities, municipal, medical, industrial and hazardous waste incinerators, chlor-alkali and other chemical manufacturing plants, taconite and other metallurgical processing facilities, pulp and paper manufacturing facilities, mining operations, cement plants, mobile sources, and a wide variety of other industrial and residential sources (EPA, 2005a).

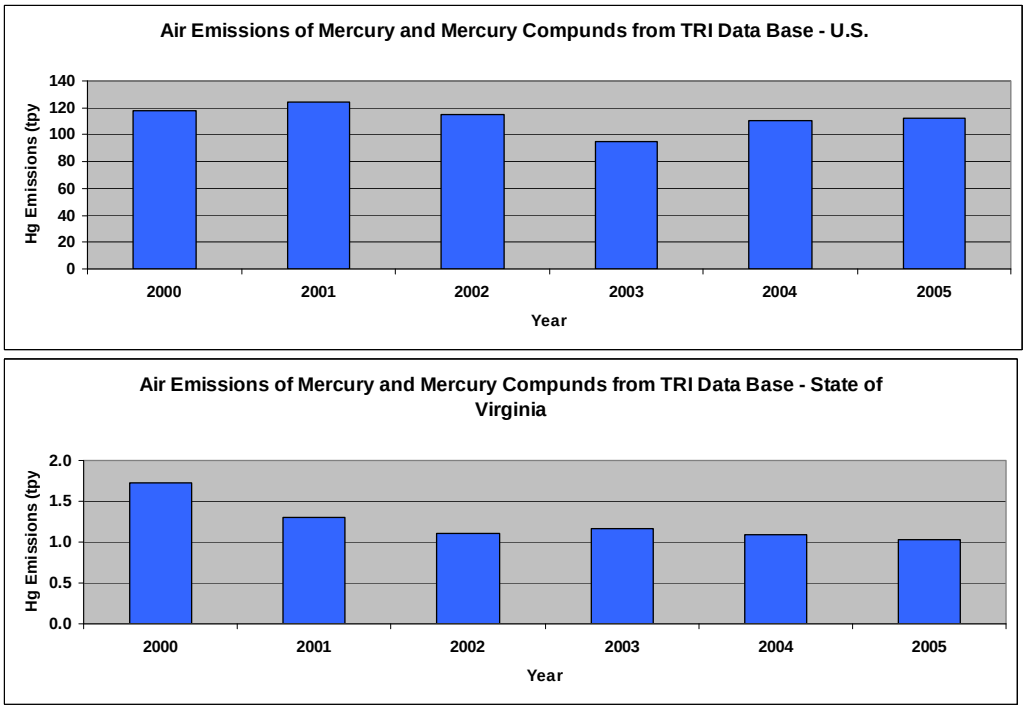
Table 4-1 summarizes total U.S. anthropogenic mercury emissions for a variety of point and non-point source categories, as contained in Version 3 of EPA's 2002 National Emissions Inventory (NEI). The table presents a breakdown by emitted species, including elemental mercury, divalent mercury, and particulate mercury. Over 60 percent of the emitted mercury is in the form of elemental mercury, 30 percent is divalent mercury, and about 10 percent is particulate mercury. The largest anthropogenic contributors to mercury emissions in the U.S. are coal-burning electric generation units (EGU's). Other large point source mercury emitters include metals processing sources and waste disposal/recycling sources.

Table 4-1. The 2002 U.S. Mercury Point and Non-Point Source Emission Inventory from Version 3 of the NEI.

	Point Source				Non-Point Source				Point and Non-Point Source			
	HG0	HG2	HGP	Total	HG0	HG2	HGP	Total	HG0	HG2	HGP	Total
TIER 2 CODES	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)
FUEL COMB. ELEC. UTIL.	61539	42851	4446	108836	8	5	3	16	61547	42856	4449	108852
Coal	59787	41975	3818	105580	2	1	1	5	59789	41976	3819	105584
Oil	1007	510	350	1867	6	3	2	11	1013	513	352	1878
Gas	0	0	0	1				0	0	0	0	1
Other	274	164	110	548				0	274	164	110	548
Internal Combustion	431	259	172	863				0	431	259	172	863
FUEL COMB. INDUSTRIAL	4008	2365	1577	7950	1723	1037	690	3449	5731	3402	2267	11399
Coal	2051	1226	818	4095	91	55	37	183	2143	1281	854	4278
Oil	1168	690	461	2319	1504	905	601	3010	2672	1595	1062	5329
Gas	59	27	19	105				0	59	27	19	105
Other	699	404	271	1373	131	79	52	263	830	483	323	1636
Internal Combustion	32	19	13	64				0	32	19	13	64
FUEL COMB. OTHER	256	154	103	513	4314	2584	1723	8621	4571	2738	1826	9134
Commercial/Institutional Coal	223	134	89	447	24	15	10	49	248	149	99	496
Commercial/Institutional Oil	25	15	10	49	2716	1628	1088	5431	2740	1643	1097	5480
Commercial/Institutional Gas	0	0	0	0				0	0	0	0	0
Misc. Fuel Comb. (Except Residential)	8	5	3	17	55	33	22	111	64	39	26	128
Residential Wood					4	3	2	9	4	3	2	9
Residential Other					1511	905	604	3021	1511	905	604	3021
CHEMICAL & ALLIED PRODUCT MFG	10804	688	114	11606				0	10804	688	114	11606
Organic Chemical Mfg	3	0	0	4				0	3	0	0	4
Inorganic Chemical Mfg	10439	568	28	11035				0	10439	568	28	11035
Polymer & Resin Mfg	1	0	0	1				0	1	0	0	1
Agricultural Chemical Mfg	165	97	65	327				0	165	97	65	327
Paint, Varnish, Lacquer, Enamel Mfg	9	1	1	11				0	9	1	1	11
Other Chemical Mfg	139	21	19	180				0	139	21	19	180
METALS PROCESSING	21973	2862	2811	27645				0	21973	2862	2811	27645
Non-Ferrous Metals Process	1781	239	232	2253				0	1781	239	232	2253
Ferrous Metals Processing	19929	2555	2526	25010				0	19929	2555	2526	25010
Metals Processing NEC	269	70	48	388				0	269	70	48	388
PETROLEUM & RELATED INDUSTRIES	180	27	25	232				0	180	27	25	232
Oil & Gas Production	0	0	0	0				0	0	0	0	0
Petroleum Refineries & Related Industries	26	7	5	38				0	26	7	5	38
Asphalt Manufacturing	153	20	20	193				0	153	20	20	193
OTHER INDUSTRIAL PROCESSES	10877	2270	1927	15075				0	10877	2270	1927	15075
Agriculture, Food, & Kindred Products	41	19	13	74				0	41	19	13	74
Textiles, Leather, & Apparel Products	0	0	0	0				0	0	0	0	0
Wood, Pulp & Paper, & Publishing Products	709	426	284	1418				0	709	426	284	1418
Rubber & Miscellaneous Plastic Products	15	9	6	30				0	15	9	6	30
Mineral Products	8541	1453	1343	11337				0	8541	1453	1343	11337
Machinery Products	58	41	7	107				0	58	41	7	107
Transportation Equipment	1	0	0	1				0	1	0	0	1
Miscellaneous Industrial Processes	1504	327	275	2106				0	1504	327	275	2106
SOLVENT UTILIZATION	107	30	23	159				0	107	30	23	159
Degreasing	0	0	0	0				0	0	0	0	0
Graphic Arts	4	2	1	7				0	4	2	1	7
Surface Coating	29	17	11	57				0	29	17	11	57
Other Industrial	74	11	10	94				0	74	11	10	94
STORAGE & TRANSPORT	562	92	85	739				0	562	92	85	739
Bulk Terminals & Plants	11	7	4	22				0	11	7	4	22
Petroleum & Petroleum Product Storage	0	0	0	0				0	0	0	0	0
Organic Chemical Storage	0	0	0	0				0	0	0	0	0
Inorganic Chemical Storage	1	0	0	1				0	1	0	0	1
Bulk Materials Storage	550	85	80	715				0	550	85	80	715
WASTE DISPOSAL & RECYCLING	24747	13578	8030	46355	23	14	9	46	24770	13592	8039	46401
Incineration	12921	11972	6468	31361	13	8	5	26	12934	11980	6473	31387
Open Burning	0	0	0	0				0	0	0	0	0
POTW	2	0	0	2				0	2	0	0	2
TSDF	1	0	0	1				0	1	0	0	1
Landfills	21	3	3	27	10	6	4	20	31	9	7	47
Other	11826	1606	1555	14987	0	0	0	0	11826	1606	1555	14987
MISCELLANEOUS	30	16	9	55	1840	1102	737	3679	1870	1118	746	3734
Agriculture & Forestry					69	41	28	138	69	41	28	138
Other Combustion					224	134	90	448	224	134	90	448
Health Services	30	16	9	55	854	513	342	1710	884	529	351	1764
Fluorescent Lamp Breakage					692	415	277	1384	692	415	277	1384
Total	135049	65017	19160	219227	7908	4742	3162	15812	142957	69759	22322	235038

Figure 4-2 presents mercury emission totals for the U.S. and the Commonwealth of Virginia derived from the national Toxics Release Inventory (TRI) for the period 2000 to 2005. This inventory provides an alternative but consistent estimate of the year-to-year variation of anthropogenic mercury emissions and can be used to discern any significant trends during this period. The data indicate no clear trends in total U.S. mercury emissions with a slight decrease in mercury emissions since 2000 for the Commonwealth of Virginia.

Figure 4-2. Mercury Emissions for the U.S. and the Commonwealth of Virginia from the TRI Data Base.



The Commonwealth of Virginia recently updated the mercury point source emission estimates for 2002 and 2005. Figure 4-3 presents a comparison of the speciated mercury emission totals for the updated 2002 inventory with those contained in EPA's NEI Version 3 inventory for Virginia. The figure provides a comparison of emissions for the top 20 mercury emitters and for all point source emitters in the state. Nearly 95 percent of mercury emissions for point and non-point sources are from the top 20 sources. The data indicate that the NEI 2002 emissions for these same 20 sources are comparable, but the NEI has higher estimates of emissions when all point sources are considered.

Figure 4-3. Mercury Emissions for the Commonwealth of Virginia: VDEQ 2002 vs. NEI.

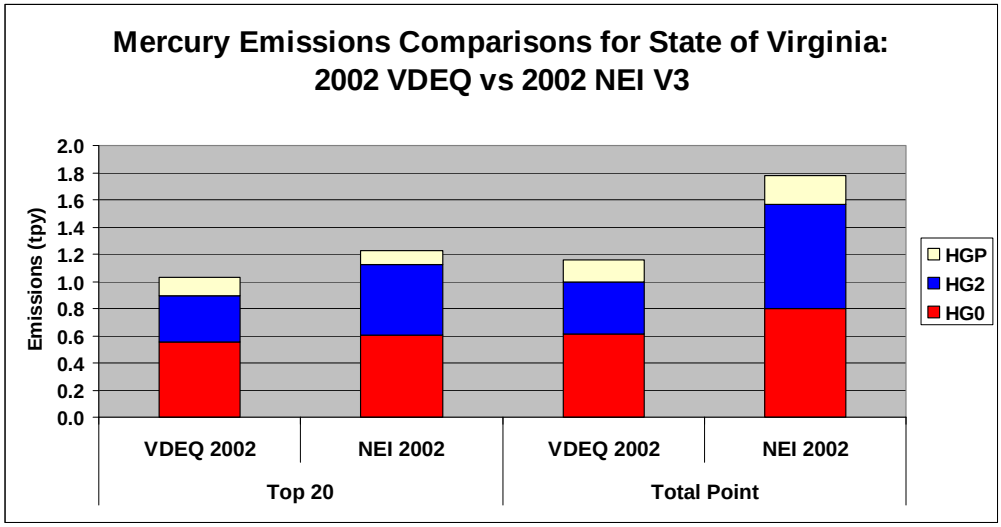
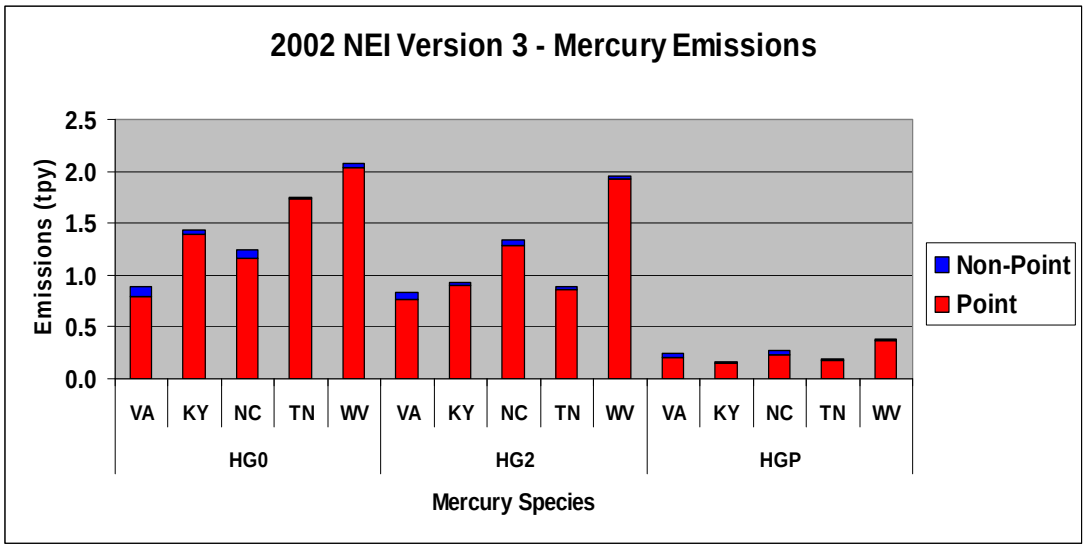


Table 4-2 presents emission totals for the top 20 Virginia mercury point sources. As noted for the national inventory, the top emitters for Virginia are the EGU's. Figure 4-4 presents speciated mercury emission totals for point and non-point sources in Virginia and the neighboring states of Kentucky, West Virginia, North Carolina, and Tennessee as contained in the 2002 NEI inventory. The higher mercury emissions in these predominantly upwind neighboring states likely influence and impact areas within Virginia.

Table 4-2. Top 20 Virginia Mercury Point Source Emitters for 2002.

		VDEQ Data						
		2002 Emissions				Speciation		
		HG0	HG2	HGP	Total	HG0	HG2	HGP
Facility Name	EGU?	(lb/yr)	(lb/yr)	(lb/yr)	(lb/yr)			
Dominion - Chesterfield Power Station	EGU	179.42	107.65	71.77	358.83	50%	30%	20%
Chaparral Steel	non-EGU	233.75	29.29	29.26	292.30	80%	10%	10%
Dominion - Bremo	EGU	83.86	50.32	33.55	167.73	50%	30%	20%
American Electric Power- Clinch River	EGU	38.21	121.00	0.00	159.21	24%	76%	0%
Dominion - Chesapeake Energy Center	EGU	78.69	47.22	31.48	157.38	50%	30%	20%
Potomac River Generating Station	EGU	11.83	106.43	0.00	118.26	10%	90%	0%
Dominion - Yorktown Power Station	EGU	53.82	32.29	21.53	107.64	50%	30%	20%
Jewel Coke Company LLP	non-EGU	84.50	10.56	10.56	105.63	80%	10%	10%
Dominion - Possum Point Power Station	EGU	50.09	30.06	20.04	100.19	50%	30%	20%
Stone Container Enterprises (Smurfit)	non-EGU	46.81	27.22	3.73	77.76	60%	35%	5%
Stone Container Corporation - Hopewell	non-EGU	34.84	20.91	13.94	69.69	50%	30%	20%
American Electric Power (Glen Lyn)	EGU	26.06	39.08	0.00	65.14	40%	60%	0%
Intermet Foundry Archer Creek	non-EGU	51.97	6.53	6.51	65.01	80%	10%	10%
RES dba Steel Dynamics	non-EGU	48.64	6.08	6.08	60.80	80%	10%	10%
Spruance Genco LLC	EGU	27.75	16.65	11.10	55.50	50%	30%	20%
Mead Westvaco Packaging Resources	non-EGU	12.96	4.88	9.07	26.91	48%	18%	34%
Covanta Fairfax, Inc.	EGU	12.87	7.72	5.15	25.73	50%	30%	20%
James River Cogeneration Company	EGU	12.65	7.59	5.06	25.30	50%	30%	20%
Celanese/Cinergy Solutions (21418)	non-EGU	9.20	5.52	3.68	18.40	50%	30%	20%
Dominion - Clover Power Station	EGU	8.34	5.00	3.34	16.68	50%	30%	20%

Figure 4-4. Comparison of Mercury Emissions for Virginia and Several Surrounding States.



5. Indications from Prior Modeling Studies

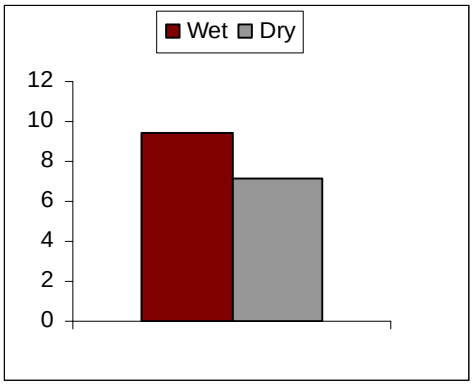
Analysis of the available MDN mercury deposition data for Virginia and the surrounding states has allowed us to examine the role of meteorology in mercury wet deposition, as well as the spatial and temporal characteristics of wet deposition throughout the region. In this section, we use existing mercury deposition modeling results to estimate the relative importance of wet versus dry deposition, examine the modeled species distributions, and quantify the potential contributions from global background as well as national, regional, and local emissions sources.

In a recent study for the EPA Office of Water (OW), Myers et al. (2006) used the REgional Modeling System for Aerosols and Deposition (REMSAD) to simulate mercury deposition for the entire U.S. for an annual simulation period of 2001. This study focused on tracking airborne mercury emissions and quantifying the contribution of various sources and source categories to mercury deposition in each of the contiguous 48 states.

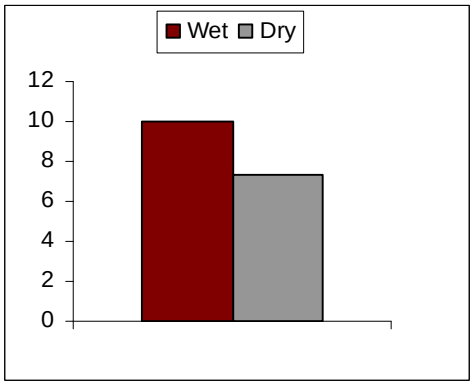
The REMSAD model simulates both wet and dry deposition. Figure 5-1 illustrates the REMSAD-derived estimates of wet and dry deposition for the Culpeper, Shenandoah, and Harcum monitoring sites. These results suggest that for all three sites, dry deposition is a significant contributing factor to total deposition. The simulated dry deposition amount is about 60 to 75 percent as large as the wet deposition amount. Overall, the simulated dry deposition represents about 40 percent or more of the total deposition.

Figure 5-1. REMSAD-Simulated Annual Wet and Dry Mercury Deposition (kg ha^{-1}) for MDN Monitoring Sites in Virginia.

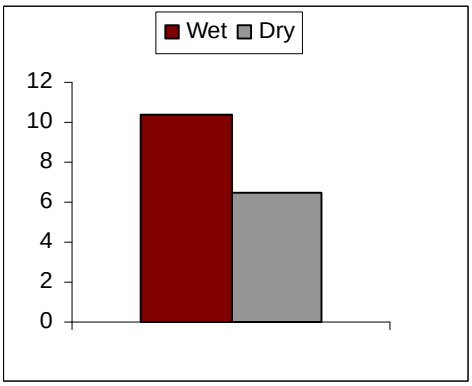
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



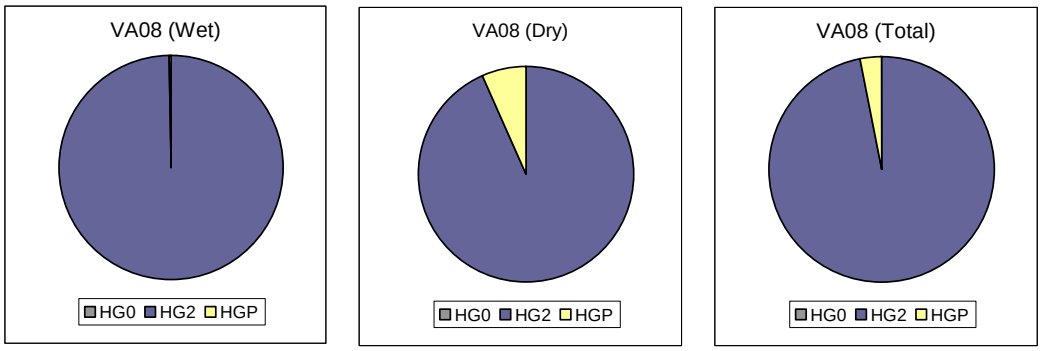
(c) Harcum (VA98)



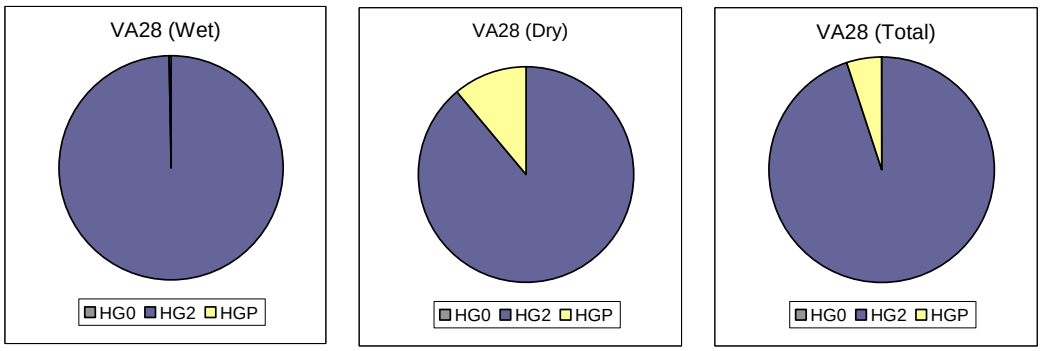
The mercury species simulated by the REMSAD model include Hg(0), Hg(2) (reactive gaseous mercury), and Hg(p). Figure 5-2 illustrates the REMSAD-derived estimates of deposition by species for the Culpeper, Shenandoah, and Harcum monitoring sites. For all three sites, wet deposition is predominantly Hg(2), where as dry deposition includes on the order of about 10 percent Hg(p). Note that in the simulations for the OW project, dry deposition of Hg(0) was assumed to be zero since deposited elemental mercury may be rapidly re-emitted back to the atmosphere.

Figure 5-2. REMSAD-Simulated Species Distribution for Wet, Dry and Total Mercury Deposition for MDN Monitoring Sites in Virginia.

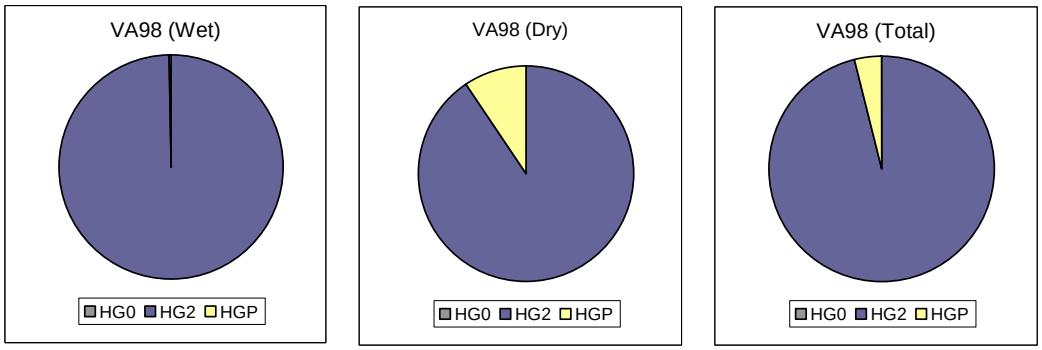
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



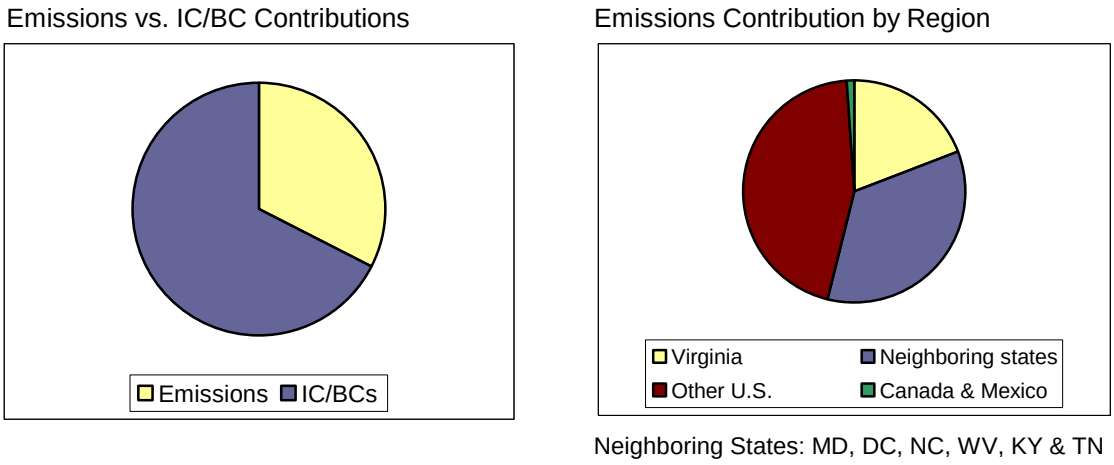
(c) Harcum (VA98)



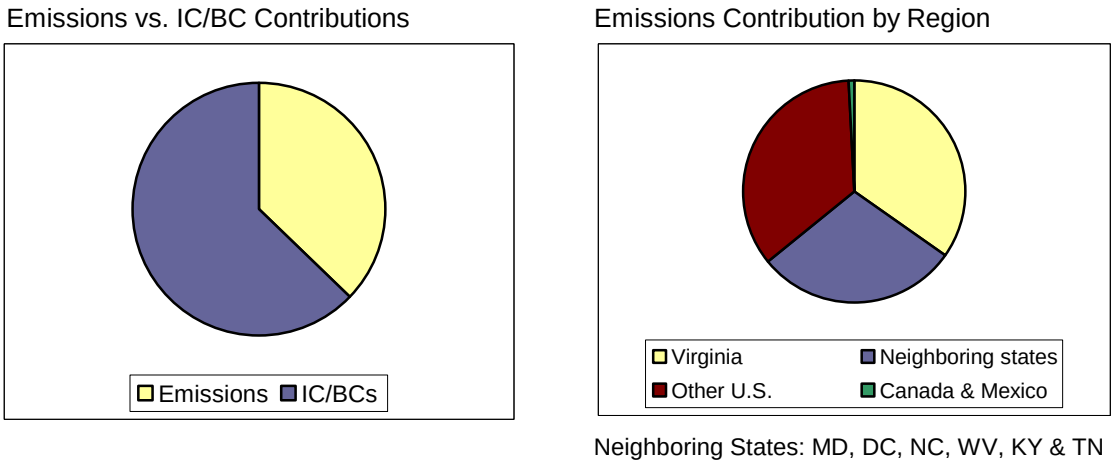
The REMSAD Particle and Precursor Tagging Methodology (PPTM) was used in the OW study to quantify the contribution of emissions from various sources and source regions to mercury deposition throughout the modeling domain. These contributions are illustrated in Figure 5-3 for the Culpeper, Shenandoah, and Harcum monitoring sites. The first pie chart presents the contribution to total deposition from all emissions sources and the model initial/boundary conditions, which we use here to represent background. Note that in the context of this display, "emissions" refers to emissions from sources in the U.S., Canada, and Mexico. The second pie further attributes the emissions contributions to 1) sources within the Commonwealth of Virginia, 2) sources in neighboring states, 3) sources in all other U.S. states, and 4) sources in Canada and Mexico. The neighboring states include Maryland, the District of Columbia, North Carolina, West Virginia, Kentucky, and Tennessee.

Figure 5-3. Contributions to REMSAD-Simulated Annual Mercury Deposition (kg ha^{-1}) for MDN Monitoring Sites in Virginia.

(a) Culpeper (VA08)

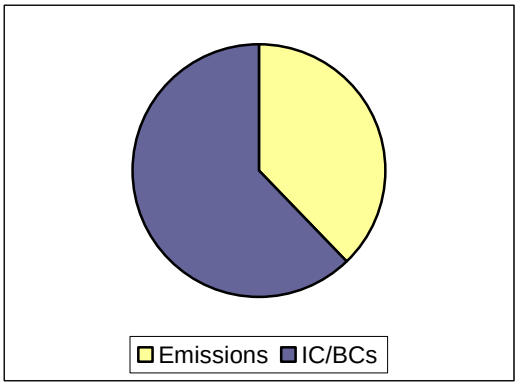


(b) Shenandoah National Park (VA28)

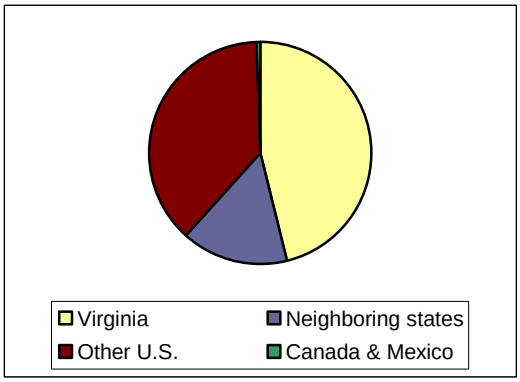


(c) Harcum (VA98)

Emissions vs. IC/BC Contributions



Emissions Contribution by Region

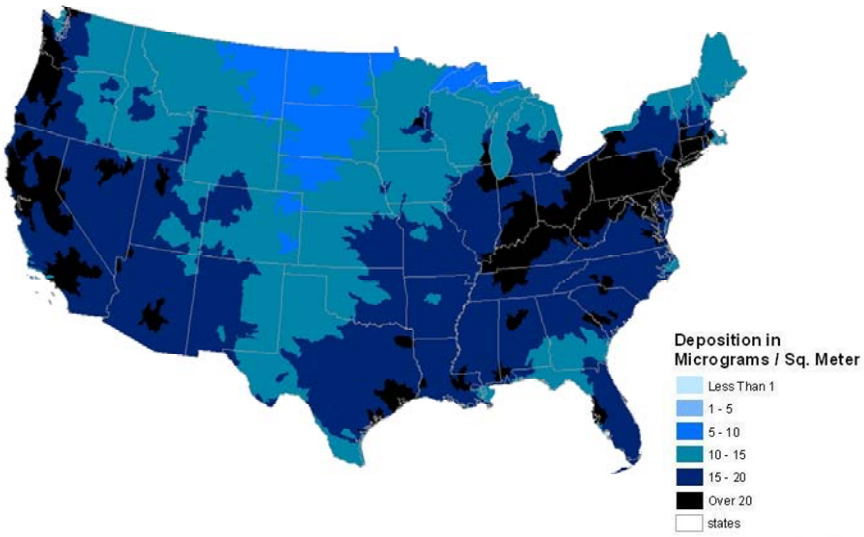


Neighboring States: MD, DC, NC, WV, KY & TN

These results indicate that global background (as characterized by the REMSAD initial and boundary conditions) may comprise 60 to 70 percent of the contribution to mercury deposition at the Virginia MDN sites. The emissions contributing to the simulated deposition are from Virginia, the neighboring states, and other states within the U.S.

EPA applied the Community Multi-scale Air Quality (CMAQ) model for the same 2001 simulation period to support the development of the Clean Air Mercury Rule (CAMR). The modeling results (EPA, 2005b) support the conclusion that mercury deposition is a regional-scale issue (see Figure 5-4).

Figure 5-4. CMAQ-Simulated Annual Mercury Deposition (μg m^{-2}) from the CAMR Modeling.



Source: EPA

In addition to the breakdown by state and region, PPTM was also used in the OW study to quantify the contribution of emissions from specific sources. These results (not shown) reveal local source-specific contributions to mercury deposition at the three monitoring sites.

6. Summary Conceptual Description

This report provides a conceptual description of mercury deposition for several locations in Virginia and the surrounding states. This description is based on observed mercury deposition data, meteorological data, emissions inventory information, and some recent existing mercury deposition modeling results.

A key focus of this discussion is mercury wet deposition for three Mercury Deposition Network (MDN) sites in Virginia: Culpeper, Shenandoah National Park, and Harcum. The period of record for the MDN data is late 2002 through 2006 for Culpeper, late 2002 to the present for Shenandoah, and approximately 2005 to the present for the Harcum site. The Culpeper site is located in north central Virginia. The Shenandoah site is a high elevation monitoring site located within the national park (in northwestern Virginia), while the Harcum site is located along the southern portion of the inner coast of the Chesapeake Bay.

Analysis of the data and recent modeling results has provided insight into some key questions regarding the nature of mercury deposition.

- **Is mercury deposition primarily a local issue, or are regional, national, and global factors important?**

  Based on a review of the available data and prior modeling results, it is expected that global, national, regional, and local factors contribute to mercury deposition in Virginia. The primary source of mercury to impaired water bodies is believed to be atmospheric deposition, which is comprised of both natural and anthropogenic emissions. These emissions can be directly emitted or re-emitted to the atmosphere after being deposited at another location.

  Various atmospheric processes influence the transport and deposition of mercury and these involve a variety of scales ranging from global to local. Specifically:

  - Mercury may be transported globally by atmospheric circulation systems and prior mercury deposition modeling results indicate that global background may comprise 60 to 70 percent of the contribution to mercury deposition at the Virginia MDN sites.
  - Mercury may also be subject to regional-scale transport. Prior modeling also indicates that emissions contributing to the simulated deposition are from Virginia, the neighboring states, and other states within the U.S. Similarities in observed mercury wet deposition among monitoring sites in Virginia and several neighboring states also support the conclusion that mercury deposition is a regional-scale issue.
  - Finally, prior modeling also reveals local source-specific contributions to mercury deposition at the three monitoring sites.

- **Does mercury deposition vary with time?**

  Annual mercury wet deposition amounts vary by year for monitoring sites in Virginia and the surrounding states.

  In addition, within each calendar year, there are variations in deposition by week, month, and quarter, primarily in accordance with variations in rainfall amount.

  Mercury deposition (and rainfall amount) appears to have an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively).

- **Does mercury deposition vary from location to location?**

  Measurements of wet mercury deposition data indicate that deposition varies from location to location. For the period 2003-2005, annual mercury deposition for the Virginia MDN sites is about the same as that for nearby sites in southern Pennsylvania, and lower than that for nearby sites in North Carolina and Tennessee. In some cases, deposition characteristics are similar for geographically similar sites within the mid-Atlantic region. For each of the Virginia MDN sites, it is possible to identify a longer term monitoring site (from a neighboring state) that has similar deposition characteristics.

  Prior modeling performed by EPA also indicates that mercury deposition varies from location to location and more specifically that annual mercury deposition is related to the distribution of emission sources, especially within the eastern U.S.

- **How does meteorology influence mercury deposition in Virginia?**

  A number of different meteorological factors influence mercury deposition in Virginia. Key factors include precipitation, temperature, wind speed, and the potential for recirculation. The relative importance of each of these factors varies among the three monitoring sites. In addition, there are different types of meteorological conditions and combinations of parameters that lead to high deposition.

  Precipitation is an important mechanism for wet mercury deposition. Mercury wet deposition is correlated with rainfall, but rainfall amount does not fully explain the observed variations in deposition.

  For all three MDN sites, there is a positive correlation between rainfall, temperature, and relative humidity such that the greater the values of these parameters, the greater the deposition. Higher deposition is associated with lower wind speeds and a well mixed atmosphere. The conditions are representative of summertime conditions and consistent with the timing of the higher observed deposition amounts.

  Wind directions, both near the surface and at upper levels, may influence the regional and local transport of mercury emissions from source regions or individual sources for subsequent deposition at the monitoring sites (and to bodies of water) in Virginia. For all three MDN sites, wind directions are slightly different during high deposition periods compared to all periods and indicate possible regional or local transport of mercury emissions from the east or northeast for Culpeper and Shenandoah, and from the south or southwest for Harcum.

  Finally, dry deposition of mercury is influenced by several meteorological factors including the temperature characteristics of the atmosphere and the wind speed.

- **Are there discernable trends in mercury deposition and have recent changes in deposition been accompanied by changes in emissions or primarily driven by meteorological variability?**

  Variations in meteorology contribute to observed variations in quarterly and annual mercury wet deposition.

  Annual deposition amounts that have been adjusted to account for these variations in meteorology exhibit much less variation among the years. For the Virginia sites, the meteorologically adjusted deposition values for 2003-2005 are consistent with changes in the emissions for Virginia. For the Culpeper and Shenandoah sites, the adjusted deposition values indicate a slight downward trend.

For sites in Pennsylvania and North Carolina, the meteorologically adjusted deposition trends for 2000-2005 are consistent with changes in the U.S. emissions. For 2003 to 2005 the trend is slightly upward, in contrast to that for the Virginia sites.

- **What is the relative importance of wet versus dry deposition, and the various mercury species?**

  Prior modeling results suggest that for all three Virginia sites, dry deposition is a significant contributing factor to total mercury deposition. Overall, the simulated dry deposition represents about 40 percent or more of the total deposition. Prior modeling also indicates that both wet and dry deposition are predominantly reactive gaseous mercury, and that dry deposition includes about 10 percent particulate mercury.

  These results are consistent with monitoring data. The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory conducted a monitoring study during the summer of 2005 at the Harcum site and found that dry deposition was significant and was dominated by reactive gaseous mercury.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7. References

Brieman, L., J. H. Friedman, R. A. Olshen, and C. J. Stone. 1984. *Classification and Regression Trees*. Wadsworth, Belmont, California.

Blanchard, P., F.A. Froude, J.B. Martin, H. Dryfhout-Clark, J.T. Woods. 2002. Four years of continuous total gaseous mercury (TGM) measurements at sites in Ontario, Canada. *Atmos. Env.,* 36: 3735–3743.

Bullock, O. R., K. Lohman, C. Seigneur, K. Vijayaraghavan, A. Dastoor, D. Davignon, N. Selin, D. Jacob, T. Myers, K. Civerolo, C. Hogrefe, J. Ku, G. Sistla, D. Atkinson, and T. Braverman. 2006. "Results from the North American Mercury Model Inter-comparison Study (NAMMIS)." Poster session at the Eighth International Conference on Mercury as a Global Pollutant, Aug. 6-11, 2006, Madison, Wisconsin.

Bullock, O.R., D. Atkinson, T. Braverman, K. Civerolo, A. Dastoor, D. Davignon, C. Hogrefe, J. Ku, K. Loman, T. Myers, C. Seigneur, N. Selin, G. Sistla and K. Vijayaraghavan. 2007. *The North American mercury model intercomparison study (NAMMIS): Study description and results*. (*In progress*)

EPA. 2005a. *Emissions Inventory and Emissions Processing for the Clean Air Mercury Rule (CAMR)*. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, March 2005. (http://www.epa.gov/ttn/atw/utility/emiss_inv_oar-2002-0056-6129.pdf).

EPA. 2005b. *Technical Support Document for the Final Clean Air Mercury Rule: Air Quality Modeling*. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, March 2005. (http://www.epa.gov/ttn/atw/utility/aqm_oar-2002-0056-6130.pdf).

EPA. 2007. EPA Toxics Release Inventory (TRI) data available at: http://www.epa.gov/tri/tridata.

Kim, J. P., and W. F. Fitzgerald. 1986. Sea-air partitioning of mercury in the equatorial Pacific Ocean, *Science*, 231: 1131-1133.

Myers, T., Y. Wei, B. Hudischewskyj, and S. Douglas. 2003. "Application of the REMSAD Modeling System to Estimate the Deposition of Mercury in Support of the Wisconsin TMDL Pilot." Prepared for the U.S. Environmental Protection Agency, Office of Water, Washington, D.C. ICF International, San Rafael, California (03-050).

Myers, T., Wei, B. Hudischewskyj, J. Haney, and S. Douglas. 2006. "Model-Based Analysis and Tracking of Airborne Mercury Emissions that May Contribute to Water Quality Impacts." Prepared for the U.S. Environmental Protection Agency, Office of Water, Washington, D.C. ICF International, San Rafael, California (06-077).

NADP. 2007. Web site for National Acid Deposition Program, Mercury Deposition Network (MDN) data and information: www.nadp.sws.uiuc.edu/mdn.

Nriagu, J., and C. Becker. 2003. Volcanic emissions of mercury to the atmosphere: global and regional inventories, *Sci. Total Environ.*, 304: 3-12.

NOAA. 2007. Web page on atmospheric deposition: http://noaa.chesapeakebay.net.

Pai, P., P. Karamchandani, and C. Seigneur. 1999. "Sensitivity of Simulated Atmospheric Mercury Concentrations and Deposition to Model Input Parameters." *J. Geophys. Res.*, 104:13855-13868.

Schluter, K. 2000. Review: evaporation of mercury from soils. An integration and synthesis of current knowledge, *Environmental Geology*, 39: 249-271.

Seigneur, C., P. Karamchandani, K. Vijayaraghavan, K. Lohman, and G. Yelluru. 2003. "Scoping Study for Mercury Deposition in the Upper Midwest." Prepared for Midwest Regional Planning Organization. AER, San Ramon, California (CP149-03-01a).

Sofiev, M.A., and M.V. Galperin. 2000. "Long-Range Transport Modeling of the Particle-Carried and Persistent Toxic Pollutants." Proceedings of the Millennium NATO/CCMS ITM, May 15-19, 2000, Boulder, CO, AMS, pp. 148-155.

Steinberg, D., and P. Colla. *1997. CART—Classification and Regression Trees*. Salford Systems, San Diego, CA.

Syrakov, D. 1998. "Long-Term Calculation of Bulgarian Impact in Mercury Pollution over SE Europe." Bulgarian contribution to 1998 Annual Report for 1998, NIMH, EMEP/MSC-E, Sofia-Moscow.

Valente, R. J., C. Shea, K. L. Humes, and R. L. Tanner. 2007. Atmospheric mercury in the Great Smoky Mountains compared to regional and global levels, *Atmos. Environ*., 41, pp. 1861-1873.

Appendix C: Emissions Data Analysis Report

Virginia Department of Environmental Quality (VDEQ)

The Virginia Mercury Study: Review and Assessment of Virginia Mercury Emissions Data and Recent Mercury Studies

Mercury Modeling Study Contract № 13360
Report

February 13, 2008

07-045

ICF INTERNATIONAL

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Virginia Department of Environmental Quality (VDEQ)

The Virginia Mercury Study: Review and Assessment of Virginia Mercury Emissions Data and Recent Mercury Studies

Mercury Modeling Study Contract № 13360 Report

February 13, 2008

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1. Introduction

This report summarizes a review and analysis of the sources of atmospheric mercury emissions located within the Commonwealth of Virginia and surrounding areas. This review was conducted as part of the Virginia Mercury Study, which includes an air quality modeling analysis focusing on mercury air deposition to waterways.

1.1. Background

Mercury in the atmosphere can be attributed to both natural and anthropogenic sources. Natural sources of mercury include soils, rocks, volcanoes, and the oceans. Within the U.S., most natural mercury emissions are associated with land types found in the western part of the continent. Prescribed burning and wild fires, which occur in many different areas throughout the U.S., can cause re-emission of natural and previously deposited emissions into the atmosphere.

Anthropogenic sources of mercury include coal-fired power plants and other industrial coal-burning facilities, municipal, medical, industrial and hazardous waste incinerators, chlor-alkali and other chemical manufacturing plants, taconite and other metallurgical processing facilities, pulp and paper manufacturing facilities, mining operations, cement plants, mobile sources, and a wide variety of other industrial and residential sources (EPA, 2005a).

Recent national control legislation promulgated by EPA in the Clean Air Interstate Rule (CAIR) will serve to reduce emissions of NO_x, SO_2, and mercury from coal-fired power plants. The Clean Air Mercury Rule (CAMR) will build on CAIR and provide for additional future mercury emission reductions from these sources. Although controls have been mandated for a number of Virginia coal-fired power plant sources, an air quality modeling analysis will be conducted to quantify the effects of these controls on future-year mercury concentrations and deposition to waterways in the Commonwealth and to determine if more controls are needed.

Recently, the Virginia Department of Environmental Quality (VDEQ) updated the statewide mercury point source emission inventory and developed inventories for 2002 and 2005. These inventories were updated using information received from 75 facilities based on a survey. The information received from each of the facilities was reviewed in this analysis and will be used to estimate future-year emissions. The future-year estimates will be used in the air quality modeling and deposition analysis.

1.2. Objectives

The objectives of this portion of the Virginia Mercury Study are to: 1) conduct a review and analysis of recently updated mercury point source information for sources located in Virginia that will subsequently be used in the air deposition analysis, 2) estimate future-year emissions for 2010, 2015, and 2018 for these sources, and 3) conduct a literature search of recently completed mercury studies related to air deposition, emissions/controls, and air quality modeling and modify the planned approach to the modeling analysis, if warranted, to take advantage of the latest science related to mercury deposition modeling. The first two objectives ensure that the best available mercury emissions inventory is used for the base and future-year modeling analyses, while the third objective ensures that the air deposition modeling analysis will be conducted using the latest available modeling tools and approaches.

1.3. Atmospheric Mercury

Airborne mercury (Hg), emitted from various manmade and natural sources, is comprised of three forms: elemental mercury (Hg(0)), reactive gaseous mercury (RGM), and particulate mercury (Hg(p)). RGM is known to be comprised almost entirely of divalent mercury (Hg^{2+} or Hg(II)), since mercury compounds at other valence states tend to be chemically unstable in the atmosphere (Bullock et al., 2007). Hg(p) is also primarily comprised of divalent mercury, but may also include elemental mercury.

Elemental mercury is the dominant atmospheric species and comprises about 99 percent of the total mercury in the atmosphere. Hg(0) is characterized by low reactivity and low solubility in water. The dry deposition velocity is believed to be relatively low. Hg(0) has a long atmospheric lifetime (perhaps on the order of months to years) and is therefore dispersed and transported/circulated globally.

RGM represents less than one percent of atmospheric mercury. It is highly reactive and highly soluble. It can be actively removed from the atmosphere through both wet and dry deposition processes. As a result, the atmospheric lifetime of RGM is expected to be on the order of one day to one week. Based on these properties, RGM likely contributes to mercury deposition near the source location (locally or regionally).

Hg(p) also represents less than one percent of atmospheric mercury. It is moderately reactive and highly soluble in water. It is likely removed from the atmosphere primarily through wet deposition, since the dry deposition velocity of Hg(p) is expected to be low (based on that for similar fine particles). The atmospheric lifetime of Hg(p) is estimated to be on the order of one day to one week, or longer in the absence of precipitation. Based on these properties, Hg(p) also likely contributes to mercury deposition near the source location (locally or regionally).

1.4. Report Outline

Section 2 of this report summarizes the review of the Virginia point source inventory and Section 3 summarizes the base- and future-year estimates that will be used for the modeling analysis. Section 4 presents a summary of recent mercury studies that were reviewed as part of the literature search task. Finally, a comprehensive bibliography of recently completed reports and presentations is provided in the Appendix.

2. Overview of the Virginia Point Source Inventory

2.1. Review of 2002 Point Source Inventory

This section provides an overview of the process followed in reviewing and updating the mercury point source emissions inventory. As part of this study, point source inventories for 2002 and 2005 were obtained from VDEQ. These inventories were recently compiled based on responses to an information survey conducted by VDEQ to obtain the latest available emission inventory data for mercury point sources located in Virginia. Information regarding process type, emission totals, and mercury speciation was solicited and obtained. For those sources that did not have any speciation information based on recent stack testing, VDEQ instructed them to specify the default speciation profiles that were used in EPA's CAMR modeling analysis.

The intent of this review was to evaluate the information and identify missing data that, if updated, would improve the overall quality of the emission inventory. As noted, the 2002 emission inventory will be used in the base-year air quality modeling analysis and will be the basis for development of the future-year mercury emission inventories, so it is important to review the information and make any changes necessary to ensure that the latest and best information be made available for the modeling analysis.

In February 2007, a CD was received from VDEQ containing emission inventory files for seventy-five Virginia point sources. Of the facilities included, thirty-four supplied complete information and forty-one facilities had some missing or questionable information. Below, we summarize the findings of the initial review of the inventory.

The following table outlines the completeness of the initial responses to the DEQ data request.

	Number of Facilities
VDEQ potential source list	75
Supplied complete information	34
No information was supplied	5
Emissions rates incomplete	6
Speciation data incomplete	15
Stack parameter information incomplete	15
General source information incomplete	10

Detailed information for each category of missing data/information is provided below. Updates received from VDEQ for each of these categories are italicized in each of the sections.

No Information Provided

Information for five facilities on VDEQ's original list of potential mercury facilities was not included in the emission inventory. The facilities, along with the Virginia registration number, include:

1.	UVA Medical Center	40359
2.	Tangier Town	40714
3.	Perdue Farms–Soybean Oil Processing	60277
4.	Norman M Cole Jr Pollution Control Plant	70714
5.	Merck & Co	80524

Upon review by VDEQ, the UVA Medical Center and the Merck & Co. sources were removed from the list of potential mercury emitters. The Tangier Town and Norman M Cole Jr Pollution Control Plant sources were deemed insignificant sources of mercury. New emissions for the Perdue Farms source were provided by VDEQ.

Incomplete Emissions Information

Mercury emission rates were missing or questionable for six of the facilities. The equations and approach to determining the emission rates varied appreciably – approaches included AP-42, mass balance, stack test data, SW-486 and NCASI. In many cases, no supporting calculations are provided. Facilities with missing mercury emission rate information include:

1.	RES dba Steel Dynamics	20131	*Provided total Hg emissions for plant*
2.	Rock Tenn Co Mill	30188	*No updates provided*
3.	Dominion–Mecklenburg Power Station	30861	*Added new Hg emissions*
4.	Philip Morris USA Inc–Park 500	50722	*No updates provided*
5.	Burlington Industries LLC Hurt Fin	30379	*Added new Hg emissions*
6.	Stone Container Enterprises (Smurfit)	40126	*Confirmed that three stacks in facility have no Hg emissions*

Specific updates, as noted in the list above, were provided by VDEQ for these sources.

Speciation Information

Speciation information was missing for fifteen of the facilities. Facilities with speciation information missing included:

1.	MeadWestvaco Packaging Resources	20328
2.	RES dba Steel Dynamics	20131
3.	Philip Morris USA Mfg Center	50076
4.	Hopewell WWTP	50735
5.	James River Cogeneration Company	50950

6.	Spruance Genco LLC	51033
7.	Cogentrix Virginia Leasing Corp	61049
8.	H L Mooney Water Reclamation Facility	71751
9.	Georgia Pacific Corp Big Island Plt	30389
10.	Honeywell Nylon LLC–Hopewell	50232
11.	Philip Morris USA Inc.–Blended Leaf	50080
12.	Philip Morris USA Inc.–Leaf Processing	50082
13.	Burlington Industries LLC Hurt Fin	30379
14.	Griffin Pipe Products Company	30397
15.	Stone Container Enterprises (Smurfit)	40126

New information on mercury speciation profiles was obtained from VDEQ for all of these sources.

Incomplete Stack Parameter Information

Stack parameter information for fifteen facilities was initially incomplete or questionable. The deficient information ranged from missing geographic location, questionable entries, and missing physical stack parameters. Facilities with stack parameter information missing include:

1.	MeadWestvaco Packaging Resources	20328
2.	Dominion–Mecklenburg Power Station	30861
3.	Dominion–Clover Power Station	30867
4.	Birchwood Power Partners, L.P.	40809
5.	Honeywell Nylon LLC–Hopewell	50232
6.	Stone Container Corporation–Hopewell	50370
7.	Philip Morris USA Inc–Park 500	50722
8.	City of Harrisonburg– Resource Recovery	81016
9.	Dan River Incorporated Schoolfield	30240
10.	University of Virginia	40200
11.	US Navy Little Creek Amphibious Base	60033
12.	Burlington Industries LLC Hurt Fin	30379
13.	Griffin Pipe Products Company	30397
14.	Stone Container Enterprises (Smurfit)	40126
15.	Hopewell Cogeneration Ltd Partnership	50967

New stack information was obtained from VDEQ for all of these sources.

Incomplete General Information

General emission unit information for ten facilities was incomplete or questionable. Primarily this included SCC and MACT codes. In many cases, it was not clear whether the sources met the requirements for MACT. It was not possible to tell if all emission sources for the individual facilities were included in the preliminary inventory. Facilities with incomplete general emission unit information included:

1. Virginia Tech 20124
2. MeadWestvaco Virginia Specialty 20329
3. Internet Foundry Archer Creek 30121
4. Solite LLC/Giant Resource Recovery 30200
5. Burlington Industries LLC Hurt Fin 30379
6. Georgia Pacific Corp Big Island Plt 30389
7. Griffin Pipe Products Company 30397
8. Stone Container Enterprises (Smurfit) 40126
9. Hopewell Cogeneration Ltd Partnership 50967
10. Mohawk Industries Inc-Lees Carpet 80269

New information was obtained from VDEQ for all of these sources.

Specific Information Requested for Updating the Virginia Point Source Inventory

In addition to the general missing information related to emissions and stack parameters identified above, efforts were made to obtain the following information:

1. SCC codes for the following facilities.
    a. Chemical Lime Company 20225
    b. Celanese/Cinergy Solutions (21418) 20304
    c. Commonwealth Chesapeake Power 40898
    d. James River Cogeneration Company 50950
    e. Spruance Genco LLC 51033
    f. Cogentrix Virginia Leasing Corp 61049

New SCC code information was obtained from VDEQ for all of these sources.

2. Verify that the mercury speciation profiles for the following electric generating units (EGUs), which were specified as default 20/30/50 (hgp/hg2/hg0), are the latest available (or obtain updated profiles, if available).
    a. Dominion–Altavista Power Station 30859
    b. Dominion–Clover Power Station 30867
    c. Dominion–Bremo 40199

d. Dominion–Gordonsville Power Station 40808
e. Dominion–Chesterfield Power Station 50396
f. Dominion–Yorktown Power Station 60137
g. Dominion–Chesapeake Energy Center 60163
h. Dominion–Southampton Power Station 61093
i. Dominion–Elizabeth River CT Station 61108
j. Dominion–Possum Point Power Station 70225
k. Covanta Alexandria/Arlington, Inc. 71895
l. Covanta Fairfax, Inc. 71920

No new facility-specific speciation profile information was available for any of these sources.

2.2. Updated 2002 Point Source Inventory

Based on the initial review of the inventory as summarized in the previous section, updated information was received from VDEQ. Table 2-1 presents the final 2002 Virginia mercury point source inventory, summarized by facility. The table includes speciated emissions for EGU's and non-EGU's (other industrial sources) and the sources are listed in descending order by total facility mercury emissions. As noted above, for those sources that did not obtain any speciation information based on recent stack testing, they were instructed by VDEQ to specify the default speciation profiles that were used in EPA's CAMR modeling analysis (EPA, 2005a).

Table 2-1 VDEQ 2002 Point Source Mercury Emissions Inventory—Ranked by Facility Total Emissions

	Facility Name	County	Source Type	HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	*Total (lb/yr)*
1	Dominion–Chesterfield Power Station	Chesterfield	EGU	179.42	107.65	71.77	*358.83*
2	Chaparral Steel	Dinwiddie	non-EGU	233.75	29.29	29.26	*292.30*
3	Dominion–Bremo	Fluvanna	EGU	83.86	50.32	33.55	*167.73*
4	American Electric Power- Clinch River	Russell	EGU	38.21	121.00	0.00	*159.21*
5	Dominion–Chesapeake Energy Center	Chesapeake	EGU	78.69	47.22	31.48	*157.38*
6	Potomac River Generating Station	Alexandria	EGU	11.83	106.43	0.00	*118.26*
7	Dominion–Yorktown Power Station	York	EGU	53.82	32.29	21.53	*107.64*
8	Jewel Coke Company LLP	Buchanan	non-EGU	84.50	10.56	10.56	*105.63*
9	Dominion-Possum Point Power Station	Prince William	EGU	50.09	30.06	20.04	*100.19*
10	Stone Container Enterprises (Smurfit)	King William	non-EGU	46.81	27.22	3.73	*77.76*
11	Stone Container Corporation -Hopewell	Hopewell	non-EGU	34.84	20.91	13.94	*69.69*
12	American Electric Power	Giles	EGU	26.06	39.08	0.00	*65.14*
13	Intermet Foundry Archer Creek	Campbell	non-EGU	51.97	6.53	6.51	*65.01*
14	RES dba Steel Dynamics	Roanoke	non-EGU	48.64	6.08	6.08	*60.80*
15	Spruance Genco LLC	Richmond	EGU	27.75	16.65	11.10	*55.50*
16	Mead Westvaco Packaging Resources	Covington	non-EGU	12.96	4.88	9.07	*26.91*
17	Covanta Fairfax, Inc.	Fairfax	EGU	12.87	7.72	5.15	*25.73*
18	James River Cogeneration Company	Hopewell	EGU	12.65	7.59	5.06	*25.30*
19	Celanese/Cinergy Solutions (21418)	Giles	non-EGU	9.20	5.52	3.68	*18.40*
20	Dominion–Clover Power Station	Halifax	EGU	8.34	5.00	3.34	*16.68*
21	Giant Yorktown Refinery	York	non-EGU	12.74	1.59	1.59	*15.93*
22	SPSA Refuse Derived Fuel Plant	Portsmouth	non-EGU	3.43	9.05	3.12	*15.61*
23	H L Mooney Water Reclamation Facility	Prince William	non-EGU	3.21	8.47	2.92	*14.61*
24	Hopewell WWTP	Hopewell	non-EGU	2.93	7.71	2.66	*13.30*
25	HRSD Chesapeake-Elizabeth Sewage	Virginia Beach	non-EGU	2.87	7.56	2.61	*13.04*
26	Cogentrix Virginia Leasing Corp	Portsmouth	EGU	5.85	3.51	2.34	*11.70*
27	Chemical Lime Company	Giles	non-EGU	9.20	1.15	1.15	*11.50*
28	Burlington Industries LLC Hurt Fin	Pittsylvania	non-EGU	5.53	3.32	2.21	*11.05*
29	HRSD Boat Harbor Sewage Treatment Plt	Newport News	non-EGU	2.11	5.56	1.92	*9.59*
30	Roanoke Cement Company	Botetourt	non-EGU	6.96	1.21	1.11	*9.28*
31	Alliant Ammunition & Powder Co.	Montgomery	non-EGU	4.57	2.74	1.83	*9.14*
32	Philip Morris USA Inc–Park 500	Chesterfield	non-EGU	4.35	2.61	1.74	*8.69*
33	Georgia Pacific Corp Big Island Plt	Bedford	non-EGU	3.84	2.30	1.53	*7.67*
34	Mohawk Industries Inc-Lees Carpet	Rockbridge	non-EGU	3.76	2.26	1.50	*7.52*
35	HRSD Virginia Initiative Plant	Norfolk	non-EGU	1.45	3.81	1.31	*6.57*
36	HRSD Army Base Sewage Treatment Plt	Norfolk	non-EGU	1.41	3.71	1.28	*6.40*
37	Intermet Corporation Radford	Radford	non-EGU	4.90	0.61	0.61	*6.12*
38	Bear Island Paper Company LLC	Hanover	non-EGU	2.96	1.77	1.18	*5.91*
39	US Navy Little Creek Amphibious Base	Virginia Beach	non-EGU	2.93	1.76	1.17	*5.87*
40	HRSD Williamsburg	James City	non-EGU	0.99	2.62	0.90	*4.51*
41	Georgia-Pacific/Emporia Plywood	Greensville	non-EGU	2.06	1.24	0.82	*4.12*

	Facility Name	County	Source Type	HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	*Total (lb/yr)*
42	Covanta Alexandria/Arlington, Inc.	Alexandria	EGU	1.96	1.17	0.78	*3.92*
43	Dan River Incorporated Schoolfield	Danville	non-EGU	1.86	1.11	0.74	*3.71*
44	International Paper Company	Isle Of Wight	non-EGU	1.82	1.09	0.73	*3.63*
45	Honeywell Nylon LLC–Hopewell	Hopewell	non-EGU	1.81	1.09	0.72	*3.62*
46	Birchwood Power Partners, L.P.	King George	EGU	1.41	2.05	0.13	*3.59*
47	Solite LLC/Giant Resource Recovery	Buckingham	non-EGU	1.45	0.50	0.55	*2.50*
48	University of Virginia	Charlottesville	non-EGU	1.25	0.75	0.50	*2.49*
49	Philip Morris USA Mfg Center	Richmond	non-EGU	1.24	0.74	0.50	*2.48*
50	Dominion-Southampton Power Station	Southampton	EGU	1.10	0.66	0.44	*2.19*
51	Dominion–Altavista Power Station	Campbell	EGU	1.09	0.65	0.44	*2.18*
52	O-N Minerals (Chemstone) Strasburg	Shenandoah	non-EGU	1.74	0.22	0.22	*2.17*
53	Rock Tenn Co Mill	Lynchburg	non-EGU	0.94	0.56	0.37	*1.87*
54	Virginia Tech	Montgomery	non-EGU	0.75	0.45	0.30	*1.49*
55	Martinsville Thermal, LLC	Henry	non-EGU	0.71	0.42	0.28	*1.41*
56	Commonwealth Chesapeake Power	Accomack	EGU	0.67	0.40	0.27	*1.34*
57	Dominion–Mecklenburg Power Station	Mecklenburg	EGU	0.84	0.25	0.03	*1.11*
58	Hopewell Cogeneration Ltd Partnership	Hopewell	non-EGU	0.53	0.32	0.21	*1.05*
59	INVISTA S.a.r.l. -Waynesboro	Waynesboro	non-EGU	0.52	0.31	0.21	*1.04*
60	Dominion–Gordonsville Power Station	Louisa	EGU	0.41	0.25	0.16	*0.82*
61	Griffin Pipe Products Company	Lynchburg	non-EGU	0.57	0.07	0.07	*0.71*
62	O-N Minerals (Chemstone) Clearbrook	Frederick	non-EGU	0.32	0.04	0.04	*0.40*
63	Hampton/NASA Steam Plant	Hampton	non-EGU	0.07	0.17	0.06	*0.30*
64	Perdue Farms–Soybean Oil Processing	Chesapeake	non-EGU	0.13	0.08	0.05	*0.26*
65	Philip Morris USA Inc.–Leaf Processing	Richmond	non-EGU	0.10	0.06	0.04	*0.20*
66	Mead Westvaco Virginia Specialty	Covington	non-EGU	0.07	0.01	0.01	*0.09*
67	Blacksburg Sanitation Authority	Montgomery	non-EGU	0.01	0.03	0.01	*0.06*
68	Philip Morris USA Inc.–Blended Leaf	Richmond	non-EGU	0.03	0.02	0.01	*0.05*
	Total			*1,217.64*	*770.03*	*329.22*	*2,316.89*

2.3. Comparison of 2002 Virginia Inventory with the NEI

The EPA compiles and maintains a national inventory of mercury emissions as contained in the National Emission Inventory (NEI). As part of this task, the latest version (Version 3) of the 2002 NEI mercury inventory was obtained from EPA. This inventory contains information for point sources and “non-point” sources, also referred to as area sources. These include various other types of fuel combustion sources that emit mercury. The NEI inventory obtained from EPA contains mercury emissions information for 379 distinct Virginia facilities. The top 25 of these sources represent 97 percent of total point source mercury emissions, so there are a number of facilities in this inventory with very small mercury emissions, the majority of which are landfills that emit less than 1 lb of mercury per year. The 2002 Virginia DEQ mercury point source inventory contains information for 68 facilities. The top 25 of these sources represent 92 percent of total point source mercury emissions. A number of the smaller facilities emit less than 5 lbs of mercury per year.

Table 2-2 presents a comparison of emissions for the 68 point sources contained in the updated Virginia inventory with those same sources contained in the NEI inventory. The table includes speciated emissions for elemental, divalent, and particulate mercury based on total mercury, and the assumed speciation profile for each source. The table shows some similarities in emissions totals but also major differences in emissions for a number of the top mercury point source emitters in Virginia. In addition, there are some differences in the assumed speciation profile for a number of sources. It is not evident why the emissions for some of the sources are different or why there are differences in assumed speciation profiles. It is assumed that the updated Virginia inventory includes the latest and most accurate information for these sources. The table also shows that some of the top mercury point sources in Virginia are not included in the current national inventory. Conversely, there are a number of moderate-sized sources listed in the NEI that are not included in the Virginia inventory and it was found that some of the sources in the NEI were closed prior to 2002. It is not clear why certain sources are missing from the NEI or why a few of the closed sources are still included, however, it is expected that emissions for Virginia's updated mercury point source inventory will be submitted to EPA, along with changes/corrections/shutdowns to any other Virginia source in the existing NEI, for inclusion in the next version of the NEI.

Table 2-2. Comparison of Mercury Emitters in the 2002 VDEQ Point Source Inventory with those same sources in the 2002 NEI Version 3 Inventory

	Facility Name	County	Source Type	Updated VDEQ Inventory							EPA 2002 NEI Version 3 Inventory						
				2002 Emissions				Speciation			2002 Emissions				Speciation		
				HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	HG0	HG2	HGP	HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	HG0	HG2	HGP
1	Dominion - Chesterfield Power Station	Chesterfield	EGU	179.42	107.65	71.77	358.83	50%	30%	20%	114.42	303.62	27.19	445.23	26%	68%	6%
2	Chaparral Steel	Dinwiddie	non-EGU	233.75	29.29	29.26	292.30	80%	10%	10%	312.79	39.10	39.10	390.98	80%	10%	10%
3	Dominion - Bremo Power Station	Fluvanna	EGU	83.86	50.32	33.55	167.73	50%	30%	20%	59.72	92.67	7.87	160.26	37%	58%	5%
4	American Electric Power- Clinch River	Russell	EGU	38.21	121.00	0.00	159.21	24%	76%	0%	41.74	110.76	9.92	162.42	26%	68%	6%
5	Dominion - Chesapeake Energy Center	Chesapeake	EGU	78.69	47.22	31.48	157.38	50%	30%	20%	46.98	124.65	11.16	182.79	26%	68%	6%
6	Potomac River Generating Station	Alexandria	EGU	11.83	106.43	0.00	118.26	10%	90%	0%	18.62	49.40	4.42	72.45	26%	68%	6%
7	Dominion - Yorktown Power Station	York	EGU	53.82	32.29	21.53	107.64	50%	30%	20%	40.07	87.88	10.98	138.93	29%	63%	8%
8	Jewel Coke Company LLP	Buchanan	non-EGU	84.50	10.56	10.56	105.63	80%	10%	10%	84.50	10.56	10.56	105.63	80%	10%	10%
9	Dominion-Possum Point Power Station	Prince William	EGU	50.09	30.06	20.04	100.19	50%	30%	20%	36.88	89.43	9.43	135.74	27%	66%	7%
10	Stone Container Enterprises (Smurfit)	King William	non-EGU	46.81	27.22	3.73	77.76	60%	35%	5%	0.03	0.02	0.01	0.06	50%	30%	20%
11	Stone Container Corporation - Hopewell	Hopewell	non-EGU	34.84	20.91	13.94	69.69	50%	30%	20%	33.70	20.22	13.48	67.39	50%	30%	20%
12	American Electric Power - Glen Lyn	Giles	EGU	26.06	39.08	0.00	65.14	40%	60%	0%	19.59	51.98	4.65	76.22	26%	68%	6%
13	Intermet Foundry Archer Creek	Campbell	non-EGU	51.97	6.53	6.51	65.01	80%	10%	10%	0.80	0.10	0.10	1.00	80%	10%	10%
14	RES dba Steel Dynamics	Roanoke	non-EGU	48.64	6.08	6.08	60.80	80%	10%	10%	185.07	23.13	23.13	231.33	80%	10%	10%
15	Spruance Genco LLC	Richmond	EGU	27.75	16.65	11.10	55.50	50%	30%	20%	3.77	1.09	1.21	6.08	62%	18%	20%
16	Mead Westvaco Packaging Resources	Covington	non-EGU	12.96	4.88	9.07	26.91	48%	18%	34%	0.45	0.27	0.18	0.89	50%	30%	20%
17	Covanta Fairfax, Inc.	Fairfax	EGU	12.87	7.72	5.15	25.73	50%	30%	20%	2.98	7.85	2.71	13.54	22%	58%	20%
18	James River Cogeneration Company	Hopewell	EGU	12.65	7.59	5.06	25.30	50%	30%	20%							
19	Celanese/Cinergy Solutions (21418)	Giles	non-EGU	9.20	5.52	3.68	18.40	50%	30%	20%	0.12	0.07	0.05	0.23	50%	30%	20%
20	Dominion - Clover Power Station	Halifax	EGU	8.34	5.00	3.34	16.68	50%	30%	20%	7.34	4.01	0.81	12.17	60%	33%	7%
21	Giant Yorktown Refinery	York	non-EGU	12.74	1.59	1.59	15.93	80%	10%	10%	10.56	1.32	1.32	13.20	50%	30%	20%
22	SPSA Refuse Derived Fuel Plant	Portsmouth	non-EGU	3.43	9.05	3.12	15.61	22%	58%	20%	3.35	8.83	3.04	15.22	22%	58%	20%
23	H L Mooney Water Reclamation Facility	Prince William	non-EGU	3.21	8.47	2.92	14.61	22%	58%	20%							
24	Hopewell WWTP	Hopewell	non-EGU	2.93	7.71	2.66	13.30	22%	58%	20%							
25	HRSD Chesapeake-Elizabeth Sewage	Virginia Beach	non-EGU	2.87	7.56	2.61	13.04	22%	58%	20%							
26	Cogentrix Virginia Leasing Corp	Portsmouth	EGU	5.85	3.51	2.34	11.70	50%	30%	20%							
27	Chemical Lime Company	Giles	non-EGU	9.20	1.15	1.15	11.50	80%	10%	10%	3.92	0.49	0.49	4.90	80%	10%	10%
28	Burlington Industries LLC Hurt Fin	Pittsylvania	non-EGU	5.53	3.32	2.21	11.05	50%	30%	20%							
29	HRSD Boat Harbor Sewage Treatment Plt	Newport News	non-EGU	2.11	5.56	1.92	9.59	22%	58%	20%							
30	Roanoke Cement Company	Botetourt	non-EGU	6.96	1.21	1.11	9.28	75%	13%	12%	4.73	0.82	0.76	6.30	75%	13%	12%
31	Alliant Ammunition & Powder Co.	Montgomery	non-EGU	4.57	2.74	1.83	9.14	50%	30%	20%	0.05	0.02	0.02	0.08	58%	20%	22%
32	Philip Morris USA Inc - Park 500	Chesterfield	non-EGU	4.35	2.61	1.74	8.69	50%	30%	20%							
33	Georgia Pacific Corp Big Island Plt	Bedford	non-EGU	3.84	2.30	1.53	7.67	50%	30%	20%							
34	Mohawk Industries Inc-Lees Carpet	Rockbridge	non-EGU	3.76	2.26	1.50	7.52	50%	30%	20%							

	Facility Name	County	Source Type	Updated VDEQ Inventory							EPA 2002 NEI Version 3 Inventory						
				2002 Emissions				Speciation			2002 Emissions				Speciation		
				HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	HG0	HG2	HGP	HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	HG0	HG2	HGP
35	HRSD Virginia Initiative Plant	Norfolk	non-EGU	1.45	3.81	1.31	6.57	22%	58%	20%							
36	HRSD Army Base Sewage Treatment Plt	Norfolk	non-EGU	1.41	3.71	1.28	6.40	22%	58%	20%							
37	Intermet Corporation Radford	Radford	non-EGU	4.90	0.61	0.61	6.12	80%	10%	10%	0.18	0.02	0.02	0.23	80%	10%	10%
38	Bear Island Paper Company LLC	Hanover	non-EGU	2.96	1.77	1.18	5.91	50%	30%	20%							
39	US Navy Little Creek Amphibious Base	Virginia Beach	non-EGU	2.93	1.76	1.17	5.87	50%	30%	20%							
40	HRSD Williamsburg	James City	non-EGU	0.99	2.62	0.90	4.51	22%	58%	20%							
41	Georgia-Pacific/Emporia Plywood	Greensville	non-EGU	2.06	1.24	0.82	4.12	50%	30%	20%	2.06	1.24	0.82	4.12	50%	30%	20%
42	Covanta Alexandria/Arlington, Inc.	Alexandria	EGU	1.96	1.17	0.78	3.92	50%	30%	20%	1.41	3.72	1.28	6.41	22%	58%	20%
43	Dan River Incorporated Schoolfield	Danville	non-EGU	1.86	1.11	0.74	3.71	50%	30%	20%	0.00	0.00	0.00	0.00	80%	10%	10%
44	International Paper Company	Isle Of Wight	non-EGU	1.82	1.09	0.73	3.63	50%	30%	20%							
45	Honeywell Nylon LLC - Hopewell	Hopewell	non-EGU	1.81	1.09	0.72	3.62	50%	30%	20%	0.53	0.32	0.21	1.06	50%	30%	20%
46	Birchwood Power Partners, L.P.	King George	EGU	1.41	2.05	0.13	3.59	39%	57%	4%	2.16	1.17	0.24	3.56	61%	33%	7%
47	Solite LLC/Giant Resource Recovery	Buckingham	non-EGU	1.45	0.50	0.55	2.50	58%	20%	22%	55.73	19.22	21.14	96.08	58%	20%	22%
48	University of Virginia	Charlottesville	non-EGU	1.25	0.75	0.50	2.49	50%	30%	20%							
49	Philip Morris USA Mfg Center	Richmond	non-EGU	1.24	0.74	0.50	2.48	50%	30%	20%	1.31	0.79	0.53	2.63	50%	30%	20%
50	Dominion-Southampton Power Station	Southampton	EGU	1.10	0.66	0.44	2.19	50%	30%	20%	0.94	0.29	0.31	1.54	61%	19%	20%
51	Dominion - Altavista Power Station	Campbell	EGU	1.09	0.65	0.44	2.18	50%	30%	20%	0.89	0.26	0.29	1.44	62%	18%	20%
52	O-N Minerals (Chemstone) Strasburg	Shenandoah	non-EGU	1.74	0.22	0.22	2.17	80%	10%	10%	1.76	0.22	0.22	2.20	80%	10%	10%
53	Rock Tenn Co Mill	Lynchburg	non-EGU	0.94	0.56	0.37	1.87	50%	30%	20%							
54	Virginia Tech	Montgomery	non-EGU	0.75	0.45	0.30	1.49	50%	30%	20%							
55	Martinsville Thermal, LLC	Henry	non-EGU	0.71	0.42	0.28	1.41	50%	30%	20%	0.13	0.08	0.05	0.25	50%	30%	20%
56	Commonwealth Chesapeake Power	Accomack	EGU	0.67	0.40	0.27	1.34	50%	30%	20%							
57	Dominion - Mecklenburg Power Station	Mecklenburg	EGU	0.84	0.25	0.03	1.11	75%	22%	2%	0.34	0.25	0.07	0.65	52%	38%	10%
58	Hopewell Cogenertion Ltd Partnership	Hopewell	non-EGU	0.53	0.32	0.21	1.05	50%	30%	20%	0.30	0.18	0.12	0.60	50%	30%	20%
59	INVISTA S.a.r.l. -Waynesboro	Waynesboro	non-EGU	0.52	0.31	0.21	1.04	50%	30%	20%							
60	Dominion - Gordonsville Power Station	Louisa	EGU	0.41	0.25	0.16	0.82	50%	30%	20%							
61	Griffin Pipe Products Company	Lynchburg	non-EGU	0.57	0.07	0.07	0.71	80%	10%	10%							
62	O-N Minerals (Chemstone) Clearbrook	Frederick	non-EGU	0.32	0.04	0.04	0.40	80%	10%	10%	0.32	0.04	0.04	0.40	80%	10%	10%
63	Hampton/NASA Steam Plant	Hampton	non-EGU	0.07	0.17	0.06	0.30	22%	58%	20%	64.92	171.16	59.02	295.11	22%	58%	20%
64	Perdue Farms - Soybean Oil Processing	Chesapeake	non-EGU	0.13	0.08	0.05	0.26	50%	30%	20%	0.98	0.59	0.39	1.95	50%	30%	20%
65	Philip Morris USA Inc. - Leaf Processing	Richmond	non-EGU	0.10	0.06	0.04	0.20	50%	30%	20%	0.03	0.02	0.01	0.07	50%	30%	20%
66	Mead Westvaco Virginia Specialty	Covington	non-EGU	0.07	0.01	0.01	0.09	80%	10%	10%							
67	Blacksburg Sanitation Authority	Montgomery	non-EGU	0.01	0.03	0.01	0.06	22%	58%	20%							
68	Philip Morris USA Inc. - Blended Leaf	Richmond	non-EGU	0.03	0.02	0.01	0.05	50%	30%	20%	2.25	1.35	0.90	4.51	50%	30%	20%

Figure 2-1 presents a comparison of total emissions for the 68 Virginia mercury point sources with emissions from those same sources contained in the NEI. A comparison of totals shows the NEI inventory with 25 percent higher emissions. As noted above, this is due to the fact that a few large emitters listed in the NEI have been closed in recent years or that this version of the NEI contains outdated and/or erroneous emission estimates for certain sources. For example, source #63 in Table 2-2 shows a total of 0.3 lbs/yr total mercury emissions in the updated Virginia inventory and 295 lbs/yr total mercury in the NEI inventory, which is obviously wrong based on the updated survey information.

For the mercury deposition modeling analysis, the updated Virginia point source inventory will be combined with emissions from point and non-point sources contained in the NEI. The emissions for the 68 facilities will be combined with emissions from other Virginia sources contained in the NEI inventory, but not included in the list of 68. The emissions for these other NEI sources were also reviewed by VDEQ as part of this work, and some of these sources were eliminated because they were either closed or were not regarded as "air" sources by VDEQ. Although the emissions from the remaining valid NEI sources are very small, they will be accounted for in the deposition modeling analysis. As noted above, it is expected that emissions for Virginia's updated mercury point source inventory will be submitted to EPA, along with changes/corrections/shutdowns to any other Virginia source in the existing NEI, for inclusion in the next version of the NEI.

Figure 2-1. Mercury Emissions for Virginia Point Sources: 2002 VDEQ vs. 2002 NEI V3

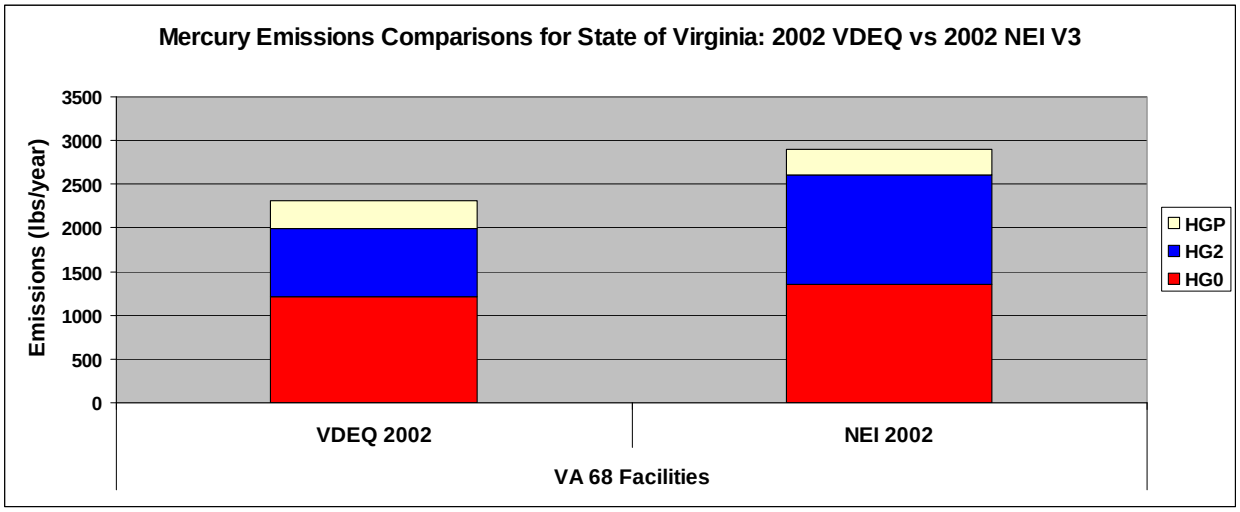
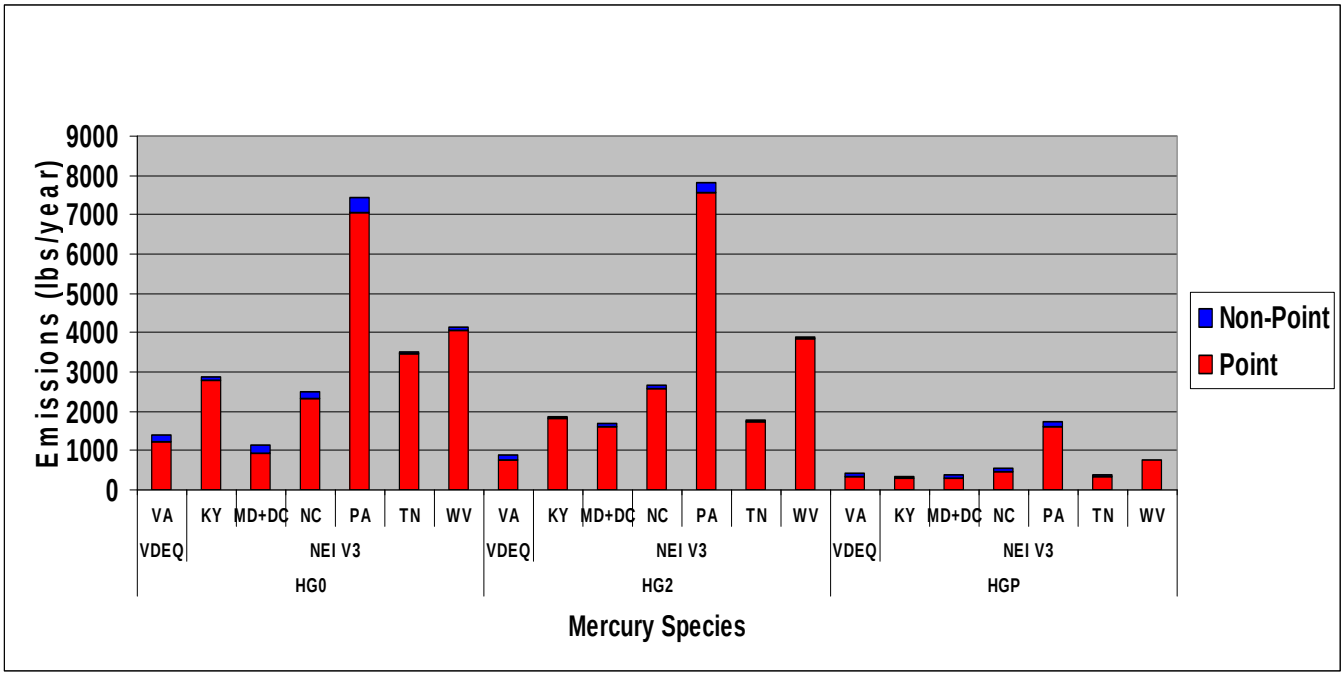


Figure 2-2 presents a comparison of the 2002 Virginia mercury emissions with those contained in the NEI for the neighboring states of Kentucky, Maryland/D.C., North Carolina, Pennsylvania, Tennessee, and West Virginia. These emissions and emissions from all other states in the modeling domain obtained from the NEI inventory will be used in the mercury air deposition modeling. Of the seven states, Virginia's emissions are comparable to the combined Maryland/D.C. emissions totals. The neighboring states have the potential to influence mercury deposition in Virginia watersheds and emissions from these states will be fully accounted for in the modeling analysis.

Figure 2-2. Comparison of the 2002 VDEQ Speciated Mercury Emissions Inventory with the 2002 NEI Version 3 Inventory for Selected Neighboring States

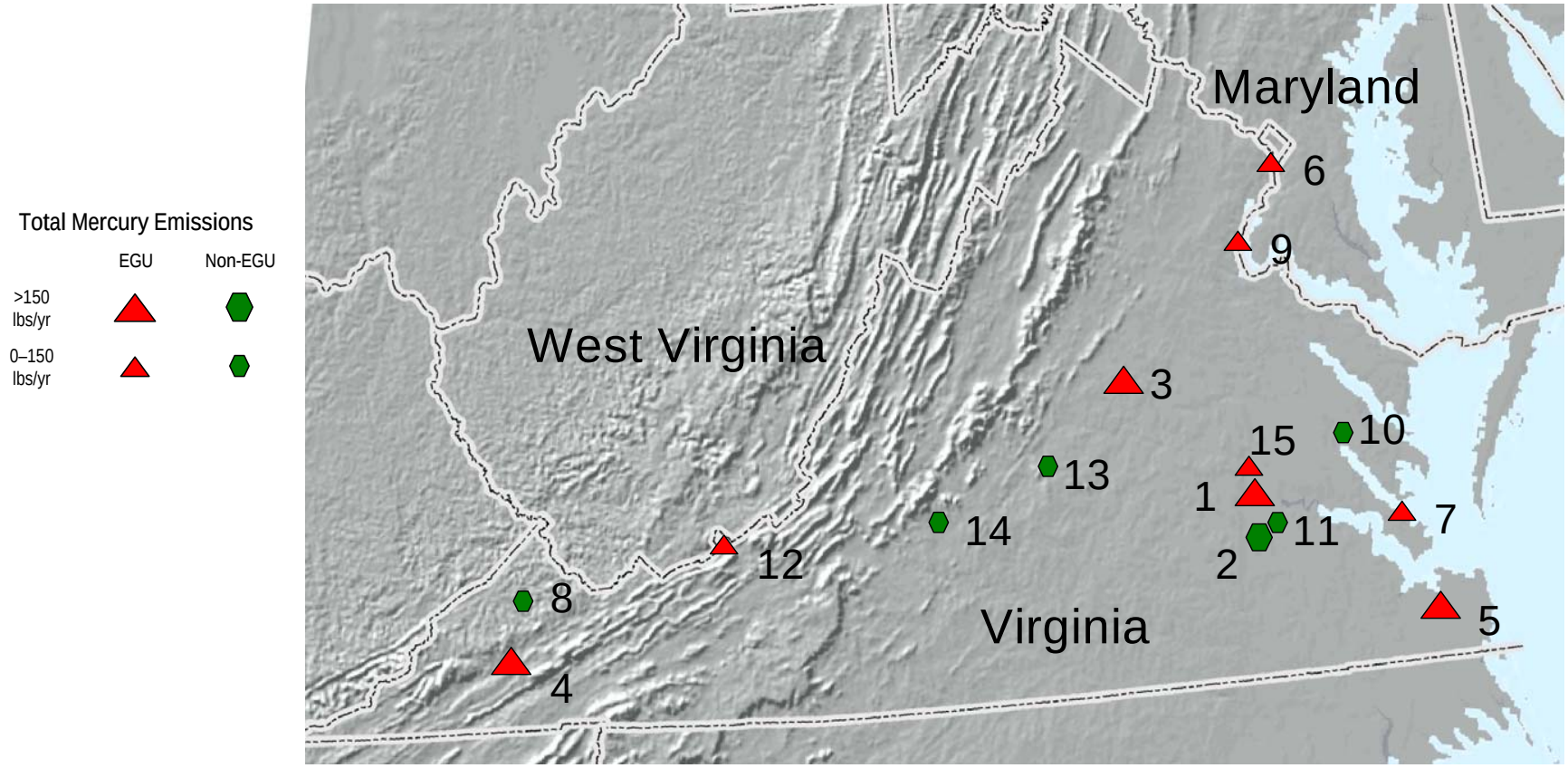


3. Summary of Virginia Mercury Inventory

3.1. Base-Year Emission Inventory for Modeling

The 2002 Virginia mercury point source inventory, as listed in Table 2-1, will be processed and used with the CMAQ air quality modeling system to estimate mercury deposition affecting Virginia waterways. To provide an example of the point-source emissions as they will be input to the model, Figure 3-1 presents the location and magnitude of the top 15 mercury point sources in Virginia for 2002 as contained in Table 2-1. These 15 EGU and non-EGU point sources represent 85 percent of total mercury point source emissions for Virginia in 2002. The figure presents information for total annual mercury emissions from these sources in two ranges: 0 – 150 lbs/yr and > 150 lbs/yr.

Figure 3-1. Location and Magnitude of the Top 15 Virginia Mercury EGU and Non-EGU Point Sources for 2002 (Hg-Total Mercury)



	Facility Name	County	Source Type		Facility Name	County	Source Type
1	Dominion–Chesterfield Power Station	Chesterfield	EGU	9	Dominion-Possum Point Power Station	Prince William	EGU
2	Chaparral Steel	Dinwiddie	non-EGU	10	Stone Container Enterprise (Smurfit)	King William	Non-EGU
3	Dominion–Bremo	Fluvanna	EGU	11	Stone Container Corporation -Hopewell	Hopewell	non-EGU
4	American Electric Power- Clinch River	Russell	EGU	12	American Electric Power	Giles	EGU
5	Dominion–Chesapeake Energy Center	Chesapeake	EGU	13	Intermet Foundry Archer Creek	Campbell	non-EGU
6	Potomac River Generating Station	Alexandria	EGU	14	RES dba Steel Dynamics	Roanoke	non-EGU
7	Dominion–Yorktown Power Station	York	EGU	15	Spruance Genco LLC	Richmond	EGU
8	Jewell Coke	Buchanan	Non-EGU				

3.2. Future-Year Emission Inventory Estimates for Virginia Sources

For this study, mercury air deposition will be assessed in the modeling analysis for 2002 and three future years: 2010, 2015, and 2018. As noted above, recent national control legislation promulgated by EPA in the Clean Air Interstate Rule (CAIR) will reduce emissions of NO_x, SO_2, and mercury from coal-fired power plants in the eastern US. Phase 1 controls for NOx are due in place by January 2009, while phase 1 controls for SO_2 are due by January 2010. Phase 2 controls for NO_x and SO_2 are both due by January 2015. Mercury emissions reduction benefits will be realized from the NO_x and SO_2 controls in place by January 2010. The Clean Air Mercury Rule (CAMR) will build on CAIR and provide for additional future mercury emission reductions from these sources. Mercury controls are mandated to be in place by January 2018 for those coal-fired power plants subject to the rule.

Presently, a number of Virginia sources have existing pollution control equipment installed and running, while others are planning on installing future controls. Table 3-1 presents a summary of control equipment currently being utilized or planned to be installed by Virginia coal-fired boilers. Most of the new control equipment is expected to be installed by 2010.

Table 3-1. Summary of Existing and Planned Emission Controls for Virginia Coal Fired Boilers

Facility Name	MW (NOx SIP Call)	MW Calculated	Control Equipment[1]	Projected Control Equipment	Projected Year To Install
Dominion - Chesterfield Power Station (1)					
3	113	110.0	OFA/LNB/ESP	FGD	2011
4	188	167.7	SCR/ESP/Staged combustion	FGD	2011
5	359	343.2	SCR/ESP/Staged combustion	FGD	2011
6	694	633.3	SCR/ESP/Staged combustion	FGD/FF	2008
Dominion - Bremo Power Station (4)					
3	69	86.9	ESP (hot sided)/BOOS		
4	185	161.8	ROFA/ESP (hot sided)		
American Electric Power - Clinch River (5)					
1	235	200.0	staged combustion/ESP		
2	235	200.0	staged combustion/ESP		
3	235	200.0	staged combustion/ESP		
Dominion - Chesapeake Energy Center[2] (6)					
1	113	123.8	OFA /ROFA/ESP	SA Coal 50% CE for Hg and 40% for S	2007
2	113	123.8	OFA/ROFA/ESP	SA Coal 50% CE for Hg and 40% for S	2007
3	185	158.4	LNB/SCR/ESP	SA Coal 50% CE for Hg and 40% for S	2007
4	239	223.4	LNB/SCR/ESP (all cold sided)	SA Coal 50% CE for Hg and 40% for S	2007
Potomac River Power Generating Station[3] (7)					
1	93	92.4	LNB/ESP		
2	93	92.4	LNB/ESP		
3	108	91.5	LNB/SOFA/ESP		
4	108	91.5	LNB/SOFA/ESP		
5	108	91.5	LNB/SOFA/ESP		
Dominion - Yorktown Power Station (8)					
1	188	161.6	LNB/OFA/SNCR/ESP	FGD	2015
2	188	166.2	LNB/OFA/SNCR/ESP	FGD	2015
Stone Container Corp., West Point Mill[4](10)					
2			Concentric firing/LNB/ESP	SO2 Scrubber	2008
Stone Container Corp., Hopewell (11)					
1		80.6	ESP		
American Electric Power - Glen Lyn (12)					
51	100	54.5	staged combustion/ESP		
52	100	54.5	staged combustion/ESP		
6	238	194.3	staged combustion/ESP		
Spruance Genco LLC (15)					
BLR01A		35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR01B	115	35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR02A		35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR02B	115	35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR03A		35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR03B	115	35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR04A		35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR04B	115	35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
James River Cogeneration (18)					
BLR01A		19.0	FGR/OFA/FF	SDA	2010
BLR01B		19.0	FGR/OFA/FF	SDA	2010
BLR01C	108.5	19.0	FGR/OFA/FF	SDA	2010
BLR02A		19.0	FGR/OFA/FF	SDA	2010
BLR02B		19.0	FGR/OFA/FF	SDA	2010
BLR02C	108.5	19.0	FGR/OFA/FF	SDA	2010
Dominion - Clover Power Station (20)					
1	424	389.0	LNB/SNCR/FF/Wet FGD		
2	424	389.0	LNB/SNCR/FF/Wet FGD		

Summary of Virginia Mercury Inventory

Facility Name		MW (NOx SIP Call)	MW Calculated	Control Equipment[1]	Projected Control Equipment	Projected Year To Install
Cogentrix Virginia Leasing-Portsmouth (26)						
	BLR01A		19.0	FGR/OFA/FF	SDA	2010
	BLR01B		19.0	FGR/OFA/FF	SDA	2010
	BLR01C	108.5	19.0	FGR/OFA/FF	SDA	2010
	BLR02A		19.0	FGR/OFA/FF	SDA	2010
	BLR02B		19.0	FGR/OFA/FF	SDA	2010
	BLR02C	108.5	19.0	FGR/OFA/FF	SDA	2010
Georgia-Pacific - Big Island Plant (33)						
	4		27.0	ESP		
	6		27.1	LNB/FGR (not coal fired)		
Dan River Inc—Schoolfield Complex (43)						
			24.0	ESP		
International Paper Co. - Franklin Mill (44)						
	3		47.2	ESP		
	17			shutdown		
	29			LNB/SCR		
Birchwood Power Partners Facility (46)						
	1	240	219.0	SCR/FF/DLS		
Dominion - Southampton Power Station (50)						
	1	71.1	38.1	OFA/DFGD/FF/Staged combustion		
62.7 MW total	2	71.1	38.1	OFA/DFGD/FF/Staged combustion		
Dominion - Altavista Power Station (51)						
	1	71.1	36.4	SNCR/LNB/DLS/FF		
	2	71.1	36.4	SNCR/LNB/DLS/FF		
Dominion - Mecklenburg Cogeneration Facility (57)						
	1		79.4	LNB/OFA/FF/FGD		
	2	139.9	79.4	LNB/OFA/FF/FGD		
Mead Westvaco Virginia Specialty, Covington (66)						
	1		52.4	LNB/ESP/FGD		
	2		41.9	FGR /ESP/FGD		
	3		55.2	FGR/ESP/FGD		
	4		76.9	LNB/ESP/FGD		
	5					
	11			LNB/FGR		

[1] Control equipment includes the following: selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), low-NOx burners (LNB), electrostatic precipitators (ESP), dry lime scrubbing (DLS), fabric filters (FF), over-fired air (OFA), flue-gas desulfurization (FGD), flue-gas recirculation (FGR), rotating opposed-fired air (ROFA), and burners out of service (BOOS).

[2] Chesapeake Energy Center was originally slated to be controlled by SDA. However, a Dominion update of the control plan notes these installations are indefinitely delayed, and South American coal with about half of the Hg content and about 40% lower sulfur content is currently being used at the facility.

[3] Potomac River is currently using Trona injection on 3, 4, and 5. They are also subject to the CAIR cap without trading provisions due to their location in a nonattainment area. They will be capped for both NOx and SO2.

[4] Installation of the SO2 scrubber by 2008 is the result of a federal consent decree and enforcement action.

For those EGU sources subject to EPA's CAMR reductions, future year emissions budgets have been established based on the CAMR provisions as well as Virginia-specific emissions rules. According to VDEQ, proposed mercury allowance allocations to coal fired electric steam generating units in Virginia, for the control period 2010 – 2017, were made according to State Air Pollution Control Board Regulation for Emission Trading Programs. A total of 95 percent of the allocated state budget of 1184 lbs (0.592 tons, excluding 4% set-aside for the new and 1%

for energy efficient units) are distributed to the existing units in proportion to their baseline heat input in million Btu. The baseline heat input for this purpose is the average of three highest amounts of the unit's control period heat input for the years 2000 through 2004.

Table 3-2 presents the estimated future-year budgets for those Virginia EGU's subject to CAMR for 2014, 2015-17, and 2018. The number in the table corresponds to the number in the 2002 inventory table (Table 2-2) above. Because many of the EGU sources listed have (or will have) controls in place to reduce mercury emissions below these budgets, the actual future year emissions to be used in the mercury deposition modeling analysis may be different than those listed in the table.

Table 3-2. Future Year Mercury Emissions Budgets for Virginia EGU's Subject to CAMR

#	Facility Name	County	Source Type	2002				2014	2015–2017	2018
				HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	Total (lb/yr)	Total (lb/yr)	Total (lb/yr)
1	Dominion - Chesterfield Power Station	Chesterfield	EGU	179.42	107.65	71.77	358.83	230.39	94.00	94.00
4	Dominion – Bremo Power Station	Fluvanna	EGU	83.86	50.32	33.55	167.73	44.45	18.14	18.14
5	American Electric Power- Clinch River	Russell	EGU	38.21	121.00	0.00	159.21	113.40	113.40	46.27
6	Dominion - Chesapeake Energy Center	Chesapeake	EGU	78.69	47.22	31.48	157.38	122.04	49.79	49.79
7	Potomac River Generating Station	Alexandria	EGU	11.83	106.43	0.00	118.26	72.96	72.96	29.77
8	Dominion - Yorktown Power Station	York	EGU	53.82	32.29	21.53	107.64	58.08	23.70	23.70
9	Dominion-Possum Point Power Station	Prince William	EGU	50.09	30.06	20.04	100.19	56.93	23.23	23.23
12	American Electric Power – Glen Lyn	Giles	EGU	26.06	39.08	0.00	65.14	47.69	47.69	19.46
15	Spruance Genco LLC	Richmond	EGU	27.75	16.65	11.10	55.50	55.50	55.50	22.64
18	James River Cogeneration Company	Hopewell	EGU	12.65	7.59	5.06	25.30	24.54	24.54	10.01
20	Dominion - Clover Power Station	Halifax	EGU	8.34	5.00	3.34	16.68	190.08	77.55	77.55
26	Cogentrix Virginia Leasing Corp	Portsmouth	EGU	5.85	3.51	2.34	11.70	19.19	19.19	7.83
46	Birchwood Power Partners, L.P.	King George	EGU	1.41	2.05	0.13	3.59	38.57	38.57	15.74
51	Dominion - Altavista Power Station	Campbell	EGU	1.09	0.65	0.44	2.18	11.07	4.52	4.52
57	Dominion - Mecklenburg Power Station	Mecklenburg	EGU	0.84	0.25	0.03	1.11	25.74	15.56	10.50

4. Summary of Recent Mercury Studies

This section summarizes information that may be relevant to the current study from recent papers and presentations on data collection and analysis, modeling, and emissions and controls studies of mercury deposition. Note that all of the references given in this section can be found in the bibliography provided in the appendix. They are also available on the Virginia DEQ Mercury Study web page: http://www.deq.virginia.gov/air/vamercury/vamercurystudy.html

4.1. General Mercury Deposition and Data Analysis Studies

Numerous reports and papers discuss the state-of-the science of mercury deposition, with emphasis on the sources of airborne mercury, mercury chemistry, global and regional transport, mercury deposition mechanisms, and mercury effects on aquatic ecosystems. Several studies focus on the analysis of collected mercury deposition data for specific locations. A few recent studies examine the relationships between meteorology and mercury deposition.

General Studies

Nearly all of the papers and reports examined discussed the **sources of mercury** in the atmosphere. It is widely understood that mercury is emitted to the atmosphere from both natural and anthropogenic sources.

Certain soils, rocks, and other geologic structures naturally contain mercury and therefore represent natural or geogenic sources of mercury emissions. Volcanic activity is thought to be an important but variable source of naturally occurring airborne mercury (Niagru and Becker, 2003). Within North America, most natural mercury emissions are associated with land types found in the western part of the continent. In addition to the land masses, the oceans are also a source of natural mercury emissions. Emissions fluxes from the ocean are thought to be greatest near the equator and to decrease toward the poles (Seigneur et al., 2003; Kim and Fitzgerald, 1986).

Anthropogenic sources of mercury include coal-fired power plants and other industrial coal-burning facilities, municipal, medical, industrial and hazardous waste incinerators, chlor-alkali and other chemical manufacturing plants, taconite and other metallurgical processing facilities, pulp and paper manufacturing facilities, mining operations, cement plants, mobile sources, and a wide variety of other industrial and residential sources (EPA, 2005).

It is also widely understood that re-emission of both natural and anthropogenic emissions from both land and water areas is an important part of the global mercury budget. Over land, prescribed burning and wild fires can increase the rate of re-emission.

Driscoll et al. (2007) estimates that approximately one-third of the emissions are direct anthropogenic emissions. Valente et al. (2007) summarizes the results of numerous studies in estimating that global mercury emissions are equally apportioned among natural emissions, direct anthropogenic emissions, and re-emission of previously deposited natural and anthropogenic emissions.

Understanding the **mercury chemistry** is an active area of research. Bullock et al. (2007) summarizes the three forms of airborne mercury (Hg) as follows: elemental mercury (Hg(0)), reactive gaseous mercury (RGM), and particulate mercury (Hg(p)). RGM is known to be comprised almost entirely of divalent mercury (Hg^{2+} or Hg(II)), since mercury compounds at other valence states tend to be chemically unstable in the atmosphere. Hg(p) is also primarily comprised of divalent mercury, but may also include elemental mercury.

Valente et al. (2007) and others offer that elemental mercury is the dominant atmospheric species and comprises about 99 percent of the total mercury in the atmosphere. Hg(0) is characterized by low reactivity and low solubility in water and has a long atmospheric lifetime. RGM represents less than one percent of atmospheric mercury. It is highly reactive and highly soluble and can be actively removed from the atmosphere through both wet and dry deposition processes. Hg(p) also represents less than one percent of atmospheric mercury. It is moderately reactive and highly soluble in water. It is removed from the atmosphere primarily through wet deposition

Seigneur et al. (2003) discuss the chemical transformations that transfer mercury mass from one of these states to another. Several gas phase and aqueous phase reactions and equilibrium processes are expected to be important.

The **global and regional transport** of mercury is the topic of much discussion in the current literature, especially in explaining deposition observed at remote locations and in the context of mercury deposition modeling. With an atmospheric lifetime that may be on the order of months to years, Hg(0) is dispersed and transported globally by atmospheric circulation systems and regionally by large-scale weather systems. Similarly, with atmospheric lifetimes on the order of a week, RGM and Hg(p) may also be subject to regional-scale transport.

With regard to **deposition mechanisms**, a key area of interest is the re-emission of mercury from both land and water surfaces (e.g., Sofiev and Galperin (2000)). Prescribed burning and wild fires may account for some of the re-emissions. Other natural processes, including microbial activity, may also account for some of the re-emission (Syrakov, 1998). Re-emission of mercury is mainly in the form of Hg(0) (Schluter, 2000).

Of primary interest for states and EPA is the **impact of mercury deposition on aquatic ecosystems**. In the U.S., more than 8,500 individual bodies of water have been identified as mercury impaired and the primary source of mercury to these water bodies is believed to be atmospheric deposition. For example, the South Florida Mercury Science Program found that atmospheric deposition of mercury accounts for more than 95 percent of the new mercury entering the Everglades each year (Fink et al., 1998).

Based on the network of mercury deposition measurements for the Northeast, Driscoll et al. (2007) concludes that mercury can be directly deposited onto surface waters or deposited in forest and wetland areas and then transported through the watershed to accumulate in the surface waters.

In certain bodies of water such as those with low dissolved oxygen, high organic matter content, and low acidity, mercury deposition can lead to the formation and build up of the highly bio-accumulative form of mercury (methyl mercury, CH_3Hg^+ or $MeHg^+$). Human exposure to mercury is linked with the consumption of contaminated fish from such water bodies.

Analysis of Mercury Deposition Data for Specific Locations

Numerous analyses of mercury deposition data (e.g., Seigneur et al. (2003) indicate that there are spatial patterns in the data and that these can vary from year to year. While the patterns are clearly related to rainfall amount, some studies (for example, Keeler et al. (2006)) suggest that there are spatial patterns in the wet deposition data that are not fully accounted for by the rainfall patterns. This suggests the potential for impact from local and regional sources.

An analysis of wet mercury deposition for two rural, coastal sites in North Carolina (Haywood et al., 2000 and others) revealed both a spatial pattern as well as a seasonal pattern of wet

mercury deposition when the data are separated into summer (April – September) and winter (October–March) months.

While most monitoring of mercury is of wet deposition, several studies have also examined mercury air concentrations and dry deposition.

Haywood et al. (2000) also found that both mercury concentration and wet deposition rates are consistently higher at Lake Waccamaw than Pettigrew State Park (both located in coastal North Carolina) and surmised that the pattern could be a result of local source influences.

The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (NOAA, 2007) conducted a monitoring study during the summer of 2005 at the Harcum site in coastal Virginia which revealed that dry deposition was significant and was dominated by RGM.

Relationships between Meteorology and Mercury Deposition

It is recognized that in addition to the location of sources and the chemical species of mercury emitted, climate and meteorology are key factors in mercury deposition. The relationship between precipitation and deposition is well established. Scavenging by wet deposition is an important mechanism for wet deposition. Few studies, however, address the potentially more complex relationships between meteorology and mercury deposition. EPA (1997) reported that, in general, humid locations have higher deposition rates than arid locations. Keeler et al. (2006) found the annual amount of precipitation to be related to annual mercury deposition. They also found that individual precipitation events can contribute significantly to the annual mercury deposition totals.

4.2. Mercury Air Modeling Studies

Current literature focuses on the development of mercury capabilities in air quality modeling and some national- and regional-scale applications.

Bullock and Brehme (2006) present a description of the methodology for modeling mercury using CMAQ Version 4.5.1. This paper provides a description of the mercury treatment in the CMAQ model that will be used in this study (although the version that will be used for this study is 4.6, the mercury treatment is effectively unchanged). Note that the Particle and Precursor Tagging Methodology (PPTM) has been added to version 4.6.

Several areas of potential uncertainty that may be useful in designing and conducting sensitivity analysis with CMAQ are pointed out in this paper. These include:

- Rates of chemical reactions.
- Deposition of elemental mercury.
- Natural emission and re-emission of mercury.

The presentation of Vijayaraghavan et al. (2005) provides a potential reference/comparison for model performance for the VDEQ study. The authors add the following to the list of potential sources of uncertainty for CMAQ:

- Global emissions.
- Input meteorology, specifically rainfall.
- Dispersion of plumes.

- Chemistry in plumes.

The authors also suggest that the lifetime of mercury in the atmosphere as 1.2 years.

Lin et al. (2004) suggest that the lifetime of mercury in the atmosphere is 0.5 to 2 years and also present some potential implementation issues regarding simulation of mercury with CMAQ. These include:

- Specific uncertainties in gas phase chemistry and in deposition
- Potential for much more rapid oxidation of Hg(0) by halogens in coastal areas

Areas of potential improvement in CMAQ are presented by Lin et al. (2005). Of interest here is the sensitivity to possible improvements in CMAQ algorithms. Some of these improvements have been addressed in Version 4.6 of CMAQ. These include natural emissions and dry deposition of elemental mercury. Additional improvements noted by Lin et al. may be considered during the selection of sensitivity simulations.

Pongprueksa and Lin (2006) conducted sensitivity simulations for mercury using CMAQ. They specifically explored the sensitivity of the simulation results to additional Hg(II) reduction reactions.

Several related papers present information on natural emissions and sensitivity to the CMAQ system to changes in emissions (Wen, 2006; Gbor et al., 2006; Gbor et al., 2004). Topics addressed in these papers include:

- A methodology for estimating natural emissions.
- Deposition vs. evasion of Hg.
- Sensitivity of simulation results to changes in emissions of Hg, NOx, VOC, etc.

To the extent possible, we may qualitatively compare the results of these sensitivity tests to the VDEQ modeling results.

A comparison of model-based and observation-based estimates of dry deposition is made in Marsik et al. (2007). The authors compare the direct measurement of dry deposition to estimates from a resistance model, such as that employed by CMAQ. This gives us some insight into the quality of the CMAQ dry deposition estimates.

A presentation by Braverman (2005) provides some information on EPA's regulatory modeling related to mercury. This presentation gives some background on the Clean Air Mercury Rule (CAMR) modeling and a summary of CMAQ model performance in CAMR. Again, this provides a potential source of comparison for model performance for the VDEQ study.

Discussions of plume models vs. grid model treatments for mercury are discussed in Karamchandani et al. (2006) and Seigneur et al. (2006). The authors present some expected benefits of a plume-in-grid treatment for point sources, with an emphasis on power plant plumes. Comparisons of Hg deposition estimates from grid models and a Gaussian model are provided. Of interest for the VDEQ modeling study is a description of a methodology for estimating deposition using a Gaussian model.

Regional modeling with the SARMAP Air Quality Model (SAQM) studies mercury concentrations in Connecticut (Xu et al., 2000a; Xu et al., 2000b). This study is limited to a small section of the

northeastern U.S. around Connecticut and uses the SAQM model with simple and probably outdated Hg chemistry. The authors include estimates of natural emissions and re-emissions, which may be of some interest for the VDEQ study.

A project update by Walcek (2005) provides information on a modeling study in New York State. It is possible that the estimates of in-state vs. out-of-state contributions to deposition in New York from this study could provide a check on the estimates obtained from the VDEQ study.

A brief project update by Seigneur (2005) summarizes estimates of global and regional contributions to mercury deposition in New York State. This work includes a modeling sensitivity analysis and estimates of deposition contributions to New York State for various emissions sectors. A key finding is that the greatest contributor is U.S. emissions sources (non-New York emissions).

Several reports present the results of national- and regional-scale mercury deposition modeling conducted for the EPA Office of Water (OW), as well as background on and results from the Particle and Precursor Tagging Methodology (PPTM). Modeling of mercury deposition in Wisconsin is reported by Myers et al. (2006a). This report was intended as a peer-reviewed prototype for mercury tagging using the REMSAD model and includes:

- PPTM results for Wisconsin sources with deposition estimates for mercury.
- An estimate of potential year-to-year variability in Hg deposition for several sites in Wisconsin.

Similar modeling in support of the Maryland TMDL is reported by Myers et al. (2004a). This study included:

- Hg tagging simulations using REMSAD for Maryland and surroundings to estimate deposition of Hg.
- An estimate of potential year-to-year variability in Hg deposition for several sites in Maryland.

Additional modeling in support of a Louisiana TMDL is reported by Myers et al. (2004b). This study included:

- Hg tagging simulations for Louisiana and surroundings using REMSAD.
- Estimates of mercury deposition loading from tagged Louisiana sources for Louisiana estuaries.

Simulation results for the entire U.S. are reported by Myers et al. (2006b). In this study, PPTM was applied for approximately 300 sources located throughout the U.S. The study results include estimates of mercury deposition contributions for some Virginia sources. These results may provide a check on similar estimates obtained from the VDEQ study.

Attribution of global emissions to mercury deposition is treated by Seigneur et al. (2004). This paper provides

- Global simulation results using the Chemical Transport Model (CTM).
- Estimates of contributions of various regions of the world to deposition in U.S.

The potential influence of Asian mercury emissions on the U.S. is examined by Lin et al. (2006). Direct deposition of Asian emissions to Virginia should be small, but their contribution to global background may be important.

As an alternative to grid-based modeling, use of the HYSPLIT model is discussed in Cohen et al. (2004) and in Cohen (2004). The authors estimate contributors to mercury deposition to Great Lakes and the Chesapeake Bay using HYSPLIT model. The results tend to differ from other modeling estimates in that very distant sources may contribute to deposition loading. The use of trajectory modeling over long periods of time adds considerable uncertainty to the HYSLPIT modeling approach.

A combination of statistical and modeling techniques is used by Michaels et al. to examine the possible link between local power plant emissions and impaired bodies of water in Virginia. This study relied on HYSPLIT trajectory modeling of Virginia power plants. The authors were not able to establish a statistical link between elevated Hg in fish tissue with power plant emissions.

4.3. Mercury Emissions and Control Studies

As noted above, mercury in the atmosphere originates from a wide variety of anthropogenic, biogenic, and geogenic sources. As mercury deposition and contamination issues have become more important in many areas of the country in the last decade, efforts have been made to prepare more accurate estimates of emissions from mercury sources. Like the criteria pollutant inventories maintained by each state, the mercury emissions inventories are used by EPA and states to assess long term trends in emissions and for rule compliance. In addition, these inventories are used in air quality modeling studies to assess deposition for a base year and as a means of evaluating changes in mercury deposition in a future year. As part of its ongoing development work with the CMAQ modeling system, EPA has developed a methodology to estimate mercury emissions from biogenic sources (Lin, et al., 2004). This methodology will be evaluated for potential use in the Virginia mercury modeling analysis. Other researchers have investigated mercury emissions from soils as a contributor to atmospheric loading. Schluter (2000) found that mercury evaporation rates from non-contaminated soils are small, but do contribute to overall emissions of both elemental and methyl mercury.

Controlling anthropogenic sources of mercury has been the focus of a number of studies conducted in recent years by EPA, the Department of Energy (DOE), and a number of state agencies, with research in control technology ranging from those placed on large industrial combustion sources (e.g., EGU's) to ensuring the proper recycling and disposal of fluorescent light bulbs. The DOE conducted a study evaluating the control efficiencies and effects of selective catalytic reduction (SCR) and fluidized gas desulfurization (FGD) on mercury speciation and removal (Withum, et al, 2006). The study found that the combination of the SCR with FGD removed a substantial amount of mercury from the flue gas. A similar study by Lee, et al. (2004) investigated the effects of SCR on mercury speciation using three different types of coal, and concluded that the effects of SCR in promoting elemental mercury oxidation and removal is highly dependent on the sulfur and chlorine content of the coal.

A number of state agencies have evaluated a list of potential mercury control technologies, including North Carolina (2005), Minnesota (2005), and NESCAUM (2004). The North Carolina and NESCAUM studies primarily focus on controls for EGU's and include various updates of control technology information, cost/benefit information, and recommendations for reducing emissions from such sources. The Minnesota report provides the 2005 annual summary for the Minnesota Legislature of efforts underway to meet the state standards. The report indicates that much of the reduction in mercury air emissions in Minnesota since 1990 has been the result of significant changes in "product use and disposal" category, which includes such items as the elimination of mercury as a preservative in paint products, the use of mercury in electric

switches, and the use of mercury in batteries. These studies provide good references for activities and controls other states have evaluated and undertaken to reduce mercury air emissions from a variety of source sectors.

4.4. Summary of Findings and Implications for Mercury Modeling Analysis

The tools and methods that will be applied for the Virginia mercury deposition modeling represent the current state-of-the-science in regulatory mercury deposition modeling. Similar approaches were used by EPA in the Clean Air Mercury Rule (CAMR) modeling. Ongoing research in the areas of mercury data collection and analysis, deposition modeling, and control technology assessment offers some possibilities for enhancing the VDEQ modeling effort, especially with regard to designing and conducting modeling sensitivity analyses, evaluating model performance, and assessing the effectiveness of local controls. Specific implications and action items for the VDEQ modeling study include:

- Qualitatively compare the modeled results for mercury concentration, wet deposition, and dry deposition with the findings from monitoring studies in North Carolina and Virginia (Harcum) regarding the observed spatial and temporal distributions and relationships among these parameters and with other modeling studies.
- As time and budget allow, conduct model-based sensitivity tests to examine the following key issues:
  - Sensitivity of the modeling results to meteorological inputs, and specifically precipitation amounts.
  - Uncertainties in the mercury chemistry and deposition algorithms.
  - Role of natural emissions.
- Ensure that future-year emissions controls are consistent with recent studies regarding effects on speciation of emissions and the overall effectiveness of control measures.
- To the extent possible, obtain and utilize future-year national emission inventories that reflect planned mercury control technologies/measures prepared by other states.

5. References

EPA. 2005a. *Emissions Inventory and Emissions Processing for the Clean Air Mercury Rule (CAMR)*. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, March 2005. (http://www.epa.gov/ttn/atw/utility/emiss_inv_oar-2002-0056-6129.pdf).

EPA. 2005b. *Technical Support Document for the Final Clean Air Mercury Rule: Air Quality Modeling*. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, March 2005. (http://www.epa.gov/ttn/atw/utility/aqm_oar-2002-0056-6130.pdf).

EPA. 2007. EPA Toxics Release Inventory (TRI) data available at: http://www.epa.gov/tri/tridata.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6. Appendix— Bibliography of Mercury-Related Literature

6.1. General Reports and State Studies

Conference of the New England Governors and Eastern Canadian Premiers*. Report to New England and Eastern Canadian Premiers on the Mercury Project***.** August 2002.

Driscoll, C.T.; D.F. Evers; K.F. Lambert; N. Kamman; T. Holsen; Y.J. Han; C. Chen; W. Goodale; T. Butler; T. Clair; and R. Munson. "Mercury Matters: Linking Mercury Science with Public Policy in the Northeastern United States." Hubbard Brook Research Foundation, *Science Links Publication*, Vol. 1, No.3: 2007.

Environmental Council of the States and National Wildlife Federation. *2005 Compendium of States' Mercury Activities*. Quicksilver Caucus: October 2005.

Environmental Council of the States. *Elements for Developing a National Mercury Reduction Strategy to Achieve Water Quality Standards*. Quicksilver Caucus: August 2003.

Ericksen, J.A.; M.S. Gustin; D.E. Schorran; D.W. Johnson; S.E. Lindberg; and J.S. Coleman. "Accumulation of Atmospheric Mercury in Forest Foliage." *Atmospheric Environment,* 37 (2003): 1613–1622.

Fink, Larry; Darren Rumbold; and Peter Rawlik. "Chapter 7: The Everglades Mercury Profile." *The Everglades Interim Report:* http://www.sfwmd.gov/org/ema/everglades/interimrpt_98/cpt7.pdf.

Huber, Kimberly. *Wisconsin Mercury Sourcebook*. Wisconsin Department of Natural Resources, Madison, Wisconsin: May 1997.

Great Lakes Binational Toxics Strategy. *2006 Progress Report*. February 2007.

International Air Quality Advisory Board of the International Joint Commission and Commission for Environmental Cooperation. *Addressing Atmospheric Mercury: Science and Policy*. Research Triangle Park, North Carolina: December 2001.

Iowa Department of Natural Resources, Air Quality Bureau. *Review of Assessment Methods for Estimating Atmospheric Deposition of Mercury Compounds in Iowa*. April 24, 2006.

Middleton, Paulette. *Project Update: A Closer Look at Mercury in the West*; Land and Water Fund of the Rockies and Environmental Defense: July 2002.

Munson, Ronald; and Charles Driscoll. *Project Update: Mercury in Adirondack Wetlands, Lakes, and Terrestrial Systems*. New York State Energy Research and Development Authority, Environmental Monitoring, Evaluation, and Protection Program: August 2005.

New Jersey Mercury Task Force. *New Jersey Mercury Task Report, Volume 1: Executive Summary and Recommendations*: December 2001.

Office of Research and Development, National Risk Management Research Laboratory. *Mercury Research Strategy;* EPA/600/R-00/073. U.S. Environmental Protection Agency; Cincinnati, Ohio: September 2000.

Reindl, John. *Status of Local, State and Federal Mercury Product Legislation and Laws 2005-2006 Legislative Sessions February 20–March 1, 2006.* Dane County, Wisconsin.

Saball, Doug; Jeff Emery; Ellen Parr-Doering; Andy Johnson; and David Wright. *Mercury Deposition in Maine: Status Report 2003*. Main Department of Environmental Protection, Bureau of Air Quality; July 15, 2003.

Seigneur, C., P. Karamchandani, K. Vijayaraghavan, K. Lohman, and G. Yelluru. 2003. "Scoping Study for Mercury Deposition in the Upper Midwest." Prepared for the Midwest Regional Planning Organization. AER, San Ramon, California (CP149-03-01a).

Schauer, Jamie; Tracey Holloway; Martin Shafer; Rob Griffin. *Sensitivity of Heterogeneous Atmospheric Mercury Processes to Climate Change*. EPA-G2006-STAR-J-1; February 15, 2007.

Southern Environmental Law Center. Press Release: "Recently Published Study Refutes Bush Administration Claims on Mercury," *Southern Environmental Law Center* (October 3, 2006): http://www.southernenvironment.org.

State and Territorial Air Pollution Program Administrators (STAPPA) Association of Local Air Pollution Control Officials (ALAPCO). *Regulating Mercury from Power Plants: A Model Rule for States and Localities*. Washington, DC (November 2005): http://www.4cleanair.org.

U. S. EPA. "Mercury Study Report to Congress: Volume I: Executive Summary." *EPA OAQPS/ORD,* EPA-452/R-97-005 (1997): (http://www.epa.gov/ttn/atw/112nmerc/volume1.pdf

6.2. Mercury Deposition and Air Studies

Blanchard, P.; F.A. Froude; J.B. Martin; H. Dryfhout; and J.T. Woods. "Four Years of Continuous Total Gaseous Measurements at Sites in Ontario, Canada." *Atmospheric Environment*. 36 (2002) 3735-3743.

Butler, T.; G. Likens; M. Cohen; and F. Vermeylen. *Mercury in the Environment and Patterns of Mercury Deposition from the NADP/MDN Mercury Deposition Network.* Final Report. Institute of Ecosystem Studies. January 2007.

Crist, Kevin. *Evaluation of the Emission, Transport, and Deposition of Mercury, Fine Particulate Matter, and Arsenic from Coal-Based Power Plants in the Ohio River Valley Region: Semi-Annual Technical Progress Report for the Period April 3, 2003–October 2, 2003*. Department of Energy, DOE Award Number DE-FC26-03NT41723; Washington, DC. (2003).

Driscoll, Charles T.; David Evers; Thomas Butler; Celia Y. Chen; Thomas A. Clair; M. Wing Goodale; Young-Ji Han; Thomas Holsen; Neil C. Kamman; Kathy Lambert; and Ron Munson. "Scientific Studies Reveal Causes of Biological Mercury Hotspots" [29 slides]. *Science Links. PLACE* (January 9, 2007): www.hubbardbrookfoundation.org.

Keeler, Gerald J., Matthew S. Landis, Gary A. Norris, Emily M. Christianson, and J. Timothy Dvonch. "Sources of Mercury Wet Deposition in Eastern Ohio, USA." *Environ*mental *Science and Technology.* 40 (2006): 5874-5881.

Florida Department of Environmental Protection. "Integrating Atmospheric Mercury Deposition with Aquatic Cycles in South Florida: An Approach for Conducting a Total Maximum Daily Load

Analysis for an Atmospherically Derived Pollutant." *Florida Department of Environmental Protection,* October 2002 (revised November 2003); 115 pages: http://www.dep.fl.us/secretary/news/2003/nov/pdf/mercury_report.pdf

Grigal, D.F. "Inputs and Outputs of Mercury from Terrestrial Watersheds: A Review." *Environmental Rev*iew 10 (2002): 1-39.

Knuffman, Nathan; and Randall Lutter. *Does Mercury in Fish Come from the Air?* Working Paper 00-6. AEI-Brookings Joint Center for Regulatory Studies; Washington, DC: September 2000.

Kroenke, Amy E.; Edward L. Shuster; Richard F. Bopp; and Mary Downes Gastrich. *Assessment of Historical and Current Trends in Mercury Deposition to New Jersey Aquatic Systems though Analysis of Sediment/Soil Cores.* New Jersey Department of Environmental Protection, Division of Science, Research and Technology; Trenton, New Jersey: February 2003.

Lee, Xuhui; Gadoury Benoit; and Xinzhang Hu. "Total Gaseous Mercury Concentration and Flux over a Coastal Saltmarsh in Connecticut, USA." *Atmospheric Environment.* 34 (2000): 4205-4213.

Miller, Eric. K.; Alan VanArsdale; Gerald Keeler; Ann Chalmers; Laurier Poissant; Neil C. Kamman; and Raynald Brulotte. "Estimation and Mapping of Wet and Dry Mercury Deposition across Northeastern North America." *Ecotoxicology.*14 (2005): 53-70.

Nelson, Sid Jr. "New Research on Mercury Transport & Deposition." *2006 Electric Utility Environmental Conference*: 2006.

Nelson, Sid Jr. "Mercury Hot Spots." *2007 Electric Utility Environmental Conference*: 2007.

Raynal, Dudley; Myron Mitchell; and Charles Driscoll. *Project Update: Effects of Atmospheric Deposition of Sulfur, Nitrogen, and Mercury on Adirondack Ecosystems.* New York State Energy Research and Development Authority, Environmental Monitoring, Evaluation, and Protection Program; August 2005.

Rea, Anne W.; Steven E. Lindberg; and Gerald J. Keeler. "Dry Deposition and Foliar Leaching of Mercury and Selected Trace Elements in Deciduous Forest Throughfall." *Atmospheric. Environ*ment. 0 (2001): 1-10.

Richardson, Catherine, et al. "Estimating Estuarine Pollutant Loading from Atmospheric Deposition using Casco Bay, Maine as a Case Study." May 2003.

Saball, Doug; Jeff Emery; Ellen Parr-Doering; Andy Johnson; and David Wright. *Mercury Deposition in Maine: Status Report 2003*. Main Department of Environmental Protection, Bureau of Air Quality; July 15, 2003.

U. S. EPA. "Deposition of Air Pollutants to the Great Waters*. Third Report to Congress". EPA OAQPS, EPA-453/R-00-005: 2*000.

U. S. EPA, Great Lakes National Program Office. *Results of the Lake Michigan Mass Balance Study: Mercury Data Report*, EPA 905 R-01-012: 2004.

U.S. EPA. "Mercury Deposition in the U.S." [chart]. 2005.

U. S. EPA. "Mercury Study Report to Congress: Volume III: Fate and Transport of Mercury in the Environment." *EPA OAQPS/ORD, EPA-452/R-97-005* (1997): (http://www.epa.gov/ttn/atw/112nmerc/volume3.pdf.

U. S. EPA Office of Wetlands, Oceans, and Watersheds. "Frequently Asked Questions about Atmospheric Deposition. A Handbook for Watershed Managers." *EPA- 453/R-01-009.* 2001.

VanArsdale, Alan; Jeri Weiss; Gerald Keeler; Eric Miller; Gille Boulet; Raynald Brulotte; and Laurier Poissant. "Patterns of Mercury Deposition and Concentration in Northeastern North America (1996-2002)." *Ecotoxicology*, 14 (2005):37-52.

Valente, R. J., C. Shea, K. L. Humes, and R. L. Tanner. 2007. Atmospheric mercury in the Great Smoky Mountains compared to regional and global levels, Atmos. Environ., 41, pp. 1861-1873.

Van Loon, Lisa L.; Elizabeth A. Mader; and Susannah L. Scott. "Sulfite Stabilization and Reduction of the Aqueous Mercuric Ion: Kinetic Determination of Sequential Constants." *The Journal of Physical Chemistry A,* 105 (2001): 3190-3195.

Wells, Deena. "Florida Everglades Study Reveals Decline in Mercury Levels" (Press Release). November 6, 2003.

Yatavelli, Reddy L.N.; Jason K Fahrni, Myoungwoo Kim, Kevin C. Crist, Christopher D. Vickers, Stephen E. Winter, and Daniel P. Connell. "Mercury, PM2.5 and gaseous co-pollutants in the Ohio River Valley region: Preliminary results from the Athens supersite". *Atmospheric Environment.* 40 (2006): 6650-6665.

6.3. Mercury Air Modeling

Ambrose, Robert B.; Ioannis X. Tsiros; and Tim A. Wool. "Modeling Mercury Fluxes and Concentrations in a Georgia Watershed Receiving Atmospheric Deposition Load from Direct and Indirect Sources." *The Journal of Air & Waste Management Association.* 55: (May 2005) 547-558.

Bash, Jesse; Thomas Meyer; Patricia Bresnahan; and David R. Miller. *A Proposed Coupling of Natural Mercury Emissions and Deposition in CMAQ.* Presentation at the 4th Annual CMAS Models-3 User's Conference; Chapel Hill, North Carolina: September 26-28, 2005.

Braverman, Thomas. *CAMR Mercury Deposition Modeling.* Presentation at the Fourth Annual CMAS Models-3 User's Conference; Research Triangle Park, North Carolina: September 28, 2005.

Bresnahan, Patricia A.; David R. Miller,; and Jesse O. Bash. *Estimating Nitrogen Deposition into the Connecticut River Basin Using CMAQ.* Presentation at the Fourth Annual CMAS Models-3 User's Conference; Chapel Hill, North Carolina: September 26–28, 2005.

Bullock, Russ. *Atmospheric Mercury Simulation with CMAQ Version 4.5.1.* Presentation at the Fifth Annual CMAS Conference; Chapel Hill, North Carolina: October 16–18, 2006.

Bullock, Russ. *CMAQ Mercury Modeling*. LADCO Mercury Workshop; Chicago, Illinois; February 22, 2006.

Bullock, O.R., D. Atkinson, T. Braverman, K. Civerolo, A. Dastoor, D. Davignon, C. Hogrefe, J. Ku, K. Loman, T. Myers, C. Seigneur, N. Selin, G. Sistla and K. Vijayaraghavan. 2007. The

North American mercury model intercomparison study (NAMMIS): Study description and results. (*In progress*)

Cohen, Mark. "Modeling the Fate and Transport of Atmospheric Mercury in the Chesapeake Bay Region." *Presentation at the NOAA Chesapeake Bay Office,* Annapolis, Maryland; May 17, 2004.

Cohen, Mark. "Modeling the Atmospheric Transport and Deposition of Mercury." *Discussion with the Maryland Department of Environment,* Baltimore, Maryland; August 25, 2005.

Cohen, Mark; Richard Artz; Roland Draxler; Paul Miller; Laurier Poissant; David Niemi; Dominique Ratte; Marc Deslauriers; Roch Duval; Rachelle Laurin; Jennifer Slotnick; Todd Nettesheim; and John McDonald. "Modeling the Atmospheric Transport and Deposition of Mercury to the Great Lakes." *Environmental Research* 95 (2004):247-265.

EPA. 2005a. Emissions Inventory and Emissions Processing for the Clean Air Mercury Rule (CAMR). EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, March 2005. (http://www.epa.gov/ttn/atw/utility/emiss_inv_oar-2002-0056-6129.pdf).

EPA. 2005b. Technical Support Document for the Final Clean Air Mercury Rule: Air Quality Modeling, EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, March 2005. (http://www.epa.gov/ttn/atw/utility/aqm_oar-2002-0056-6130.pdf).

Gbor, Philip K.; Deyong Wen; Fan Meng; Fuquan Yang; Baoning Zhang; and James J. Sloan. "Improved Model for Mercury Emission, Transport, and Deposition." *Atmospheric Environment*. 40 (February 2006): 973-983.

Gbor, Philip K.; Deyong Wen; Fan Meng; Fuquan Yang; and James J. Sloan. *Modeling of Mercury Emission, Transport, and Deposition in Northeastern North America*. Natural Sciences and Engineering Research Council of Canada; Ontario Power Generation; and Ontario Research and Development Challenge Fund. *Presentation at the Third Annual CMAS Models-3 User's Conference*, Chapel Hill, North Carolina: September 26–28, 2004.

Karamchandani, Prakash; Krish Vijayaraghavan; Shu-Yun Chen; and Christian Seigneur. *Plume-in-Grid Modeling for PM and Mercury.* Presentation at the Fifth Annual CMAS Conference; Chapel Hill, North Carolina: October 16–18, 2006.

Lin, Che-Jen; Pruek Pongprueksa; Thomas C. Ho; Hsing-Wei Chu; and Carey Jang. *Development of Mercury Modeling Schemes within CMAQ Framework: Science and Model Implementation Issues.* Texas Commission on Environmental Quality (Contract No. 582-4-64582 and Gulf Coast Hazardous Substance Research Center under Contract No. 043LUB0855); Presentation at the Third Annual CMAS Models-3 User's Conference, Chapel Hill, North Carolina: September 26–28, 2004.

Lin, Che-Jen; Pruek Pongprueksa; Taruna Vanjani; Thomas C. Ho; Hsing-Wei Chu; and Carey Jang. *New Science Implementation in CMAQ-Hg: Test over a Continental United States Domain.* Presentation at the Fourth Annual CMAS Models-3 User's Conference, Research Triangle Park, North Carolina: September 26, 2005.

Lin, Che-Jen; Pruek Pongprueksa; Taruna Vanjani; Thomas C. Ho; Hsing-Wei Chu; Carey Jang; Tom Braverman; David G. Streets; and Joshua S. Fu. *Trans-Pacific Transport of Mercury: Sensitivity Analysis on Asian Emission Contribution to Mercury Deposition in North America Using*

CMAQ-Hg. US Environmental Protection Agency (USEPA, RTI subcontract No. 3-93U-9606) and Texas Commission on Environmental Quality (TCEQ work order No. 64582-06-15). Presentation at the Fifth Annual CMAS Conference, Chapel Hill, North Carolina: October 16-18, 2006.

Pai, P., P. Karamchandani, and C. Seigneur. 1999. "Sensitivity of Simulated Atmospheric Mercury Concentrations and Deposition to Model Input Parameters." *J. Geophys. Res*., 104:13855-13868.

Marsik, Frank J.; Gerald J. Keeler; and Matthew S. Landis. "The Dry-Deposition of Speciated Mercury to the Florida Everglades: Measurements and Modeling." *Atmospheric Environment*. 41(January 2007): 136-149.

Michaels, Patrick J.; Philip J. Stenger; Stephen D. Gawtry; and Michael Figura (Virginia State Climatology Office). "Estimating the Transport and Distribution of Mercury in Virginia from Virginia Coal-fired Point Sources." Virginia State Climatology Office Department of Environmental Sciences, Charlottesville, Virginia.

Myers, Thomas C.; YiHua Wei; A. Belle Hudischewskyj; Jay L. Haney; and Sharon G. Douglas. *EPA Region 3 Mercury Air Deposition TMDL Development for Maryland* Draft Report, 04-068, EPA Region 3; ICF Consulting; October 2004.

Myers, Thomas C.; YiHua Wei; A. Belle Hudischewskyj; Jay L. Haney; and Sharon G. Douglas. *Model-Based Analyses and Tracking of Airborne Mercury Emissions to Assist in Watershed Planning, Final Report*, 06-077; U.S. EPA Office of Water; ICF International; November 30, 2006.

Myers, Thomas C. et al. *Application of the REMSAD Modeling System to Estimate the Deposition of Mercury in Support of the Wisconsin TMDL Pilot Revised, Final Report*, 06-017, EPA OW; Systems Application International/ICF Consulting; March 2006.

Myers, Thomas C.; and YiHua Wei*. REMSAD Air Deposition Modeling in Support of TMDL Development for Southern Louisiana, Final Report*, 04-038, EPA Region 6; ICF Consulting; August 5, 2004.

Pongprueksa, Pruek; and Che-Jen Lin. *Sensitivity Evaluation of Gas-Phase Reduction Mechanisms of Divalent Mercury Using CMAQ-HG in a Contiguous US Domain.* Presentation at the Fifth Annual CMAS Conference; Chapel Hill, North Carolina: October 16–18, 2006.

Ryaboshapko, Alexey; Russell Bullock; Ralf Ebinghaus; Ilia Ilyin; Kristen Lohman; John Munthe; Gerald Petersen; Christian Seigneur; and Ingvar Wangberg. "Comparison of Mercury Chemistry Models." *Atmospheric Environment.* 36 (2002): 3881-3898.

Seigneur, Christian; Kristen Lohman; Krish Vijayarghavan; John Jansen; Leonard Levin. "Modeling Atmospheric Deposition in the Vicinity of Power Plants," *Journal of the Air and Waste Management Association*, 56 (2006): 743-751.

Seigneur, Christian; Krish Vijayarghavan; Kristen Lohman; Prakash Karamchandani; Courtney Scott. "Global Source Attribution for Mercury Deposition in the United States," *Environmental Science and Technology*, 38 (2004): 555-569.

Seigneur, Christian. *Project Update: Contributions of Global and Regional Sources to Mercury Deposition in New York State.* New York State Energy Research and Development Authority, Environmental Monitoring, Evaluation, and Protection Program; August 2005.

Tetra Tech, Inc. and SAI, Inc. /ICF Consulting. *Developing a Quantitative Assessment of Mercury Inputs and Cycling in Devil's Lake, Wisconsin: A Pilot Study for Conducting a Total Maximum Daily Load Analysis for an Atmospherically Derived Pollutant.* Tetra Tech, Inc., Gainesville, FL and Systems Applications International, Inc. /ICF Consulting, San Rafael, California: 2006.

Tsiros, I.X. "A Screening Model-Based Study of Transport Fluxes and Fate of Airborne Mercury Deposited onto Catchment Areas." *Chemosphere* 44 (July 2001): 99-107.

Vijayaraghavan, Krish; Prakash Karamchandani; Shu-Yun Chen; and Christian Seigneur. *Development and Application of CMAQ-MADRID-Mercury*. Presentation at the 4th Annual CMAS Models-3 User's Conference, Chapel Hill, North Carolina: 2005.

Walchek, Chris. *Project Update: Atmospheric Transport and Fate of Mercury in New York State.* New York State Energy Research and Development Authority, Environmental Monitoring, Evaluation, and Protection Program; August 2005.

Wen, Deyong. *Modelling of Atmospheric Mercury Emission, Transport, Transformation and Deposition in North America.* University of Waterloo; Waterloo, Ontario, Canada: 2006.

Xu, Xiaohong; Xiusheng Yang; David R. Miller; Joseph J. Helble; and Robert J. Carley. "A Regional Scale Modeling Study of Atmospheric Transport and Transformation of Mercury. I. Model Development and Evaluation." *Atmospheric Environment*. 34 (2000):4933-4944.

Xu, Xiaohong; Xiusheng Yang; David R. Miller; Joseph J. Helble; and Robert J. Carley. "A Regional Scale Modeling Study of Atmospheric Transport and Transformation of Mercury. II. Simulation Results for the northeast United States." *Atmospheric Environment*. 34 (2000):4945-4955.

6.4. Emissions and Controls

Amar, Praveen. *Mercury and Coal-Fired Power Plants: Science, Technology, and Emerging States and Federal (?) Regulations.* MIT Endicott House Symposium on Air Toxics; August 3–5, 2004.

Lee, C.W.; R.K. Srivastava; S.B Ghorishi; J. Karwowski; T. Hastings; and J. Hirschi. *Effect of SCR Catalyst on Mercury Speciation.* U.S. EPA Office of Research and Development, National Risk Management Research Laboratory, Research Triangle Park, North Carolina: 2004.

Lin, Che-Jen; Steve E. Lindberg; Heng Yang; Thomas C. Ho; Hsing-wei Chu; and Carey Young. *Preparation of Vegetation Mercury Emission Using BEIS3-Prototype Development and Preliminary Processing*. Texas Commission on Environmental Quality (Contract No. 582-4-64582) and Gulf Coast Hazardous Substance Research Center (Contract No. 043LUB0855). Presentation to the Third Annual CMAS Conference; Chapel Hill, North Carolina: October 18–20, 2004.

Minnesota Pollution Control Agency. *2005 Mercury Reduction Project Report to the Minnesota Legislature*. Public. No. lrp-p2s-lsy06; October 2005.

North Carolina Dept. of Environment and Natural Resources Division of Air Quality. *Mercury Emissions and Mercury Controls for Coal-Fired Electrical Utility Boilers. Final Report;* September 1, 2005

Ross and Associates, Environmental Consulting, Ltd. *Mercury Reduction Options: Great Lakes Binational Toxics Strategy*, Draft report for U.S. EPA Great Lakes National Program Office: 2000.

Schluter, K. "Review: evaporation of mercury from soils. An Integration and Synthesis of Current Knowledge." *Environmental Geology,* 39: (January 2000) 249-271.

U. S. EPA. "Mercury Study Report to Congress: Volume II: An Inventory of Anthropogenic Mercury Emissions in the United States." *EPA OAQPS/ORD, EPA-452/R-97-005* (1997): http://www.epa.gov/ttn/atw/112nmerc/volume2.pdf).

Virginia Department of Environmental Quality. *Virginia Department of Environmental Quality Supporting Information—Regulatory Ad Hoc Advisory Group Concerning Clean Air Mercury Rule. Mercury Advisories (VADPH) and Mercury Emission Sources (VADEQ TRI over 10lbs/yr)* [Map]. Commonwealth of Virginia Department of Environmental Quality—Air Division; Virginia, September 7, 2005.

Withum, J. A., *Evaluation of Mercury Emissions from Coal-Fired Facilities with SCR and FGD Systems.* U.S. DOE NETL Cooperative Agreement DE-FC26-02NT41589, CONSOL Energy Inc., South Park, PA: April 2006.

6.5. Mercury Related Websites

EPA, *EPA Regulatory Impact Analysis of the Clean Air Mercury Rule, Final Report,* March 2005: http://www.epa.gov/ttn/atw/utility/ria_final.pdf.

EPA, *EPA Mercury* home web page: http://www.epa.gov/mercury.

Florida, *Information on the South Florida Science Program*: http://www.dep.state.fl.us/labs/mercury/index.htm.

University of South Florida, *Bay Regional Atmospheric Chemistry Experiment* home web page: http://www.hsc.usf.edu/publichealth/EOH/BRACE.

Massachusetts, *Massachusetts Mercury* home page: http://www.mass.gov/dep/toxics/stypes/hgres.htm#hgtrend.

Massachusetts, *Massachusetts Zero Mercury Strategy:* http://www.mass.gov/envir/Sustainable/resources/pdf/Resources_Hg_Strategy.pdf.

NADP. 2007. Web site for National Acid Deposition Program, Mercury Deposition Network (MDN) data and information: www.nadp.sws.uiuc.edu/mdn.

NOAA. 2007. Web page on atmospheric deposition: http://noaa.chesapeakebay.net.

Wisconsin, *Wisconsin Mercury Sourcebook* to implement new mercury strategy: http://www.p2pays.org/ref/04/03851.htm.

Washington, *Washington's Mercury Chemical Action Plan*:
http://www.ecy.wa.gov/programs/eap/pbt/mercuryplan.html

North Carolina, *North Carolina's Mercury Information Page*:
http://www.p2pays.org/mercury/general.asp#ncgen

National Energy Technology Laboratory

This list server is produced by the National Energy Technology Laboratory (NETL) to provide monthly updates on recent events, publications, presentations, and technical reports related to mercury. For further information, please visit the Environmental & Water Resource (E&WR) website at http://www.netl.doe.gov/technologies/coalpower/ewr/index.html.

The following are new mercury project reports that have been recently added to the E&WR website. Each link will take you directly to the report.

- A report, "The Economics of Powder River Basin Coalbed Methane Development," prepared by Advanced Resources International, Inc., January 2006, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/netl%20Cost%20of%20Produced%20Water%20Treatment%200106.pdf.

- A quarterly progress report, "Field Testing of Activated Carbon Injection Options for Mercury Control at TXU's Big Brown Station," prepared by University of North Dakota Energy & Environmental Research Center for the period of October 1–December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/JP-ACI%20at%20BB-42305-Dec05.pdf.

- A quarterly progress report, "Evaluation of MerCAP™ for Power Plant Mercury Control," prepared by URS Group, Inc. for the period of October 1–December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41993_Q123105.PDF.

- A quarterly progress report, "Pilot Testing of Mercury Oxidation Catalysts for Upstream of Wet FGD Systems," prepared by URS Corporation for the period of October–1 December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/GRE-CPS123105.pdf.

- A quarterly progress report, "Pilot Testing of Mercury Oxidation Catalysts for Upstream of Wet FGD Systems," prepared by URS Corporation for the period of October 1–December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/TXU-Duke-SCC123105.pdf.

- A final site report for testing conducted at the Laramie River Station for the project entitled "Evaluation of Sorbent Injection for Mercury Control," prepared by ADA-ES, Inc., for the period of October 1, 2003 through December 31, 2005 has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/toprpt_laramie_river_station.pdf.

- Two quarterly progress reports for the project entitled "Field Test Program for Long-Term Operation of a COHPAC® System for Removing Mercury from Coal-Fired Flue Gas," prepared by ADA-ES, Inc., have been posted:

  1. Quarterly period of July 1–September 30, 2005: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41591%20Q093005.pdf.

  2. Quarterly period of October 1–December 31, 2005, has been posted: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41591%20Q123105.pdf.

- Three quarterly progress reports for the project entitled "Low-Cost Options for Moderate Levels of Mercury Control," prepared by ADA-ES, Inc., have been posted:

  1. Quarterly period of April 1–June 30, 2005: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/42307%20Q063005.pdf.

  2. Quarterly period of July 1–September 30, 2005: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/42307%20Q093005.pdf.

  3. Quarterly period of October 1–December 31, 2005: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/42307%20Q123105.pdf

- A quarterly progress report, "Amended Silicates for Mercury Control," prepared by Amended Silicates, LLC for the period of July 1–September 30, 2005 has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41988%20Q093005.pdf.

- A quarterly progress report, "Large-Scale Mercury Control Technology Testing For Lignite-Fired Utilities Oxidation Systems for Wet FGD," prepared by University of North Dakota Energy & Environmental Research Center for the period of July 1–September 30, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41991%20Q093005.pdf.

- A quarterly progress report, "Evaluation of Sorbent Injection for Mercury Control," prepared by ADA-ES, Inc. for the period of October 1 December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41986%20Q123105.pdf.

- For additional information on NETL mercury related activities, please visit the Environmental & Water Resources' Mercury site located at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/index.html.