



Environment

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# SO<sub>2</sub> Characterization Modeling Analysis for the H.A. Wagner and Brandon Shores Power Plants in Baltimore, Maryland



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## 1.0 Introduction

### 1.1 Background

The United States Environmental Protection Agency (EPA) promulgated a 1-hour National Ambient Air Quality Standard (NAAQS) for SO<sub>2</sub> in 2010. The 1-hour SO<sub>2</sub> NAAQS has a level set at 75 ppb and the form of the standard is the average of the 99<sup>th</sup> percentile of the daily maximum 1-hour average concentrations realized in each of three consecutive calendar years (the “design value,” or DV).

The EPA is implementing the 2010 1-hour SO<sub>2</sub> National Ambient Air Quality Standard (NAAQS) in an approach that involves either a dispersion modeling or monitoring approach to characterize local SO<sub>2</sub> concentrations near isolated emission sources. On March 20, 2015, EPA informed affected states that certain emission sources within their states will be addressed in an expedited round of designations under the 1-hour SO<sub>2</sub> NAAQS due to terms of the SO<sub>2</sub> Consent Decree negotiated between the Sierra Club and EPA. The EPA intends to designate the affected areas as either unclassifiable/attainment, nonattainment or unclassifiable by July 2, 2016 after a review of available modeling or monitoring data to support the SO<sub>2</sub> concentration characterizations.

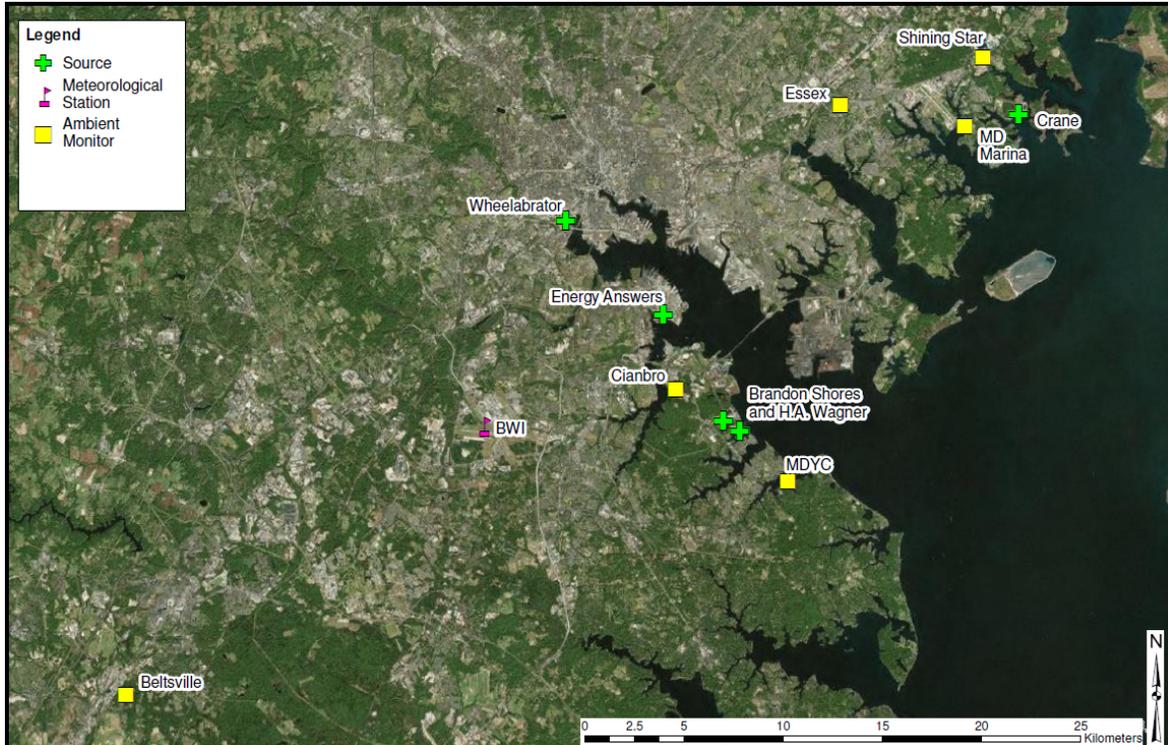
One of the affected sources evaluated in this Consent Decree analysis is the H. A. Wagner Generating Station (“Wagner”). Due to its proximity to Wagner, the Brandon Shores Generating Station is also part of the SO<sub>2</sub> characterization process.

In July 2015, the Maryland Department of the Environment (MDE) provided Raven Power, owner of the Brandon Shores, H. A. Wagner and C.P. Crane Generating Stations) with dispersion modeling files for the Fort Smallwood Complex (encompassing Brandon Shores and Wagner) as well as the Crane Generating Station (“Crane”) and other minor sources located in the vicinity of Baltimore, Maryland for the 1-hour SO<sub>2</sub> NAAQS demonstration. Raven Power contracted AECOM to review the modeling files and update them as needed. In the intervening time, EPA released a new version of AERMOD with new technical options. This modeling analysis, which results from the AECOM review and use of updated modeling procedures, summarizes the dispersion modeling procedures to characterize SO<sub>2</sub> concentrations for these sources and the results of the modeling analysis.

### 1.2 Document Organization

Section 2 provides a review of the ambient background monitor trends. Section 3 provides a discussion of SO<sub>2</sub> emission sources considered for the modeling demonstration. The SO<sub>2</sub> emissions from major sources were modeled using actual hourly emission rates for the purpose of characterizing SO<sub>2</sub> concentrations in the Baltimore area. Section 4 outlines the modeling procedures used, including model options, meteorological data, receptors, and background concentrations, as well as the modeling results.

Figure 1-1: Locations of Current and Proposed SO<sub>2</sub> Sources in the Baltimore Area



## 2.0 Review of Ambient Background Monitoring Data

There are two permanent SO<sub>2</sub> monitors located in the Baltimore area, the Essex monitor located northeast of the city and the Beltsville monitor located southwest of the city. The Beltsville monitor began collecting data in 2006 and the Essex monitor began collecting data in 2003. In addition to the state monitors, AECOM collected hourly SO<sub>2</sub> data on behalf of Raven Power for several months in 2013 at four locations in the Baltimore area, two located near Fort Smallwood and two located near Crane. These data were used to determine ambient concentrations of SO<sub>2</sub> upwind of Fort Smallwood.

Table 2-1 shows the 1-hr SO<sub>2</sub> 99<sup>th</sup> percentiles of the daily 1-hour maximum concentrations from 2007 through 2014 for the Essex and Beltsville SO<sub>2</sub> monitors. The 3-year average design values were above the then-future 1-hour NAAQS in the mid-2000's at the Essex monitor, but emissions reductions have reduced ambient monitor concentrations in the last five years and as such the design values have leveled off to approximately 29% of the 1-hour NAAQS at Essex and 15% of the NAAQS at Beltsville.

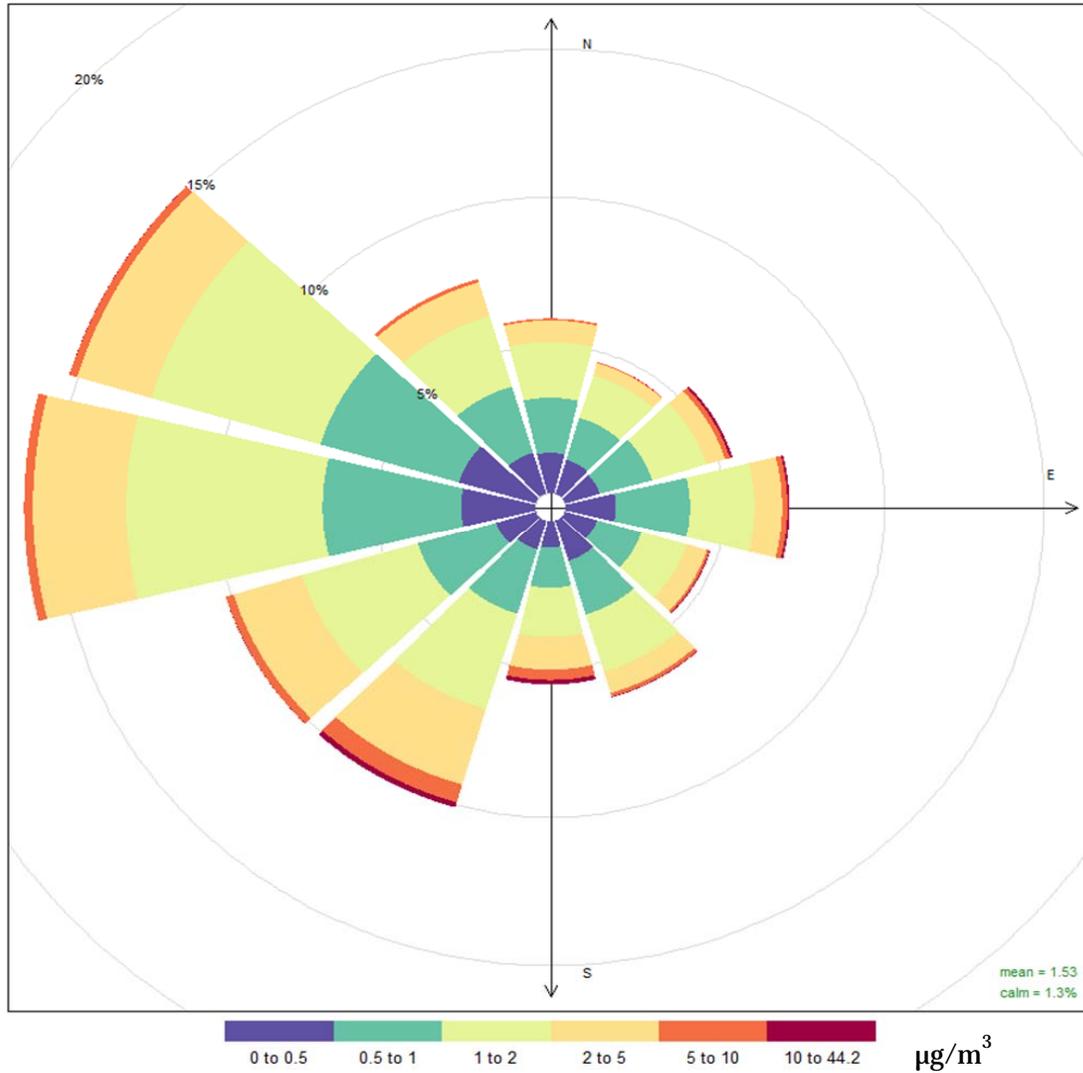
**Table 2-1: 99<sup>th</sup> Percentile of the Daily 1-hour Maximum SO<sub>2</sub> Concentrations at the Essex and Beltsville Monitors**

Year	99 <sup>th</sup> Percentile of the Daily 1-hour Maximum Concentrations (ppb)		3-Year Average Design Values (ppb)	
	Essex	Beltsville	Essex	Beltsville
2007	129	34	--	--
2008	56	28	--	--
2009	54	24	79.7	28.7
2010	20	10	43.3	20.7
2011	27	12	33.7	15.3
2012	19	12	22.0	11.3
2013	21	7	22.3	10.3
2014	26	14	22.0	11.0
2015 <sup>a</sup>	18	8	21.7	9.7

<sup>a</sup> Data through September 30, 2015.

As shown in Figure 1-1, the Essex monitor is located near or downwind of all sources included in the modeling. Figure 2-1 shows a pollution rose for combined years 2012-2014. The wind direction data is taken from Baltimore-Washington International Airport, MD ASOS station. The predominant winds for the highest (dark red) concentrations are from the west/southwest (Fort Smallwood and Wheelabrator) and east (from Crane). As such, to avoid double-counting the SO<sub>2</sub> concentrations from the modeled sources with the regional background estimates, Raven Power excluded the use of the Essex monitor when developing the ambient background concentrations included in this modeling analysis. The development of the background concentrations input to AERMOD is discussed in Section 4.7.

Figure 2-1: Pollution Rose for Essex SO<sub>2</sub> Monitor for years 2012-2014



## 3.0 Emission Source Inventory

### 3.1 Sources to be Modeled

The MDE provided initial model input files in July 2015 that included the three coal-fired power plants operated by Raven Power in the Baltimore area. In the modeling files provided by MDE, stack parameters were held constant but the emission rates varied on an hourly basis. MDE modeled the most recent three years (2012-2014) of actual emissions data that had been submitted to MDE by Raven Power per the guidance in EPA's SO<sub>2</sub> NAAQS Designations Modeling Technical Assistance Document<sup>1</sup>. Model inputs for two additional sources (Wheelabrator and the yet to be constructed Energy Answers facility) were provided on December 8, 2015. Figure 1-1 shows the sources located in the Baltimore area. Table 3-1 lists the sources and parameters modeled. Brandon Shores Units 1 and 2 exhaust to a common stack with height and internal exit diameter as reported in Table 3-1. When both units were operating, the combined emission rate, average flow rate and weighted average temperature were used in AERMOD, consistent with EPA Model Clearinghouse Memo 91-II-01. When Unit 1 or 2 operated alone, the single flue diameter was used. AECOM updated the flue gas temperature and exit velocity data in the hourly emissions file. These data were derived via examination of 2012-2014 data collected using the certified flue gas flow monitors (CEMs data) installed in the Brandon Shores, Wagner, and Crane stacks.

The stack temperature data includes several periods of erroneous temperature data for Wagner Unit 3. Four hours erroneously reported a temperature of 0 degrees F (March 21, 2013 Hour 8, June 12, 2013 Hour 9, August 8, 2013 Hour 19, and September 3, 2013 Hour 13). These values were replaced with the temperature provided in the MDE modeling file (289.99 degrees F / 416.48 K).

Intermittent sources and transient conditions such as emergency generators, auxiliary boilers, and startup/shutdown operations were not modeled as explained in the March 2011 EPA guidance document<sup>2</sup> for modeling 1-hour NO<sub>2</sub> and SO<sub>2</sub>. These emission sources are of insufficient duration and frequency to affect NAAQS compliance.

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<sup>1</sup> <http://www3.epa.gov/airquality/sulfurdioxide/pdfs/SO2ModelingTAD.pdf>

<sup>2</sup> [http://www3.epa.gov/scram001/guidance/clarification/Additional\\_Clarifications\\_AppendixW\\_Hourly-NO2-NAAQS\\_FINAL\\_03-01-2011.pdf](http://www3.epa.gov/scram001/guidance/clarification/Additional_Clarifications_AppendixW_Hourly-NO2-NAAQS_FINAL_03-01-2011.pdf)

**Table 3-1: Emissions and Stack Parameters for Input to AERMOD**

Stack	SO <sub>2</sub> Emissions (g/s)	Stack Height (m)	Exit Diameter (m)	Exit Temperature (K)	Exit Velocity (m/s)
Crane Unit 1	Variable <sup>a</sup>	107.59	3.328	Variable <sup>a</sup>	Variable <sup>a</sup>
Crane Unit 2	Variable <sup>a</sup>	107.59	3.330	Variable <sup>a</sup>	Variable <sup>a</sup>
Brandon Shores Unit 1	Variable <sup>a</sup>	121.92	9.50	Variable <sup>a</sup>	Variable <sup>a</sup>
Brandon Shores Unit 2	Variable <sup>a</sup>	121.92	9.50	Variable <sup>a</sup>	Variable <sup>a</sup>
Brandon Shores Merged Stack	Variable <sup>a</sup>	121.92	13.435	Variable <sup>a</sup>	Variable <sup>a</sup>
Wagner Unit 1	Variable <sup>a</sup>	87.48	3.099	330.00	30.48
Wagner Unit 2	Variable <sup>a,d</sup>	87.48	3.100	Variable <sup>a</sup>	Variable <sup>a</sup>
Wagner Unit 3	Variable <sup>a</sup>	105.46	4.215	Variable <sup>a</sup>	Variable <sup>a</sup>
Wagner Unit 4	Variable <sup>a</sup>	104.24	5.334	610.93	35.357
Wheelabrator	12.6	96.01	2.130	485.93	22.55
Energy Answers <sup>c</sup>	13.76	89.92	1.298	439.26	25.94

<sup>a</sup> Actual hourly monitor values were used in the modeling, as provided by Raven Power

<sup>b</sup> Wagner Units 1 and 4 are not equipped with stack flow meters.

<sup>c</sup> Energy Answers has a permit to construct. If this permit expires, this source should not be included in the modeling. This source should arguably not be included in the modeling for past emissions.

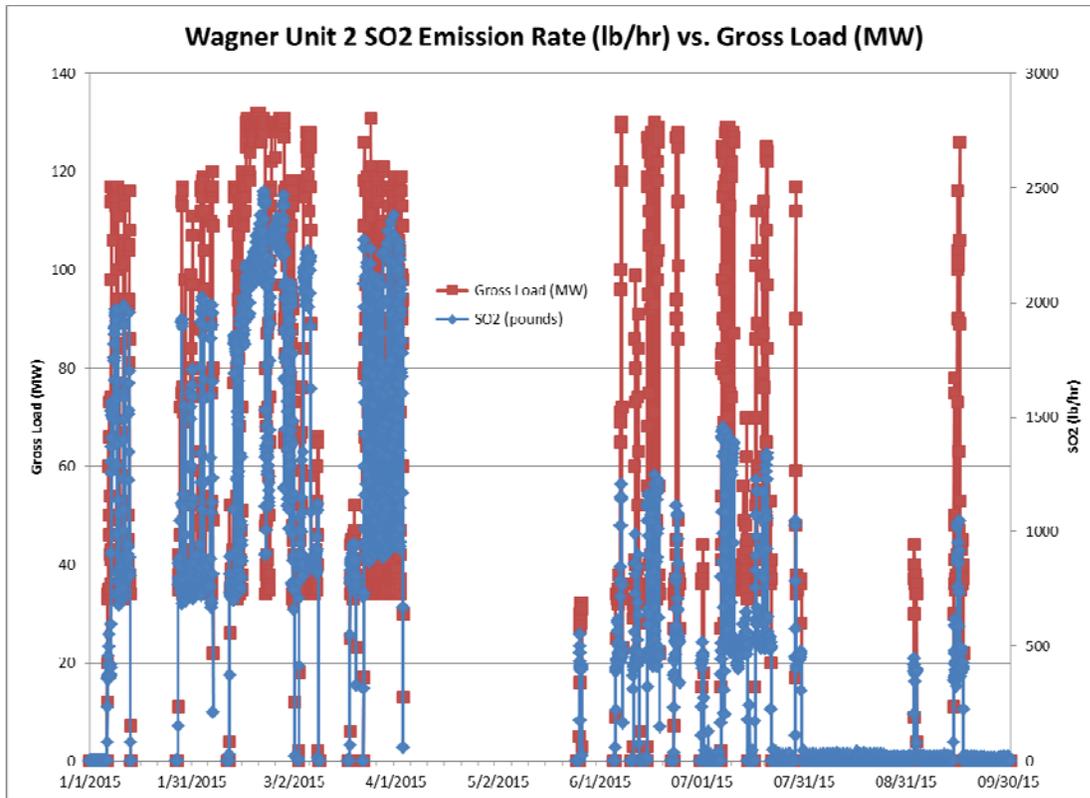
<sup>d</sup> Wagner Unit 2 emission rate was capped at 1.0 lb/MMBTU to represent future operations.

In April 2015, Raven Power reduced emissions at Wagner Unit 2 by changing to Colorado coal, a lower chlorine and lower sulfur bituminous coal that will comply with the Mercury and Air Toxics Standards (MATS). Figure 3-1 shows the comparison of megawatt (MW) output to SO<sub>2</sub> emissions for the year 2015 through September 30<sup>th</sup>. Maximum SO<sub>2</sub> emissions before the change were on the order of 2500 lb/hr and after the maximum emission rate has been less than 1500 lb/hr or less than 1.0 lb/MMBTU (~40% reduction in SO<sub>2</sub> emissions) at the same MW output. Raven Power plans to continue burning this or similar coal in Wagner Unit 2 in order to meet MATS. In order to represent this reduction at Wagner Unit 2 in the hourly emissions file, the emission rate for each hour was recalculated using the actual hourly heat input and a conservative cap of 1.0 lb SO<sub>2</sub>/MMBTU. The resulting record of adjusted actual emissions used in the modeling represents a conservative estimate of actual emissions over a 3-year period. This is basically a characterization of the air quality under current conditions, extended to account for 3 years of typical variability in meteorological and emission conditions.

The modeling for Brandon Shores was initially performed without considering the effects of plume moisture, which is not accounted for in AERMOD without special considerations. This is an important issue for Brandon Shores due to the effects of wet scrubbing. AECOM employs a new technique, "AERMOIST", to derive effective hourly stack temperatures that account for the effect of the heat of condensation. The technical details of this process are described in submittals to the EPA Appendix

W proposal docket<sup>3</sup> and included in Appendix A. A peer-reviewed paper<sup>4</sup> to be published in Atmospheric Environment also documents and supports this and other source characterization techniques. Additional modeling using this technique will be submitted in the near future.

**Figure 3-1: Wagner Unit 2 Emission Reductions in 2015**



<sup>3</sup> See Appendix M at <http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2015-0310-0110>.

<sup>4</sup> Paine, R., L. Warren, and G. Moore. Source characterization refinements for routine modeling applications. Atmospheric Environment (2016). <http://dx.doi.org/10.1016/j.atmosenv.2016.01.003>.

## 4.0 Modeling Procedures

### 4.1 Dispersion Model Selection

This modeling analysis utilized the most recent version of the AERMOD dispersion model<sup>4</sup> (Version 15181) to evaluate air quality impacts from the emission sources of interest. The AERMOD modeling system consists of two preprocessors and the dispersion model. AERMET is the meteorological preprocessor component and AERMAP is the terrain pre-processor component that characterizes the terrain and generates receptor elevations along with critical hill heights for those receptors.

### 4.2 Land Use Classification

One of the factors affecting input parameters to dispersion models is the presence of either rural or urban conditions near the source site and the meteorological site(s). The choice of rural or urban for dispersion conditions at the source site depends upon the land use characteristics within 3 kilometers of the facility being modeled (Appendix W to 40 CFR Part 51)<sup>5</sup>. Factors that affect the rural/urban choice, and thus the dispersion, include the extent of vegetated surface area, the water surface area, types of industry and commerce, and building types and heights within this area. For this application, AECOM ran AERMOD with rural dispersion for all sources per the modeling files initially provided by MDE and as shown in Figure 4-1, more than 50% of the area within 3 kilometers of Fort Smallwood is water (blue) and vegetation (green/brown).

### 4.3 Good Engineering Practice (GEP) Analysis

Federal stack height regulations limit the stack height used in performing dispersion modeling to predict the air quality impact of a source. Sources must be modeled at the actual physical stack height unless that height exceeds the Good Engineering Practice (GEP) formula stack height. If the physical stack height is less than the formula GEP height, the potential for the source's plume to be affected by aerodynamic wakes created by the building(s) must be evaluated in the dispersion modeling analysis.

A GEP formula stack height analysis has been performed for sources of interest located at the Brandon Shores, Wagner, and Crane Generating Stations in accordance with the EPA's "Guideline for Determination of Good Engineering Practice Stack Height" (EPA, 1985)<sup>6</sup>. A GEP stack height is defined as the greater of 65 meters (213 feet), measured from the ground elevation of the stack, or the formula height ( $H_g$ ), as determined from the following equation:

$$H_g = H + 1.5 L$$

where

H is the height of the nearby structure which maximizes  $H_g$ , and

L is the lesser dimension (height or projected width) of the building.

For a squat structure, i.e., height less than projected width, the formula reduces to:

$$H_{GEP} = 2.5H_B$$

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<sup>5</sup> EPA's Guideline on Air Quality Models, available at [http://www.epa.gov/ttn/scram/guidance/guide/appw\\_05.pdf](http://www.epa.gov/ttn/scram/guidance/guide/appw_05.pdf).

<sup>6</sup> Available at <http://www.epa.gov/scram001/guidance/guide/gep.pdf>.

In the absence of influencing structures, a “default” GEP stack height is credited up to 65 meters (213 feet). Both the height and the width of the building are determined through a vertical cross-section perpendicular to the wind direction. In all instances, the GEP formula height is based upon the highest value of  $H_g$  as determined from H and L over all nearby buildings over the entire range of possible wind directions. For the purposes of determining the GEP formula height, only buildings within 5L of the source of interest are considered.

The GEP analyses were conducted with the latest version of the US EPA’s Building Profile Input Program software (BPIP-PRIME version 04274). The locations and dimensions of the buildings/structures relative to the exhaust stacks for Brandon Shores, Wagner, and Crane Generating Stations are depicted in Figures 4-2 through 4-4. Building heights and the base elevations of buildings and stacks were updated from previous modeling based on 2004 USGS LIDAR data<sup>7</sup> and confirmed with Google Earth Pro (shown in Figures 4-5 and 4-6) for the Fort Smallwood Complex. 3D representations of the buildings and stacks as output from BPIP-PRIME are shown in Figures 4-7 and 4-8.

#### 4.4 Meteorological Data Processing

The meteorological data required for input to AERMOD were created with the latest version of AERMET (15181) using the adjusted  $u_*$  option. This option is currently a beta non-guideline option; justification for its use is discussed below. Hourly surface observations from Baltimore-Washington International Airport, MD along with concurrent upper air data from Sterling, VA were used as input to AERMET. The surface data (wind direction, wind speed, temperature, sky cover, and relative humidity) is measured 10 m above ground level. A wind rose for 2012-2014 is shown in Figure 4-9.

AERMET creates two output files for input to AERMOD:

- SURFACE: a file with boundary layer parameters such as sensible heat flux, surface friction velocity, convective velocity scale, vertical potential temperature gradient in the 500-meter layer above the planetary boundary layer, and convective and mechanical mixing heights. Also provided are values of Monin-Obukhov length, surface roughness, albedo, Bowen ratio, wind speed, wind direction, temperature, and heights at which measurements were taken.
- PROFILE: a file containing multi-level meteorological data with wind speed, wind direction, temperature, sigma-theta ( $\sigma_\theta$ ) and sigma-w ( $\sigma_w$ ) when such data are available. For this application involving representative data from the nearest NWS station, the profile file contained a single level of wind data and the temperature data.

AERMET requires specification of site characteristics including surface roughness ( $z_o$ ), albedo ( $r$ ), and Bowen ratio ( $B_o$ ). These parameters were developed according to the guidance provided by US EPA in the recently revised AERMOD Implementation Guide<sup>8</sup> (AIG).

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<sup>7</sup> <http://earthexplorer.usgs.gov/> under Digital Elevation/LIDAR. Uploaded in 2013.

<sup>8</sup> Available at [http://www.epa.gov/ttn/scram/7thconf/aermod/aermod\\_implmtn\\_guide\\_19March2009.pdf](http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_implmtn_guide_19March2009.pdf).

The AIG provides the following recommendations for determining the site characteristics:

1. The determination of the surface roughness length should be based on an inverse distance weighted geometric mean for a default upwind distance of 1 kilometer relative to the measurement site. Surface roughness length may be varied by sector to account for variations in land cover near the measurement site; however, the sector widths should be no smaller than 30 degrees.
2. The determination of the Bowen ratio should be based on a simple un-weighted geometric mean (i.e., no direction or distance dependency) for a representative domain, with a default domain defined by a 10-km by 10-km region centered on the measurement site.
3. The determination of the albedo should be based on a simple un-weighted arithmetic mean (i.e., no direction or distance dependency) for the same representative domain as defined for Bowen ratio, with a default domain defined by a 10-km by 10-km region centered on the measurement site.

The AIG recommends that the surface characteristics be determined based on digitized land cover data. EPA has developed a tool called AERSURFACE that can be used to determine the site characteristics based on digitized land cover data in accordance with the recommendations from the AIG discussed above. AERSURFACE<sup>9</sup> incorporates look-up tables of representative surface characteristic values by land cover category and seasonal category. AERSURFACE was applied with the instructions provided in the AERSURFACE User's Guide.

The current version of AERSURFACE (Version 13016) supports the use of land cover data from the USGS National Land Cover Data 1992 archives<sup>10</sup> (NLCD92). The NLCD92 archive provides data at a spatial resolution of 30 meters based upon a 21-category classification scheme applied over the continental U.S. The AIG recommends that the surface characteristics be determined based on the land use surrounding the site where the surface meteorological data were collected.

As recommended in the AIG for surface roughness, the 1-km radius circular area centered at the meteorological station site can be divided into sectors for the analysis; the default 12 sectors was used for this analysis.

In AERSURFACE, the various land cover categories are linked to a set of seasonal surface characteristics. As such, AERSURFACE requires specification of the seasonal category for each month of the year. The following five seasonal categories are supported by AERSURFACE, with the applicable months of the year specified for this site.

1. Midsummer with lush vegetation (June-August).
2. Autumn with un-harvested cropland (September- November).
3. Late autumn after frost and harvest, or winter with no snow (December - February)
4. Winter with continuous snow on ground (none).
5. Transitional spring with partial green coverage or short annuals (March - May).

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<sup>9</sup> Documentation available at [http://www.epa.gov/ttn/scram/dispersion\\_related.htm#aersurface](http://www.epa.gov/ttn/scram/dispersion_related.htm#aersurface).

<sup>10</sup> See additional information at <http://landcover.usgs.gov/natl/landcover.php>.

For Bowen ratio, the land use values are linked to three categories of surface moisture corresponding to average, wet, and dry conditions. The surface moisture condition for the site may vary depending on the meteorological data period for which the surface characteristics should be applied. AERSURFACE applies the surface moisture condition for the entire data period. Therefore, if the surface moisture condition varies significantly across the data period, then AERSURFACE can be applied multiple times to account for those variations.

As such, the surface moisture condition for each season was determined by comparing precipitation for the period of data to be processed to the 30-year climatological record, selecting “wet” conditions if precipitation is in the upper 30<sup>th</sup>-percentile, “dry” conditions if precipitation is in the lower 30<sup>th</sup>-percentile, and “average” conditions if precipitation is in the middle 40<sup>th</sup>-percentile. The 30-year precipitation data set to be used in this modeling was taken from the National Climatic Data Center<sup>11</sup>.

The monthly designations of surface moisture that were input to AERSURFACE are summarized in Table 4-1.

**Table 4-1: AERSURFACE Bowen Ratio Condition Designations**

Month	Bowen Ratio Category		
	2012	2013	2014
January	Average	Wet	Average
February	Average	Dry	Wet
March	Dry	Average	Average
April	Dry	Dry	Wet
May	Dry	Average	Average
June	Average	Wet	Wet
July	Average	Average	Average
August	Wet	Dry	Wet
September	Average	Dry	Average
October	Wet	Wet	Average
November	Dry	Average	Average
December	Average	Wet	Average

#### 4.5 Receptors to be Modeled

MDE provided the receptor grid to AECOM for modeling. Receptors are placed in nested Cartesian grids centered on the Fort Smallwood Complex and Crane with the following spacing:

- Every 25 meters along the property boundary
- Every 100 meters out to a distance of 2 km

<sup>11</sup> <http://www.ncdc.noaa.gov/cdo-web/>

- Every 250 meters between 2 and 5 km, and
- Every 500 meters between 5 and 10 km.

The current version of AERMAP has the ability to process USGS National Elevation Dataset (NED) data in place of Digital Elevation Model files. The appropriate file for 1-arc-second, or 30-m, NED data were obtained from the Multi-Resolution Land Characteristics Consortium (MRLC) link at <http://www.mrlc.gov/viewerjs/>.

Per EPA's SO<sub>2</sub> Technical Assistance Document for modeling<sup>12</sup>, receptors in inaccessible areas such as over water and on Aberdeen Proving Ground were removed for this modeling analysis as shown in Figure 4-10.

#### 4.6 Model Configurations and Options

AERMET and AERMOD (Versions 15181) were run with the updated "ADJ\_U\*" option in AERMET and the LOWWIND3 option in AERMOD. The history of the development of these low wind options is provided below.

In 2010, the results of an evaluation<sup>13</sup> of low wind speed databases for short-range modeling applications were provided to EPA. The reason for the study was that some of the most restrictive dispersion conditions and the highest model predictions occur under low wind speed conditions, but there had been very little model evaluation for these conditions. The results of the evaluation indicated that in low wind conditions, the friction velocity formulation in AERMOD results in under-predictions of this important planetary boundary layer parameter. There were several modeling implications of this under-prediction: mechanical mixing heights that were very low (less than 10 meters), very low effective dilution wind speeds, and very low turbulence in stable conditions. In addition, the evaluation study concluded that the minimum lateral turbulence (as parameterized using sigma-v) was too low by at least a factor of 2.

After these issues were once again stated at the 10<sup>th</sup> EPA Modeling Conference in March 2012, EPA made some revisions in late 2012 to the AERMOD modeling system to correct the model deficiencies in this area. This culminated in EPA releasing AERMET and AERMOD Version 12345, which include "beta" options in AERMET for a revised u\* formulation under stable conditions and two different low wind speed options in AERMOD. After its release, a bug was found with the "beta" options by AECOM. The EPA subsequently released AERMET and AERMOD Version 13350 with corrections to this issue and other updates.

Among the changes incorporated into AERMOD 13350 are updates to the AERMET meteorological processor; these are described in the model change bulletin which may be found at: [http://www.epa.gov/ttn/scram/7thconf/aermod/aermet\\_mcb4.txt](http://www.epa.gov/ttn/scram/7thconf/aermod/aermet_mcb4.txt).

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<sup>12</sup> <http://www3.epa.gov/airquality/sulfurdioxide/pdfs/SO2ModelingTAD.pdf>.

<sup>13</sup> Paine, R.J., J.A. Connors, and C.D. Szembek. AERMOD Low Wind Speed Evaluation Study: Results and Implementation. Paper 2010-A-631-AWMA, presented at the 103rd Annual Conference, Air & Waste Management Association, Calgary, Alberta, Canada. 2010.

One of the changes provides a “bug fix” to the friction velocity ( $u_*$ ) computation, as stated in the bulletin:

“Modified subroutine UCALST to incorporate AECOM's recommended corrections to theta-star under the ADJ\_U\* beta option, based on Qian and Venkatram<sup>14</sup>, that was incorporated in version 12345 of AERMET.”

EPA's discussion of this  $u_*$  option indicates that it is a beta non-default option. However, in their webinars provided on January 14, 2014 and August 12, 2014<sup>15</sup>, as well as at the EPA's 11<sup>th</sup> modeling conference<sup>16</sup>, EPA noted that since this option is based upon peer-reviewed literature and due to favorable evaluation results for this option as documented in the EPA presentations, a citation to the literature and the results of the EPA testing could be provided to obtain approval for its use at this time. EPA has now released AERMET/AERMOD version 15181 that incorporates low wind options as default techniques. Based upon this action, we used the new version of AERMET and AERMOD with the default low wind options. Appendix B includes a discussion of the issues involved in acceptance of a non-guideline modeling option that provides further support for use of this option.

In addition to this information from EPA, AECOM has conducted additional testing of the low wind options for tall stack databases. The results of the testing were published as a peer-reviewed paper<sup>17</sup> in the Journal of the Air & Waste Management Association; this paper is provided in Appendix C. The favorable results of supplemental testing of the proposed options with these databases are presented in Appendix D.

## 4.7 Background Concentrations

The Beltsville, MD monitor, which is located about 33 km to the southwest of the Fort Smallwood Complex, was used to determine the uniform regional background component for the NAAQS SO<sub>2</sub> modeling. EPA's March 2011 clarification memo<sup>18</sup> regarding 1-hour SO<sub>2</sub> NAAQS modeling allows for an approach using the 99<sup>th</sup> percentile monitored values whereby the background values vary by season and by hour of the day. AECOM applied this approach to its modeling, using data from the 3-year period of 2012 - 2014. The SO<sub>2</sub> concentrations that were used are listed in Table 4-2. Figure 4-11 shows a plot of the hourly background values by season and hour.

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<sup>14</sup> Qian, W., and A. Venkatram, 2011: "Performance of Steady-State Dispersion Models Under Low Wind-Speed Conditions", *Boundary Layer Meteorology*, 138:475-491.

<sup>15</sup> Available at <http://www.epa.gov/ttn/scram/>.

<sup>16</sup> Available at [http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5\\_Proposed\\_Updates\\_AERMOD\\_System.pdf](http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5_Proposed_Updates_AERMOD_System.pdf).

<sup>17</sup> Paine, R., O. Samani, M. Kaplan, E. Knipping and N. Kumar (2015) Evaluation of low wind modeling approaches for two tall-stack databases, *Journal of the Air & Waste Management Association*, 65:11, 1341-1353, DOI: 10.1080/10962247.2015.1085924.

<sup>18</sup> Available at [http://www.epa.gov/ttn/scram/guidance/clarification/Additional\\_Clarifications\\_AppendixW\\_Hourly-NO2-NAAQS\\_FINAL\\_03-01-2011.pdf](http://www.epa.gov/ttn/scram/guidance/clarification/Additional_Clarifications_AppendixW_Hourly-NO2-NAAQS_FINAL_03-01-2011.pdf).

One direction sector that is unique to the Fort Smallwood site involves winds generally from the east (upwind sector from 70 to 130 degrees), for which the upwind fetch involves approximately 20 kilometers over open water, and then at least 10 additional km of no large SO<sub>2</sub> sources on the eastern shore of the Chesapeake Bay before reaching Fort Smallwood as shown in Figure 4-12. For this sector only, AECOM included a sector-dependent background concentration, as described in EPA's September 2014 Clarification Memo<sup>19</sup>. The AERMOD User's Guide Addendum<sup>20</sup> states that such sectors should be 60 degrees or more (a warning will be issued for sectors less than 60 degrees). AECOM reviewed the monitoring data collected in Summer 2013 for the Maryland Yacht Club located southeast of Fort Smallwood (i.e., upwind of Fort Smallwood during southeast winds). The observed concentrations when winds are from the overwater sector are very low, ~1.5 ppb (3.9 µg/m<sup>3</sup>) or less. AECOM used this value (1.5 ppb) for the overwater sector, with the Beltsville monitor hour-of-day/seasonal values used for all other directions. An hourly background concentration file was developed in Excel to substitute the 1.5 ppb background when the wind direction was from the 60 degree sector.

According to the EPA's "Table 5c. Monitoring Site Listing for Sulfur Dioxide 1-Hour NAAQS" ([http://www3.epa.gov/airtrends/pdfs/SO2\\_DesignValues\\_20122014\\_FINAL\\_8\\_3\\_15.xlsx](http://www3.epa.gov/airtrends/pdfs/SO2_DesignValues_20122014_FINAL_8_3_15.xlsx)), the completeness criteria for 2012-2014 (Column W) is satisfied, therefore, the Beltsville 1-hour SO<sub>2</sub> monitoring data is complete and is acceptable to use in the modeling.

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<sup>19</sup> [http://www3.epa.gov/scram001/guidance/clarification/NO2\\_Clarification\\_Memo-20140930.pdf](http://www3.epa.gov/scram001/guidance/clarification/NO2_Clarification_Memo-20140930.pdf)

<sup>20</sup> [http://www.epa.gov/ttn/scram/models/aermod/aermod\\_userguide.zip](http://www.epa.gov/ttn/scram/models/aermod/aermod_userguide.zip)

**Table 4-2: 1-hr SO<sub>2</sub> Ambient Background Concentrations for Beltsville Monitor (2012-2014)**

Hour	3-Year Averaged Hourly Values for Winter (µg/m <sup>3</sup> )	3-Year Averaged Hourly Values for Spring (µg/m <sup>3</sup> )	3-Year Averaged Hourly Values for Summer (µg/m <sup>3</sup> )	3-Year Averaged Hourly Values for Fall (µg/m <sup>3</sup> )
1	7.9	6.0	2.1	5.1
2	5.8	5.5	1.3	4.6
3	9.8	6.2	1.5	4.1
4	8.5	5.4	1.6	3.4
5	9.3	5.8	1.8	2.7
6	10.8	6.4	1.7	2.8
7	9.6	5.7	3.1	2.9
8	10.3	6.7	6.5	3.9
9	10.7	10.3	7.9	6.1
10	13.1	12.8	8.9	9.4
11	17.8	12.3	9.5	11.5
12	14.0	10.7	8.5	21.3
13	13.1	11.8	9.5	13.2
14	11.1	11.5	7.2	10.7
15	12.1	10.3	4.9	9.2
16	11.7	11.8	6.5	10.4
17	11.8	9.8	5.2	8.6
18	9.3	14.2	4.8	7.1
19	12.1	10.5	3.6	6.6
20	11.8	11.7	3.3	4.5
21	10.7	6.7	2.7	4.5
22	10.7	5.7	2.2	4.5
23	14.7	5.5	2.8	4.1
24	9.8	4.8	2.3	4.0

## 4.8 Results of SO<sub>2</sub> Characterization Analysis

The results of this SO<sub>2</sub> characterization using modeling can be used to inform the decision as to whether to designate the area around Ft. Smallwood as being in attainment of the SO<sub>2</sub> NAAQS. This modeling process has some conservative features included, such as:

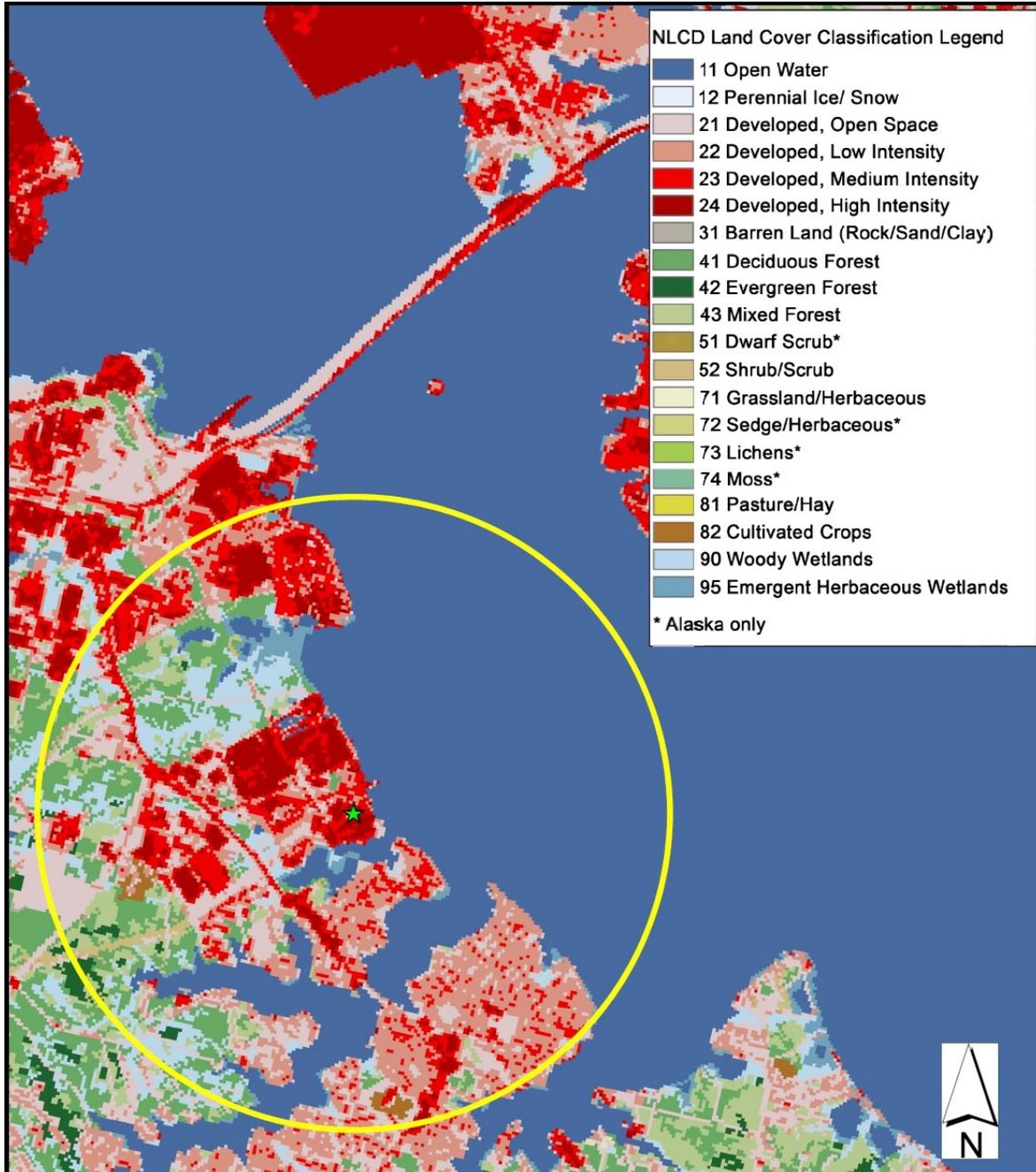
- Use of allowable emission rates for background sources, including sources such as Energy Answers that does not yet exist.
- For Wagner Unit 2, a conservatively high 1 lb/MMBtu emission rate was assumed for periods adjusted for the current use of Colorado coal.
- As the appendices indicate, the modeling approaches have been independently evaluated and result in modest overpredictions.
- To date, the effects of moist plume rise for Brandon Shores has not been incorporated into the modeling. As a result, the plume rise from that source is likely underestimated.

Therefore, since with these conservative assumptions, the modeling results provided in Table 4-3 and in Figure 4-13 show that the 3-year average of the 99<sup>th</sup> percentile peak daily 1-hour maximum concentration is 71 ppb, which below the NAAQS of 75 ppb, the area should be considered as being in attainment of the SO<sub>2</sub> NAAQS based upon current emission practices.

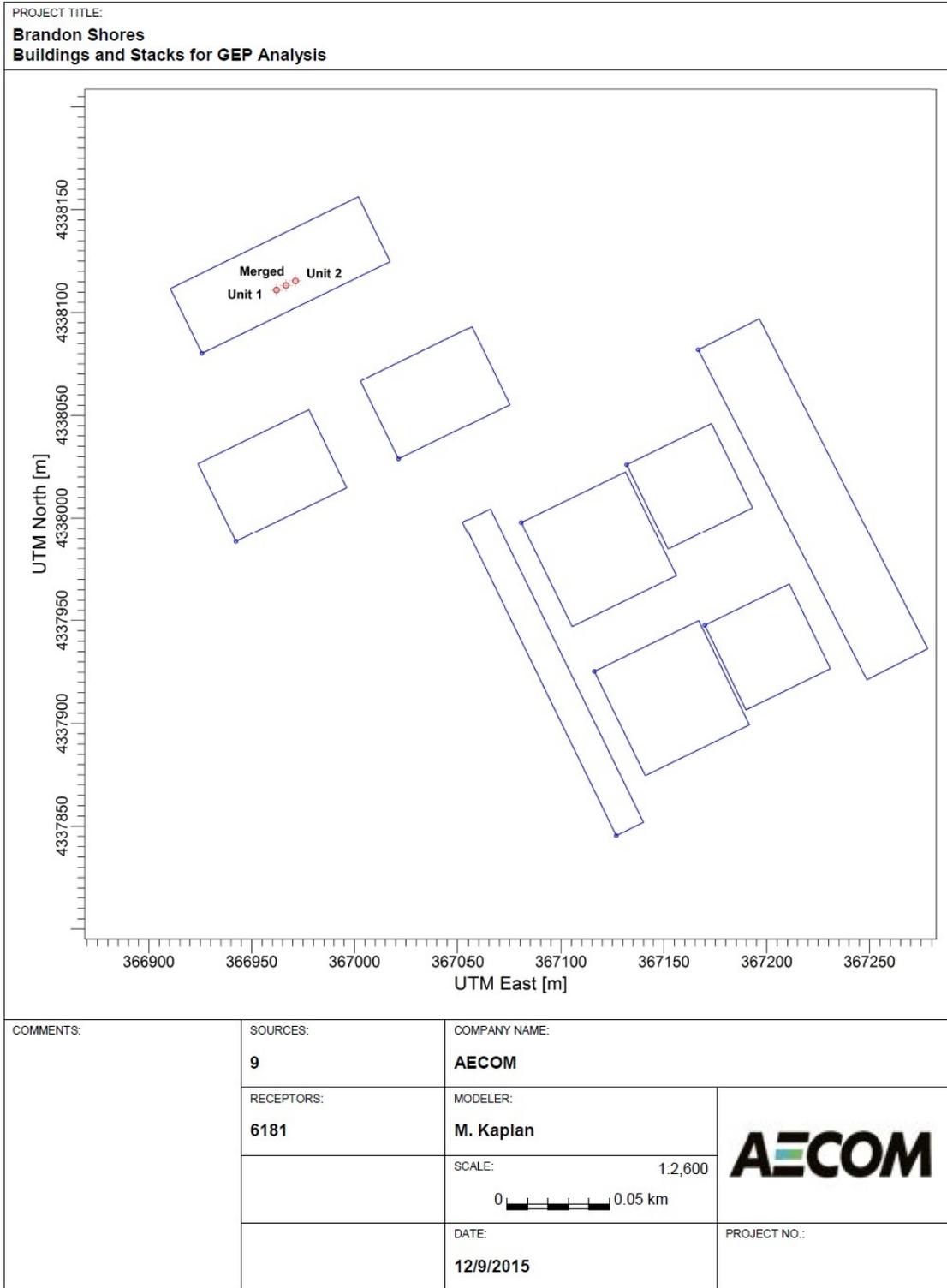
**Table 4-3 1-hour SO<sub>2</sub> Modeling Culpability Results for Controlling Receptor**

Emission Source	Brandon Shores	H.A. Wagner	Crane	Nearby sources	Background	Total
Concentration (µg/m <sup>3</sup> )	16.3	158.0	0.0	1.4	10.3	186.0 (71 ppb)

Figure 4-1: 2011 Land Cover Classification within 3 Kilometers of Fort Smallwood

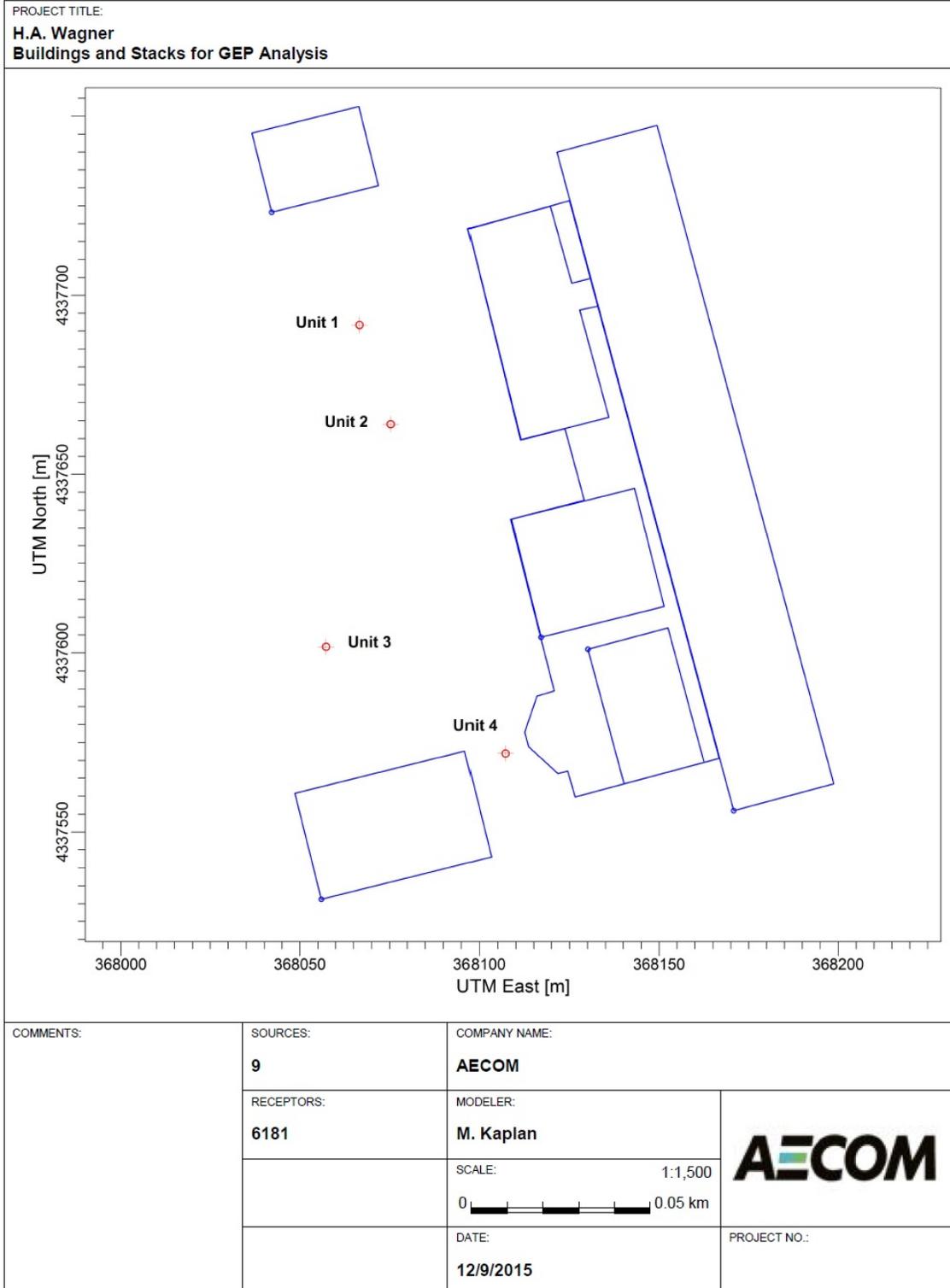


**Figure 4-2: Stacks and Buildings Used in the GEP Analysis for Brandon Shores**



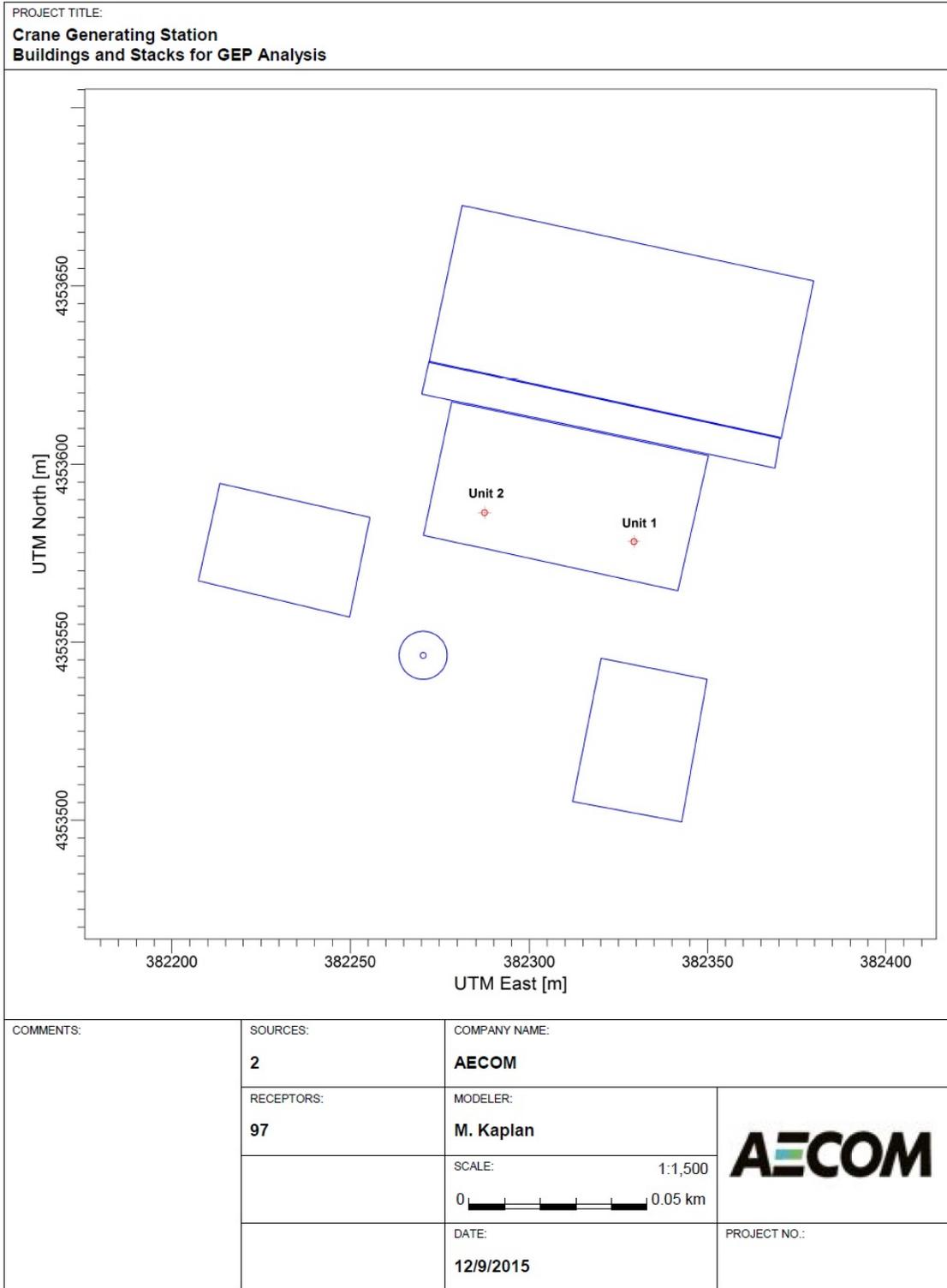
AERMOD View - Lakes Environmental Software

**Figure 4-3: Stacks and Buildings Used in the GEP Analysis for H.A. Wagner**



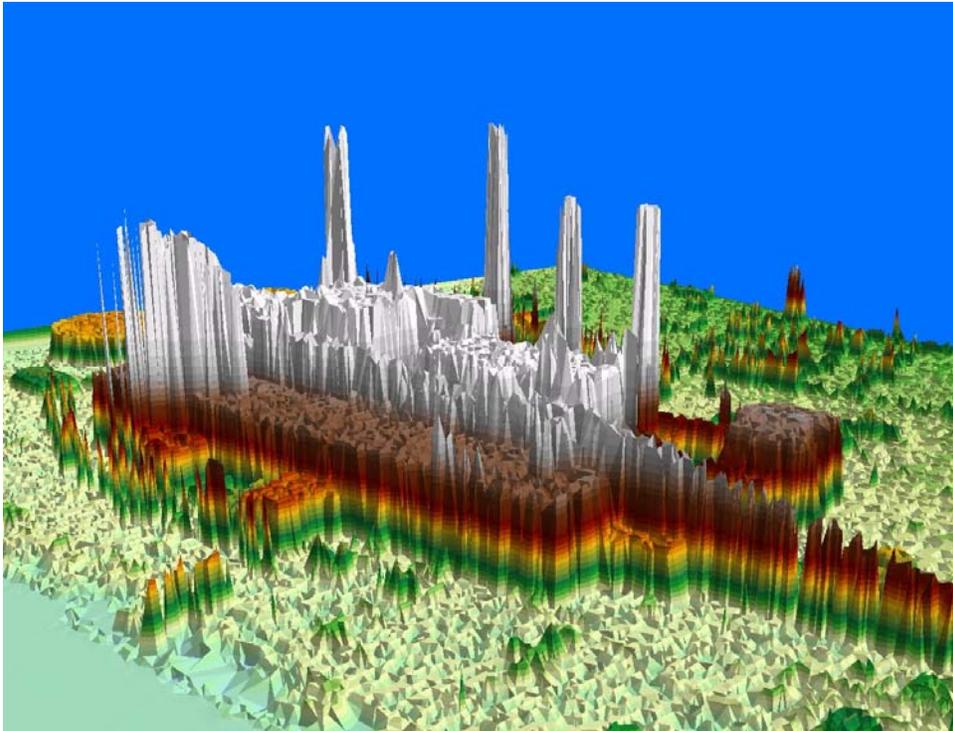
AERMOD View - Lakes Environmental Software

**Figure 4-4: Stacks and Buildings Used in the GEP Analysis for Crane Generating Station**



AERMOD View - Lakes Environmental Software

**Figure 4-5: USGS LIDAR Data for Wagner Station**



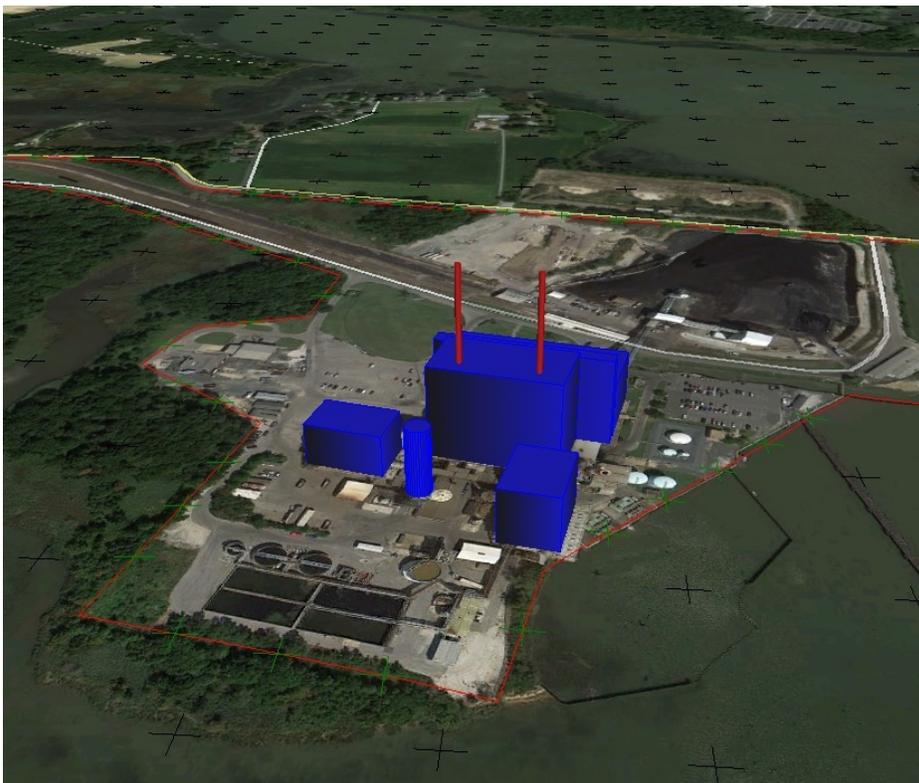
**Figure 4-6: USGS LIDAR Data for Brandon Shores**



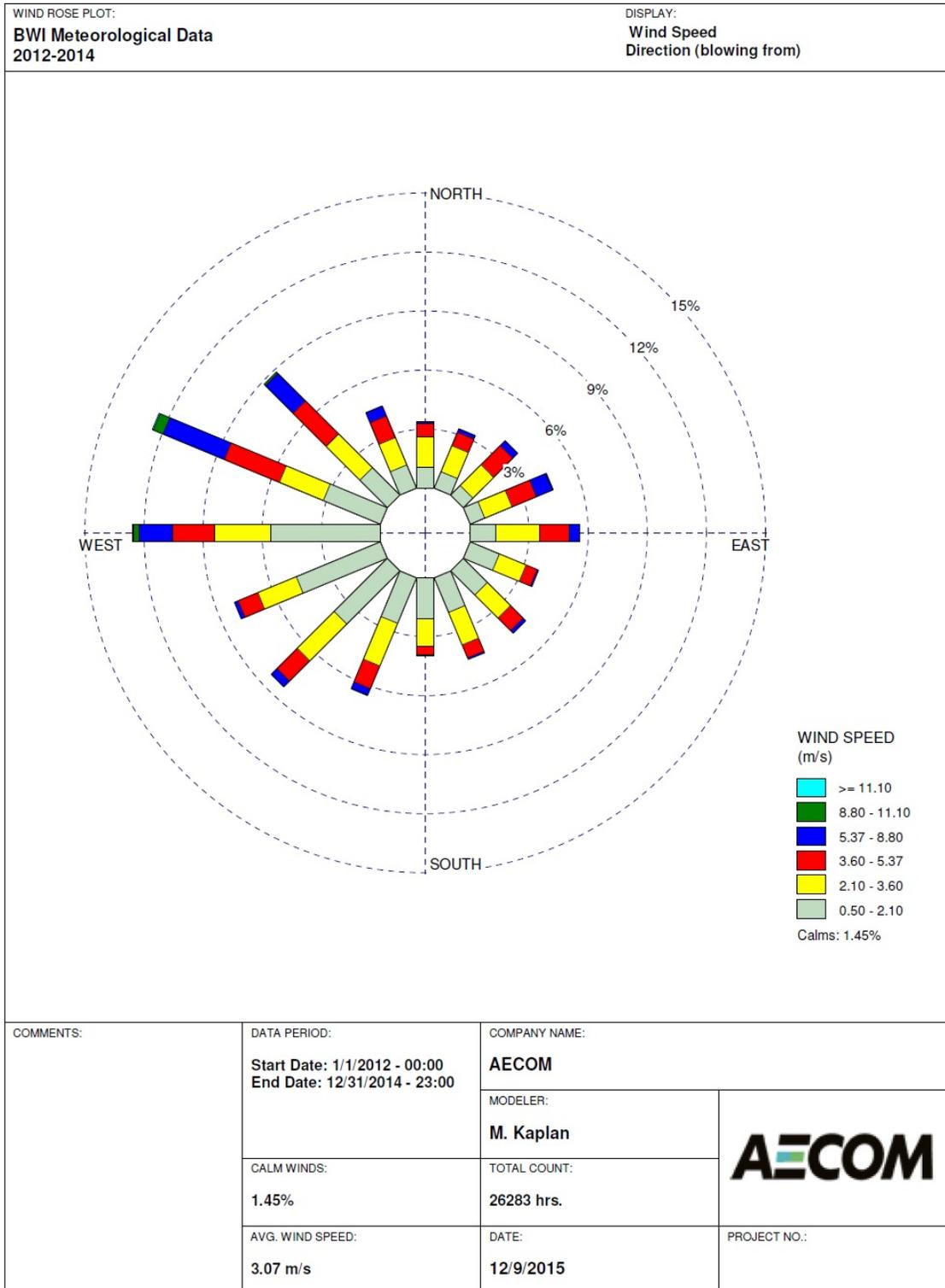
Figure 4-7: 3D View of Brandon Shores and Wagner Buildings and Stacks



Figure 4-8: 3D View of Crane Buildings and Stacks

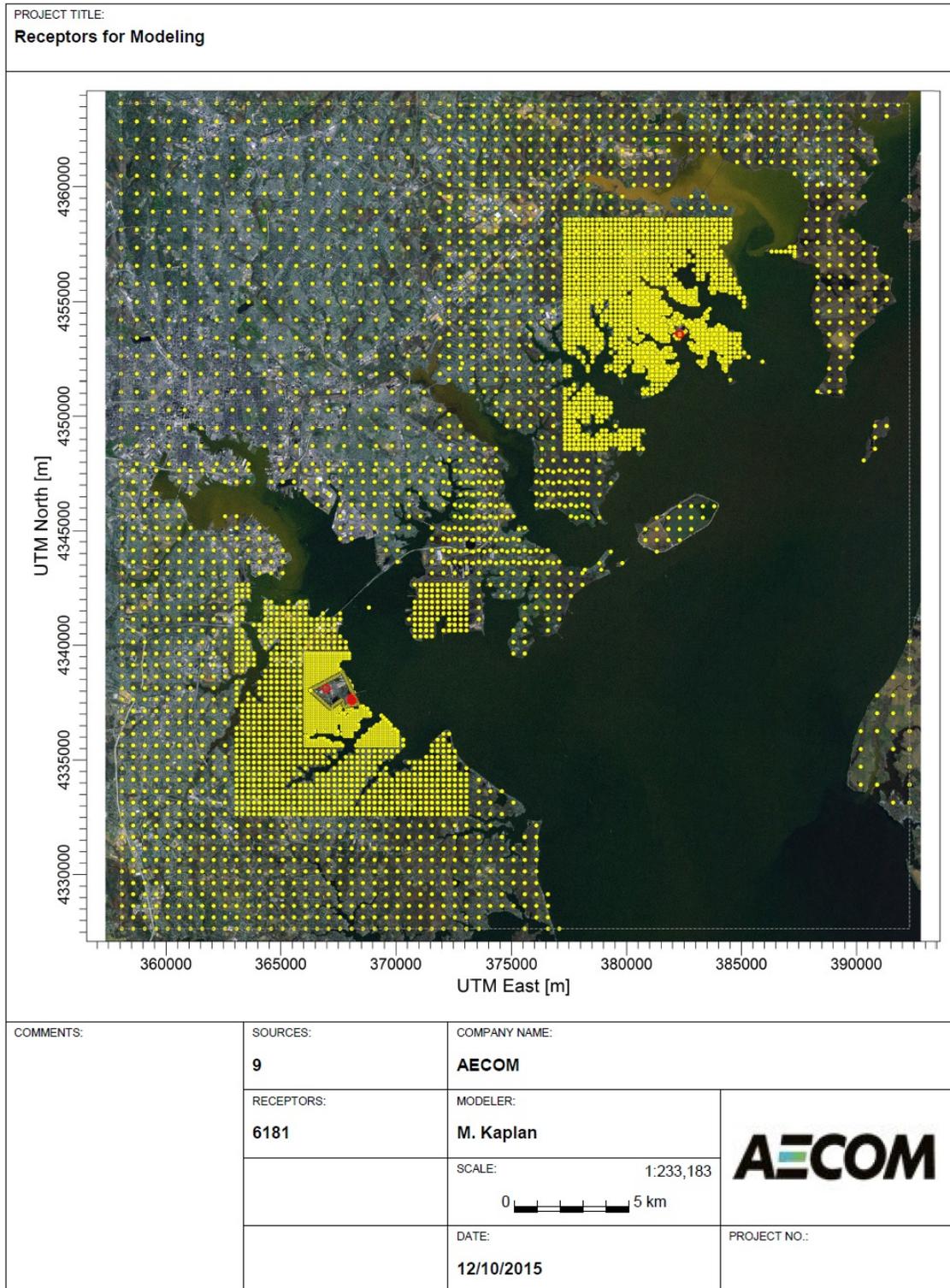


**Figure 4-9: BWI Airport 3-Year (2012-2014) Wind Rose**



WRPLOT View - Lakes Environmental Software

**Figure 4-10: Receptor Grid for Modeling**



AERMOD View - Lakes Environmental Software

**Figure 4-11: Three-Year Averaged SO<sub>2</sub> Background Concentrations Varying by Season and Hour-of-Day (µg/m<sup>3</sup>)**

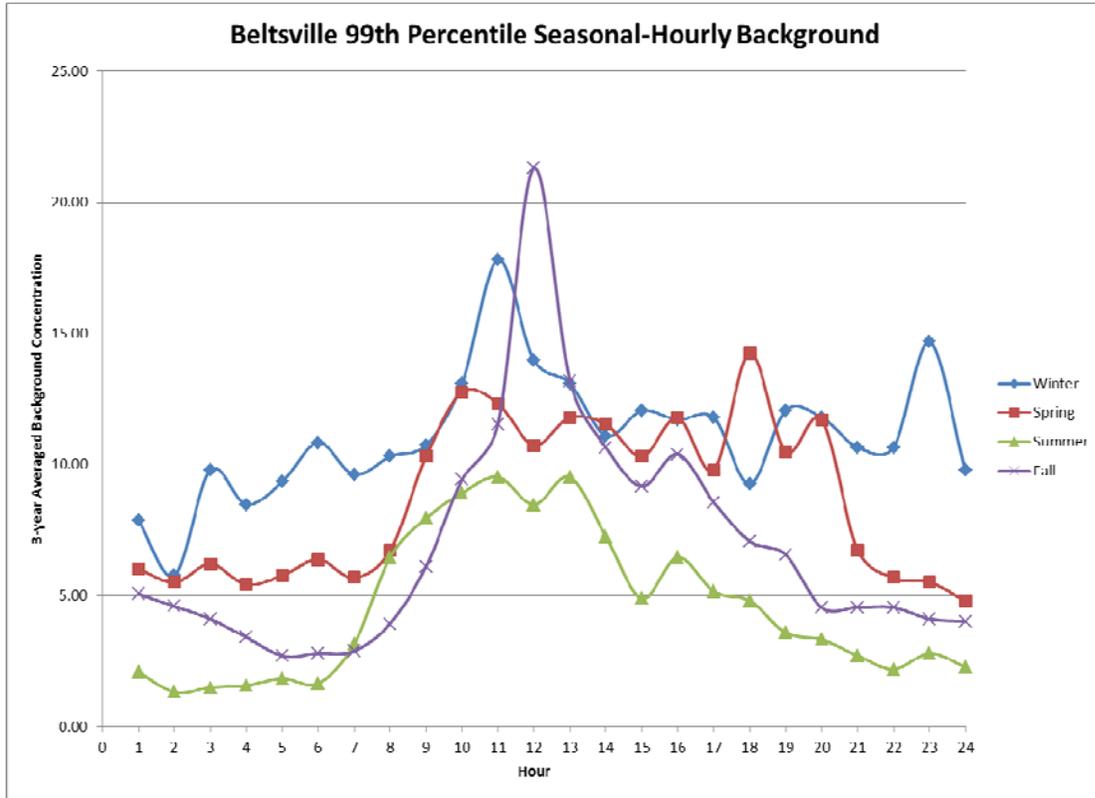


Figure 4-12 60 degree Sector For East Wind Fetch over Water

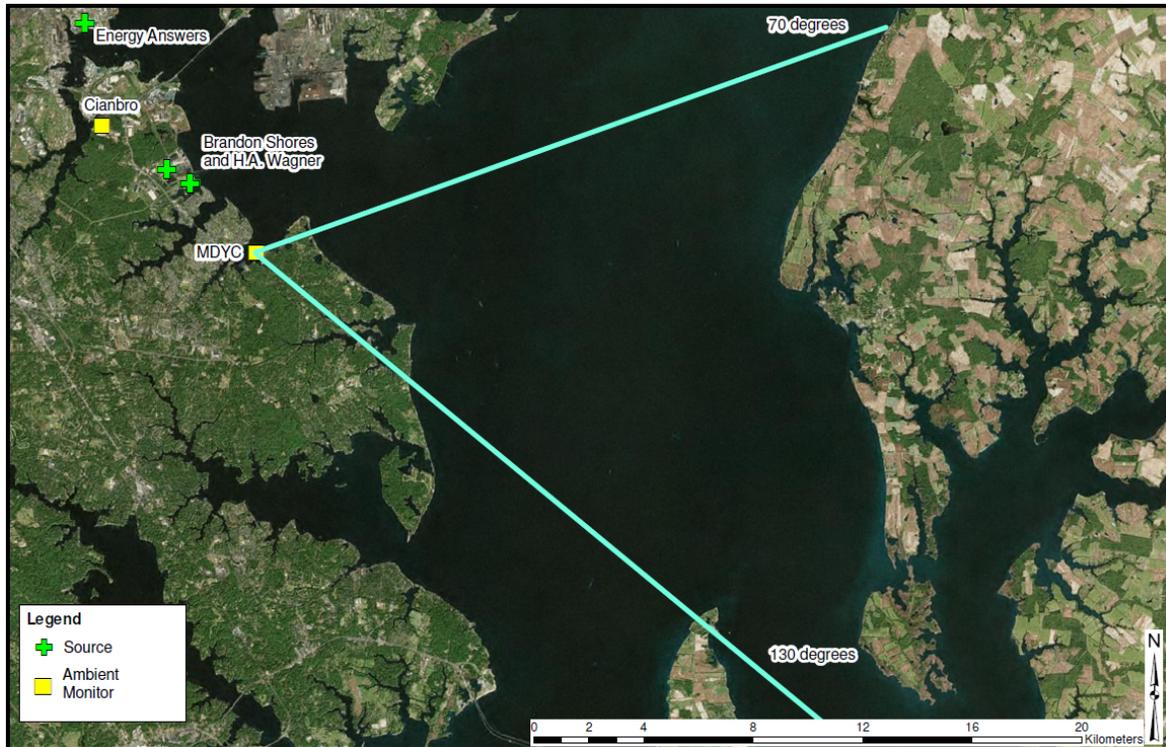
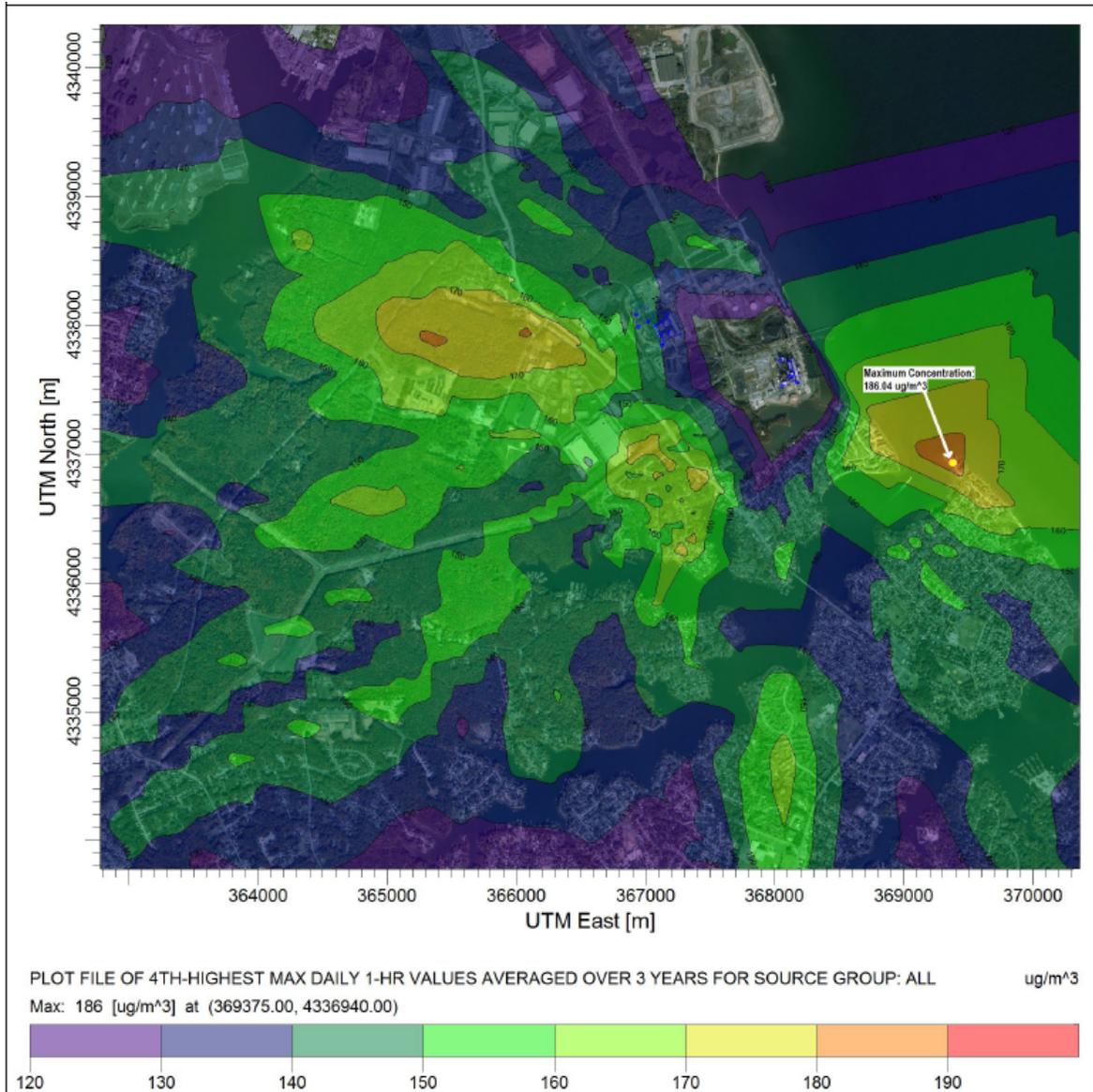


Figure 4-13: 99<sup>th</sup> percentile SO<sub>2</sub> modeling results



## **Appendix A**

### **Adjustment of Briggs Final Plume Rise Formula for Saturated Stack Exhaust**

# Adjustment of Briggs Final Plume Rise Formula for Saturated Stack Exhaust

Gary Moore, Laura Warren, and Robert Paine, AECOM

May 18, 2015

## Introduction

Wet scrubbers have been designed to remove several pollutants from combustion plumes. The wet scrubbing process acts to saturate the remaining plume gases while minimizing any liquid “drift” emerging from the scrubber. This is done in order to minimize chemically erosive processes. The scrubbing process acts to cool the plume and retard its momentum to the point where sometimes blowers must be engaged. When emitted from stacks, the plume rise is significantly reduced relative to an unscrubbed plume. Despite scrubbing, the nearby maximum surface concentrations may be modeled to be relatively high due to reduced plume rise, thus potentially requiring expensive stack modifications or reheating.

This “penalty” of wet scrubbers is overstated in modeling studies when the actual plume rise is underestimated due to a failure to treat the exiting plume as either partially or fully saturated. The heat of condensation as liquid water particles rapidly form on exit acts to make the plume gases warmer and gives the plume a “boost” in its buoyant vertical velocity. Some of the plume rise “boost” is lost as the droplets eventually evaporate on mixing. However, the heating/cooling process, like that of an updraft in a cloud, is asymmetric and in the bulk sense a net gain in plume rise is realized. The largest net rise is realized for the situation where the ambient air itself is near saturation. The discussion below describes how this effect can be better simulated in steady-state plume models such as AERMOD<sup>1</sup> with an adjustment in the input temperature data.

## Saturated Plume Rise Formulation

Currently, the final plume rise formula in air quality models like that of AERMOD is based on the assumption of a “dry” plume, where the chimney plume is far from being saturated and carries no liquid water load. Ad hoc arguments<sup>2</sup> have been made that the increase in final rise for saturated plumes is relatively small and is not worth pursuing. However, in some cases, small increases in plume rise can be beneficial and are sometimes important.

The objective of this study to provide a method whereby adjustments can be made to “recover” the currently unaccounted buoyant rise “boost”. This is done by using a moist plume rise model (IBJpluris<sup>3</sup>) that, on review and evaluation, has been found to accurately predict the final rise of an initially saturated plume. The model is exercised for the traditional “dry” conditions and then is exercised for a moist plume. If the environment the plume rises through is identical for both a dry and wet plume then a reasonable assumption is that:

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<sup>1</sup> [http://www.epa.gov/ttn/scram/dispersion\\_prefrec.htm#aermod](http://www.epa.gov/ttn/scram/dispersion_prefrec.htm#aermod).

<sup>2</sup> Personal communication from Dr. Jeffrey Weil to Robert Paine, 2015.

<sup>3</sup> Available at <http://www.janicke.de/en/download-programs.html>.

$$[\Delta h_{wet}(aermod)]/[\Delta h_{dry}(aermod)] = [\Delta h_{wet}(IBJpluris)]/[\Delta h_{dry}(IBJpluris)] \quad [1]$$

The dry and moist IBJpluris plume rise estimates are used to scale the dry rise estimated by AERMOD so that it will provide an equivalent moist rise as that estimated by IBJpluris (Janicke and Janicke, 2001). The approach assumes that the scaling ratio defined by eq 1 is independent from changes in wind speed and stability although the variations in rise may be rather large. This assumption is reasonable since the rise is functionally related to the sum of exiting buoyancy and vertical momentum fluxes and the difference between dry and moist rise depends mainly on buoyancy, which is primarily temperature and relative humidity dependent. Since the plume rise formulation in AERMOD is not an integral plume model, variations in the vertical profiles of relative humidity, lapse, and wind speed are expected to have minimal impact on the scaling defined by eq 1. An exception to this view may occur if the plume rises into an atmosphere with a vertical temperature profile that is divided into two layers by an abrupt change in stability.

Using typical environmental profiles, the scaling ratio can be applied if the ambient environment's influences on plume potential energy generation due to buoyancy are accounted for. The initial model development assumes near-neutral conditions with a relative humidity that is constant with height. When a plume exits a stack in a saturated state with little or no liquid water droplets, it has a greater potential energy than a plume that is dry, owing to the heat of condensation. Later as the plume is diluted and cools, evaporation takes back some of the energy gain. The net, however, is a gain in plume rise. Moist unsaturated plumes which exhibit a condensate plume also gain some rise as well due to condensation.

The rising plume, by analogy, can be treated as if it were a rising moist thermal and cloud dynamic process. Concepts such as the buoyancy factor<sup>4</sup> (Jacobson, 2005) can be applied since this same buoyancy factor appears in the Briggs dry plume rise. The major difference is that the cloud buoyancy depends on the virtual temperature, which depends on temperature, pressure and relative humidity (RH) of both the plume and the environment. Operationally, it will be shown that the implementation of this technique can be made with only plume temperature adjustments must be made rather than changing both plume and ambient temperatures, which would be required if virtual temperature is used directly. This revised plume temperature is called an "equivalent temperature", and it is always greater than or equal to the original plume temperature, and it does not equal the virtual temperature. This hourly equivalent plume temperature can be input to AERMOD on an hourly basis so that the moist plume rise boost is accurately specified.

The PLURIS model is described by Janicke and Janicke (2001). Its formulation includes a general solution for bent-over moist (initially saturated) chimney plumes. The model was reviewed<sup>5</sup> by Presotto et al. (2005) which indicated that despite a number of entrainment formulas available, IBJpluris possessed the physical capability of representing the impacts of heat of condensation on symmetric chimney plume rise. This model can serve as the basis for developing and applying a simple adjustment method to the standard Briggs (1975) plume rise formula used by AERMOD to account for thermodynamic modification of plume rise. In this section, we summarize the application of the model and how it is applied for use in plume rise adjustment.

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<sup>4</sup> Jacobson, Mark Zachary (2005). *Fundamentals of Atmospheric Modeling*, 2nd Edition, Cambridge University Press. ISBN 0-521-83970-X.

<sup>5</sup> Presotto, L., R. Bellasia, and R. Bianconi, 2005. Assessment of the visibility impact of a plume emitted by a desulphuration plant. *Atm. Env.*, Vol 39:719-737.

**Formulation of Saturated Plume Rise Adjustment**

The proposed approach builds off the work done on cloud formation dynamics. A thorough mathematical treatment of cloudy air is given in Jacobson’s text book<sup>4</sup> in section 9.5. The key physical idea is that the heat of condensation provides an initial boost in vertical acceleration due to buoyancy. The buoyancy factor for both wet plume and cloud water is given as normalized density:

$$F_b = (\rho_a - \rho_p)/\rho_p = [T_{vp} - T_{va}]/T_{vp} + [P_a - P_p]/P_p \approx (T_p - T_a)/T_a \text{ when } T_v = T \tag{2}$$

The approximate term appears in Briggs final plume rise formula for the dry buoyancy flux term,  $F_b$ . The final rise  $\Delta H_f$  is a power law function of the  $F_b$ , where the power is one third as derived by Briggs (1975).

Following Jacobson, the moist buoyancy can be expressed in terms of the virtual temperatures and water vapor partial pressures of the plume, (p), and the ambient environment, (a), as  $T_v(a)$ ,  $T_v(p)$ , and  $P_a$ ,  $P_w(a)$ ,  $P_w(p)$ , where  $P_w(p)$  is assumed to be saturated,  $P_s$ . The virtual temperature  $T_v$  can be expressed in terms of dry bulb temperature as:

$$T_v = T(1 + 0.608q_v) = T[1 + 0.608(0.622(RH)P_s)/(P_{da} + 0.622(RH)P_s)] \tag{3}$$

where  $P_{da}$  is the dry atmosphere pressure, RH is relative humidity as a fraction and  $P_s$  is the partial pressure of water vapor at saturation. When water vapor is present, the virtual temperature is always larger than the dry bulb temperature, T. Table 1 illustrates this for several temperatures. This table shows that as the saturated plume temperature increases, so do the effects of virtual temperature (very substantially for higher stack temperature and relative humidity).

**Table 1. Virtual temperature as a function of the dry bulb temperature and relative humidity.**

RH (%)	Virtual Temperature (deg K)		
	$T_a = 290 \text{ deg K, RH} = 0\%$	$T_a = 325 \text{ deg K, RH} = 0\%$	$T_a = 360 \text{ deg K, RH} = 0\%$
25	290.52	329.04	378.97
50	291.04	332.92	394.91
75	291.56	336.64	408.50
100	292.08	340.22	420.21

A general formula is used for estimating the saturation vapor pressure of water, and is of the form:

$$P_s = 6.112 \exp [6816 ((1/273.15) - (1/T)) + 5.1309 \ln (273.15/T)] \tag{4}$$

where all pressures are in millibars (mb). The relative humidity of a plume is estimated from the moisture content (%) at the plume exit temperature. For example, a moisture content of 10% implies an approximate water vapor pressure of 100 mb. At 325 deg K, the saturation vapor pressure is 134.24 mb. This would suggest that such a plume is sub-saturated. The IBJpluris model has the ability to treat sub-saturated plumes as long as the plume emission temperature is held constant. Using eq 4 and the moisture content of the exiting plume, the relative humidity of the plume can be estimated. Although the exiting plume flux is sub-saturated, the plume rise gain can still be estimated.

There is one other effect that comes into play and that is the role of relative humidity on the adiabatic processes involved in moving the rising plume from one pressure level to another. The moist adiabatic rate is less steep than the dry adiabat with the neutral lapse rate being about 6 deg K per kilometer for the moist adiabat rather than 9.8 deg K per kilometer for the dry adiabat. As the ambient air retains more

moisture, the plume travels higher before reaching equilibrium with the ambient air. As a result, like a rising cloud element, the final rise of an initially wet plume in a moist environment increases with increasing ambient humidity rather than decreasing. However, accounting for this effect requires estimating the virtual temperature at two elevations rather than one. Such an approach is currently beyond the scope of the present study.

### **Algorithm for Use in a “Dry” Model**

The scaling relation based on the right hand side of equation (1) forms the first part of the adjustment model. The plume height scaling parameter is given by the moist over the dry buoyancy fluxes:

$$\beta = (\Delta h_w^3 / \Delta h_d^3) \quad [5]$$

where subscripts w and d refer to moist and dry buoyancy fluxes, respectively.

The second part involves solving for the equivalent plume temperature for use by a “dry” model like AERMOD that describes the difference in the final plume rise due to heat of condensation, water vapor pressure excess, and the increased rise due to a moist rather than a dry adiabat. There are two equations and two unknowns. The two equations relating final rise to equivalent plume and ambient temperature are:

$$\Delta h_d^3 = \lambda F_{bd} = \lambda [(T_p - T_a) / T_p] \quad [6]$$

$$\Delta h_w^3 = \lambda F_{bw} = \lambda [(T_p^{eq} - T_a) / T_p^{eq}] \quad [7]$$

A buoyant rise exponent of  $p = 3$  is due to the fact that the Briggs final buoyant plume rise depends on  $F_b$  to the one third power. However, Briggs final momentum rise depends upon the momentum flux to the 1.5 power. Therefore, due to the role of both momentum and buoyancy in the final plume rise, as the vertical momentum flux becomes a larger fraction of the total flux, the exponent for the total plume rise would be expected to become smaller than 3. The exponent can be treated as a user input in order to be conservative ( $p < 3$ ) when the total plume rise may have appreciable momentum at release. A smaller exponent such as 2.5 would insure that the model is always conservative and the plume rise is not overstated. The coefficient of rise,  $\lambda$ , can be arithmetically removed. The  $\beta$ s are determined through two IBJpluris exercises, dry and moist, as indicated previously by eq 1. The equivalent plume temperature  $T_p^{eq}$  can be solved for directly as:

$$T_p^{eq} = T_p T_a / [(1 - \beta) T_p + \beta T_a] \quad [8]$$

The ratio,  $\beta$ , is a function of both humidity and temperature and is found by the dry and moist IBJpluris simulations. As  $\beta$  goes to 1, the equivalent plume temperature approaches the dry plume temperature,  $T_p$ .

In order to model this relationship, a simple interpolation bilinear model was constructed using a series of  $\beta$ 's across a range of temperature and relative humidity. At the endpoints of each range, the value of  $\beta$  is calculated using IBJpluris. This information can be expressed as a Taylor first-order expansion to create a bilinear model for the wet to dry ratio of plume rise within each ambient temperature range. This model takes the form:

$$\beta(T_a, RH_a) = \beta(T_o, RH_o) + (T_a - T_o) \Delta\beta(T_o, RH_o) / \Delta T_a + (RH_a - RH_o) \Delta\beta(T_o, RH_o) / \Delta RH_o \quad [9]$$

where the subscript, o, denotes the minimum value of each temperature range in  $\beta$ -space. Currently, the model assumes that ambient air at stack exit will be in the range between -20 degrees C and 40 degrees C (253 - 313 degrees-K). Ambient temperatures outside of this range are clipped. The relative humidity

is assumed to lie between 0% and 95%. Values above 95% RH lie in a range of extreme sensitivity to conditional instability and the RH is therefore clipped at 95%.

The IBJpluris model is exercised in both dry and wet mode for each range and an array of N by M  $\beta(T_i, RH_j)$  ratios is saved for each stack that is modeled. These are used to estimate the model sensitivity coefficients as:

$$C_{i,j} = [ \beta_{i+1,j} - \beta_{i,j} ] / [ T_{i+1} - T_i ] \quad [10]$$

$$D_{i,j} = [ \beta_{i,j+1} - \beta_{i,j} ] / [ RH_{j+1} - RH_j ] \quad [11]$$

The continuous model for the moist to dry plume rise ratio becomes:

$$\beta(T_a, RH_a) = \beta(T_i, RH_j) + (T_a - T_i) C_{i,j} + (RH_a - RH_j) D_{i,j} \quad [12]$$

The  $\beta(T_a, RH_a)$  are used in eq 8 to estimate the equivalent plume temperature for AERMOD for each hour of emissions. By modifying only the plume temperature, multiple sources, each with their own equivalent temperature, can be exercised each hour at the same time in AERMOD.

### **Moist Plume Modeling**

After a literature review, we selected the IBJpluris-2.7 model for use as a wet plume rise model. Technical details of the model are described in Janicke and Janicke (2001). Details of model implementation are provided in the AERMOIST User's Guide.<sup>6</sup> This moist plume rise model was exercised for a typical saturated, scrubbed power plant, with characteristics as listed in Table 2.

**Table 2. Test saturated plume source that was modeled.**

Stack Height (m)	Exit Diameter (m)	Exit Temperature (K)	Exit Velocity (m/s)
171.45	14.23	325.37	15.16

The exiting plume moisture content for this test case is 13.4% and for a surface pressure of 1000 mb  $P_s = 134$  mb which, according to equation 8, translates into a saturated plume ( $RH_{plume} = 100\%$ ) for an observed stack temperature of 325 deg K. Table 1 suggests that such an observed temperature (dry bulb) equates to nearly 340 deg K in terms of the virtual temperature for the saturated plume.

Details of the IBJpluris model including example tables and file contents can be found in the User's Guide for AERMOIST. IBJpluris requires two user supplied input data files. The first input file is a control file that specifies how the model is to be exercised and the stack parameters of the source. A second file contains the vertical profile of environmental meteorology. The profile assumes neutral conditions with a height constant humidity and turbulence profile, although these may be changed if the user has good local profile data according to instructions in the User's Guide.

For a given environmental humidity value, the plume itself was modeled with initial dry humidity (0%) and a moist humidity based on the moisture content of the plume. A set of environmental RH values that were modeled are typical 0%, 25%, 50%, 75%, 85%, 90%, and 95% (again - more ranges and different endpoints can be supplied by the user).

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<sup>6</sup> AECOM, 2015. AERMOIST v1.3 and IBJPLURIS v2.7 User's Guide, AECOM 250 Apollo Drive, Chelmsford, MA 01824.

The resulting plume rise as a function of downwind distance are illustrated for the dry (0% plume RH) and the saturated (100% plume RH) plume cases in Figure 1. The ambient humidity is assumed to be dry (0% ambient RH). The figure illustrates the impact of the condensation heating adding to the buoyancy. The third curve presents the increase in rise when a saturated plume is emitted into a nearly saturated environment. The rise at 2000 m downwind is 189.8 m for the dry plume and dry environment, 209.3 m for a saturated plume in a dry ambient environment, and 219 m for the saturated plume rise in a 90% constant RH environment. The percent boost over the dry case is 10.3 % and when a moist environment is considered, it is 15.4%.

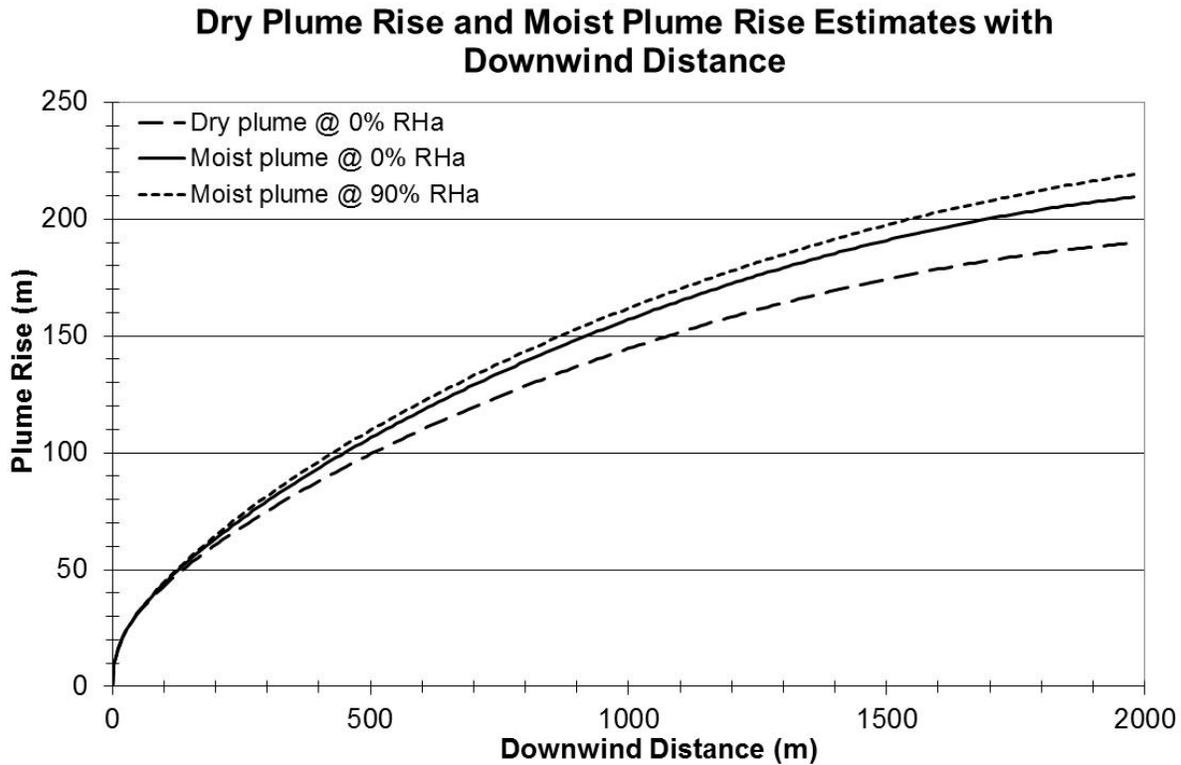
AERMOIST systematically exercises IBJpluris for each of the temperatures and relative humidity ranges (bins). An example of the final rise estimates at 2000 m downwind are presented in Table 3 for a select set of temperature and relative humidity ranges. The results indicate that the largest rise of the saturated plume occurs at 90% humidity environmental conditions for the cooler ambient temperatures. The humidity dependency of final rise at any temperature is rather small for a dry plume. Therefore, like other modelers have done, it makes sense to ignore the RH dependency for dry plumes.

However, for moist plumes, the plume rise increases rather abruptly as the ambient humidity approaches saturation with an increase of over 10% from dry, cool air to moist cool air. Using virtual temperature by itself does not explain this effect when looking at a table of plume and ambient virtual temperature, as illustrated in Table 3. As the ambient temperature warms and the buoyancy factor decreases, the change in plume rise with humidity is reduced. When the environmental air becomes warmer (>308 deg K), the difference in the rise between dry and wet cases actually becomes fractionally larger under saturated conditions with the saturated plume rising more than 22% than the dry rise case for the test case source.

**Table 3. Plume rise estimates at 2000 m downwind as produced by IBJpluris-2.7 under neutral conditions and test case stack emission parameters (original temperature and RH ranges).**

Dry Bulb		Plume Rise Height at Select Ambient RH Profiles (m)				
Temperature	Plume State	0%	25%	50%	75%	90%
273 deg K	dry	214.5	214.9	215.4	215.8	216.1
	wet	227.7	228.8	230.6	240.2	271.1
278 deg K	dry	209.2	209.6	210.1	210.5	210.8
	wet	223.4	224.2	225.4	229.5	256.0
283 deg K	dry	203.4	203.9	204.4	204.9	205.2
	wet	219.0	219.7	220.7	223.0	242.8
288 deg K	dry	197.0	197.6	198.1	198.7	199.0
	wet	214.3	215.1	216.0	217.5	230.3
293 deg K	dry	189.8	190.4	190.9	191.5	191.8
	wet	209.3	210.2	211.1	212.2	219.0
298 deg K	dry	181.8	182.2	182.6	182.9	183.1
	wet	203.9	204.9	205.7	206.7	209.4
303 deg K	dry	172.5	172.6	172.5	172.3	172.2
	wet	198.0	198.9	199.7	200.5	201.3
308 deg K	dry	161.6	160.7	159.6	158.2	157.2
	wet	191.5	192.2	192.7	193.1	193.3

**Figure 1. The plume rise as a function of downwind distance for dry rise and an initially saturated plume (test source) under two constant relative humidity environmental conditions.**



Using the equivalent plume temperature,  $T_p^{eq}$ , an empirical prediction can be made that will act as a surrogate for moist plume rise. All of this is done operationally by using the IBJpluris model to compute the ratio,  $\beta(T,RH)$ , of wet over dry rise and then modeling that ratio so as to not require the resources and inconvenience of running IBJpluris for each hour and injecting the results into AERMOD. The hourly  $T_p^{eq}$  input into AERMOD represents one of the best and most direct ways to introduce the added moist rise.

**Evaluation of AERMOIST**

An important evaluation step was to compare the rise predicted by the ‘ $\beta$ ’ approximation with the original IBJpluris moist modeled rise. To do this, a randomly sampled subset of the AERMOD modeling run hours was used to exercise IBJpluris. Four simulations were conducted on each sampled hour including:

- Dry plume rise representing the Briggs estimation in a current AERMOD simulation,
- Virtual temperature adjusted plume temperature rise (constant with time),
- Hourly adjusted plume temperature using the  $T_p^{eq}$  estimate developed from the model for the plume rise ratio beta,  $\beta$  and equation (8), and
- Moist plume rise using the actual degree of plume moisture content (% of exhaust mass) quoted off engineering sheets to estimate the plume relative humidity on exit.

The evaluation exercise provides a set of several hundred evaluation hours on which various statistical and graphical comparisons can be made.

The most direct comparison, looking for a linear prediction versus observation-model relationship, was to produce a scatter plot (Figure 2) of the IBJpluris moist plume rise against the dry IBJpluris model prediction made using the  $T_p^{eq}$ , which represents AERMOIST. A sample set of 439 hours of  $T_p^{eq}$  estimates was used along with hourly observed dry bulb temperature and ambient surface relative humidity for the source described by Table 2. Figure 2 indicates a good linear relationship (reduction of variance is 98%) with a slight under prediction (slope < 1). The groups of points lying significantly in under prediction space are hours when the ambient relative humidity is >95%. The surface relative humidity is clipped at 95% in the current model application leading to an overly conservative estimate of plume rise. The slope is also affected by what appears to be a group of slight over predictions of plume rise by AERMOIST. This can be noted more clearly by a scatter plot of the residuals,  $\Delta H = [H_w - H(T_p^{eq})]$  displayed in Figure 3.

The residuals show that most of the hours under predict the IBJpluris moist plume rise estimate with a group of smaller rises being over predicted. This feature makes the residuals a nonlinear function of plume rise (quadratic polynomial) as displayed in Figure 3. The systematic bias in the residuals as a function of rise magnitude explains more than 78% of the remaining variance. In Briggs (1984)<sup>7</sup>, there is a discussion of when the '2/3' law gives way to the '1/3' law. As a result, it is likely given the mix of jet and convective rise characteristics that the actual value of the exponent,  $p$ , is likely to be less than 3, but well above 1.5 for buoyancy-dominated plumes. In order to test this to see if this represents a simple way to avoid over prediction estimates of adjusted equivalent plume temperature, the plume rise was estimated using an exponent of  $p = 2.5$ .

Other investigators<sup>8</sup> have received EPA approval to utilize the stack exit gas virtual temperature rather than dry bulb temperature to more accurately model a moist plume rise. While this increases the effective stack temperature due to moisture (and hence the plume rise), such a model does not account for variations in environmental virtual temperature. Table 3 indicates that in the limit as the ambient air becomes saturated, the plume rise increases for cooler conditions. This would indicate that virtual temperature should be used for the ambient air. However its use reduces the gain in plume rise introduced by the plume temperature increase. Furthermore, it requires that the ambient temperatures would need to be modified in the AERMOD's meteorological input files. A sensitivity test to determine whether over predictions of plume rise occur was to increase the stack gas exit temperature to be virtual temperature, and compare with the other three plume rise estimates.

A box and whisker plot of the plume rises and residuals from this comparison are presented in Figure 4. This plot shows that the plume virtual temperature alone does not match the largest 10% of moist plume rises. It does however do a credible job for predicting the smallest 50% of plume rises. The AERMOIST model does considerably better than  $T_{vp}$  at predicting the larger plume rise. It does, however over predict slightly with an exponent ( $p$ ) value of 3.0. When  $p = 2.5$  is used, the model performance is about the same, but the over predictions (negatives) are avoided as shown in Figure 5.

The changes in the  $T_p^{eq}$ -derived plume rise are more subtle as depicted in the histogram plots of the equivalent plume temperatures in Figure 6. In this figure, we note that the large extremes in the equivalent temperature are reduced while, at the same time, the number of smaller equivalent

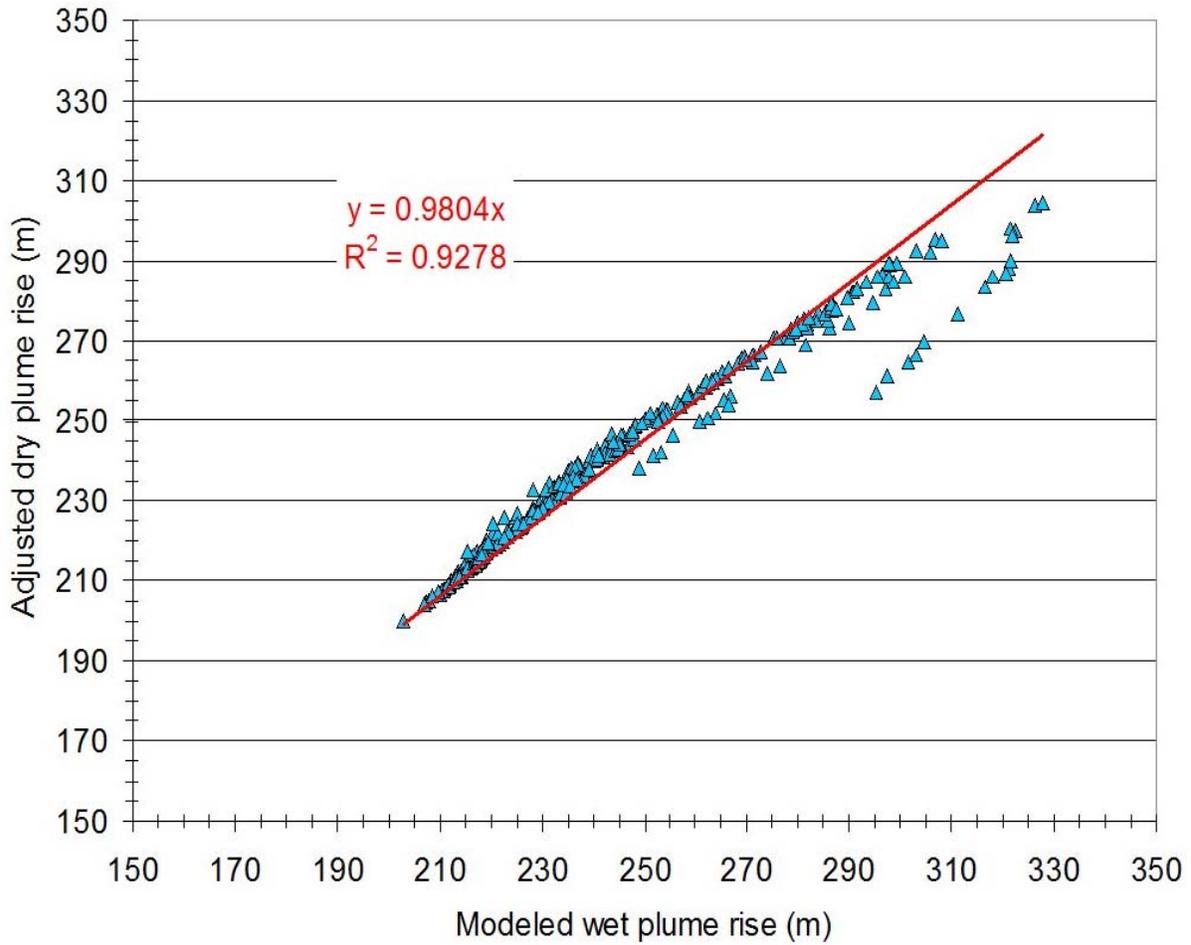
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<sup>7</sup> Briggs, G. A., 1984. Chapter 8: Plume Rise and Buoyancy Effects, *Atmospheric Science and Power Production* edited by D. Randerson, Technical Information Center, Office of Scientific and Technical Information, United States Department of Energy.

<sup>8</sup> Personal communication of John Jansen, Southern Company to Robert Paine, 2015.

temperatures increases. This is equivalent to making the typical plume exit temperature look more like one is using virtual plume temperature while simultaneously providing a response when other environmental variables change.

**Figure 2. Scatter plot of the moist plume IBJpluris estimated plume rises versus those made using equivalent plume temperature,  $T_p^{eq}$ , as input to a dry version of the IBJpluris plume.**



**Figure 3. Scatter plot of the moist plume IBJpluris estimated plume rises versus the difference,  $\Delta H = [H_w - H(T_p^{eq})]$ , of the moist plume rise minus the equivalent plume temperature using a dry plume IBJpluris estimated plume rise.**

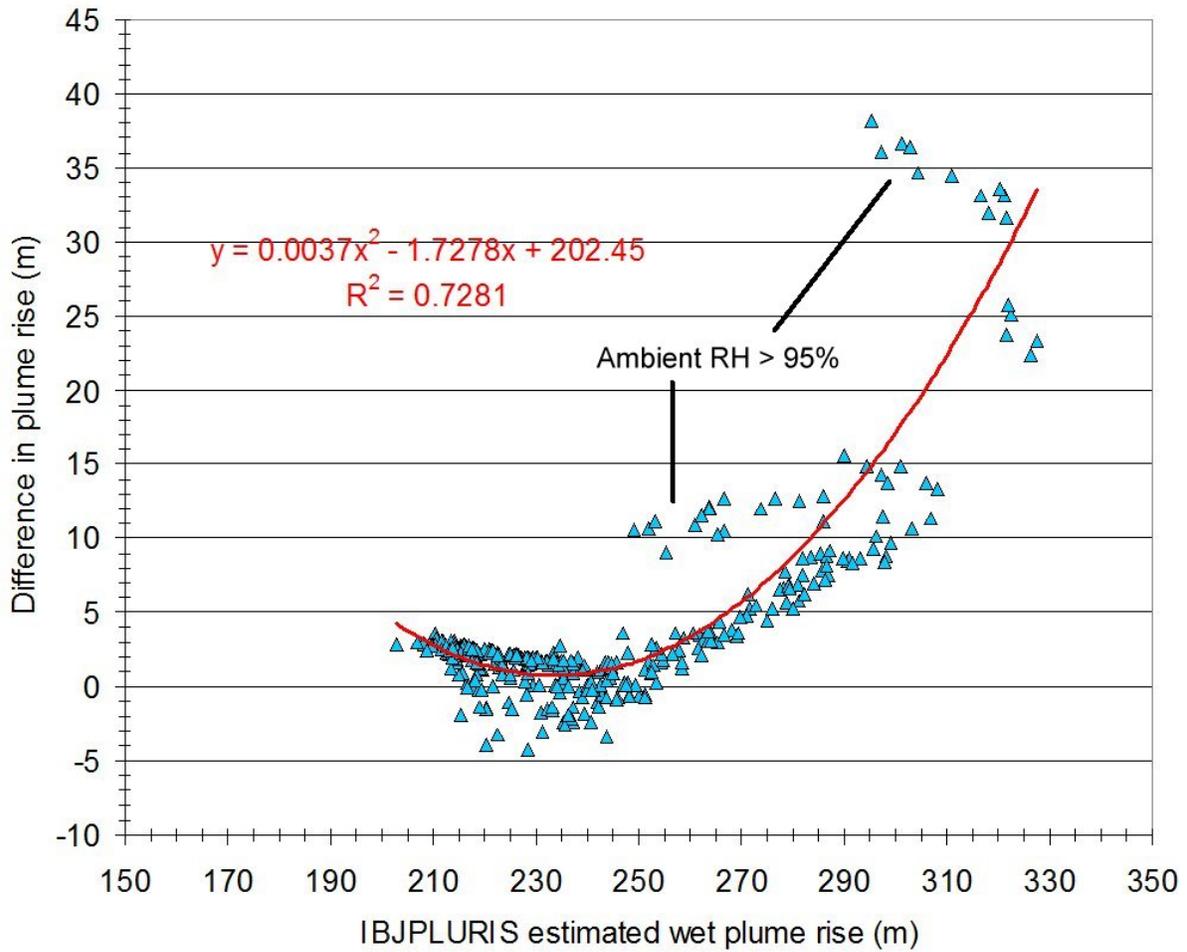


Figure 4. Box and whisker plot of the 438 hourly samples of plume rise using  $p = 3$  for four plume rise estimate techniques along with differences between full moist plume rise and the three other estimators including the two AERMOIST rises ( $H_{Tpeq}$ ).

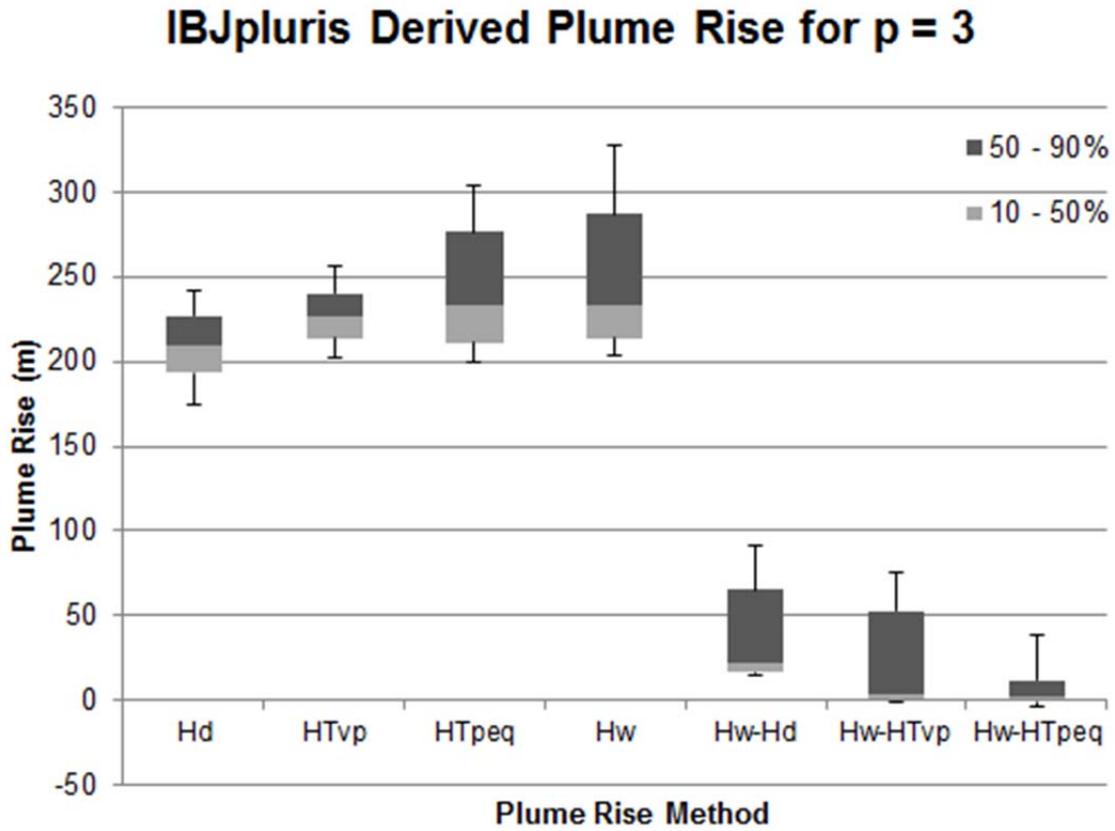


Figure 5. Box and whisker plot of the 438 hourly samples of plume rise using  $p = 2.5$  for four plume rise estimate techniques along with differences between full moist plume rise and the three other estimators.

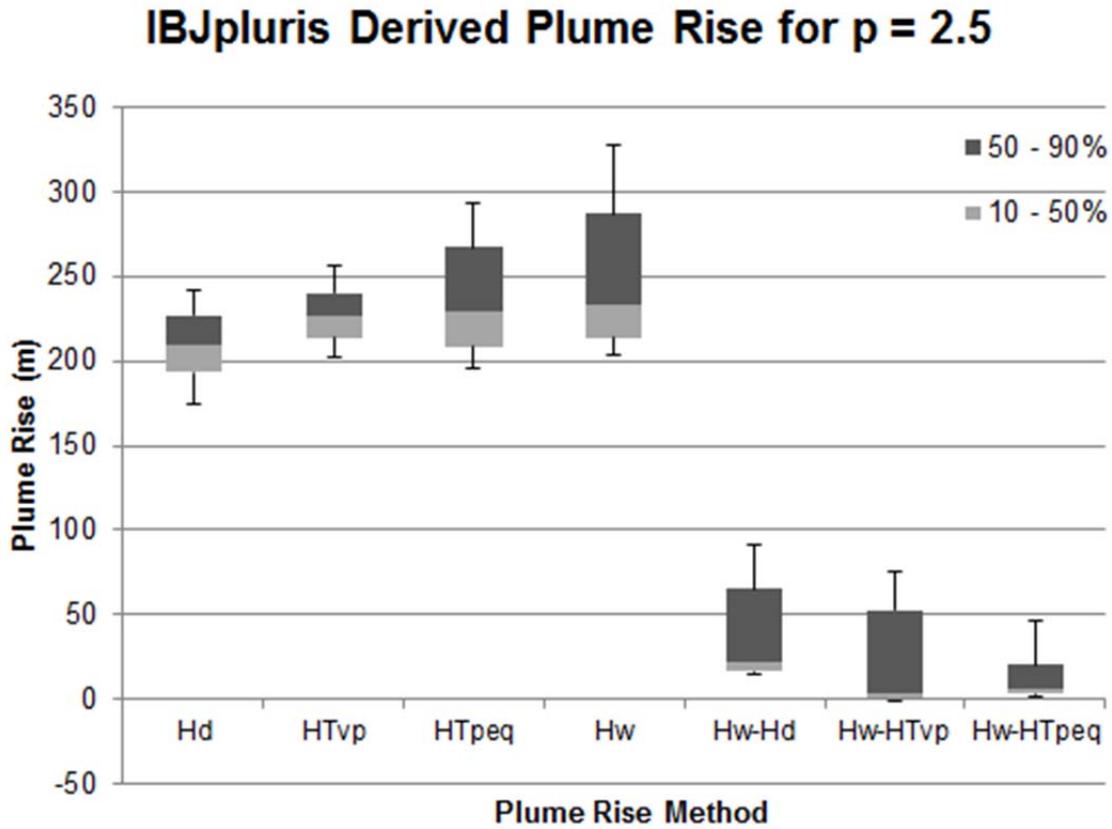
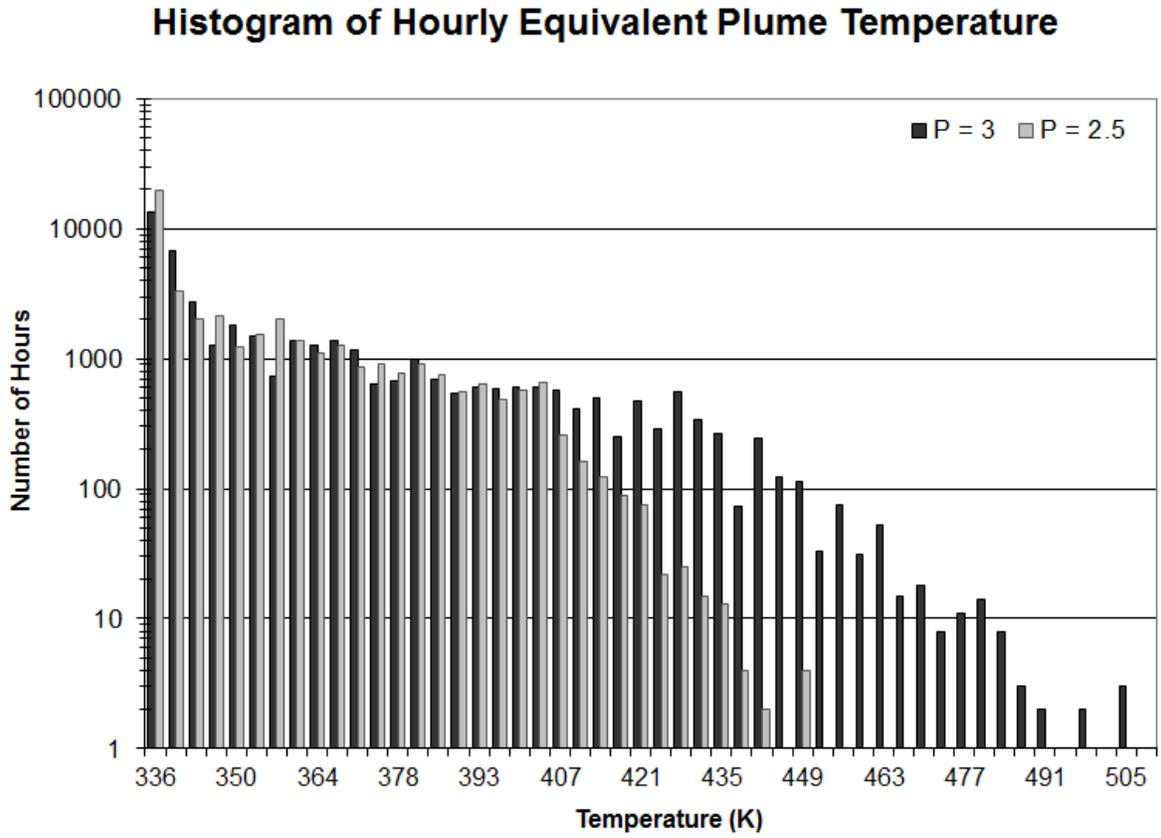


Figure 6. Histogram of hourly equivalent plume exit gas temperatures for 5 years of meteorological data.



## **Evaluation of Two Methods for Moist Plume Rise Adjustment in the AERMOD Modeling System**

There are a few limitations to be aware of for the AERMOIST modeling approach. First and foremost is the assumption that IBJpluris is accurate and generally conservative in predicting moist plume rise. The second is that the model is run for idealized vertical profiles of meteorology and that the moist-to-dry plume rise ratio, beta, does not significantly vary with the vertical profiles of meteorology as used by AERMOD. It is also assumed that the ratio is not affected by wind speed, temperature, and RH vertical gradients since the same U, T, RH profiles are used in the wet and dry applications.

Three test AERMOD simulations were performed for this evaluation analysis. The first AERMOD exercise applied just the dry rise formulation for estimated hourly final plume rise. As noted earlier, the plume virtual temperature has been used and accepted by regulatory agencies and thus should be included in any AERMOD model performance evaluation. In our test example, the plume exit gas temperature (constant) was increased to 340 deg K from 325 deg K, and AERMOD was exercised. In the third and fourth AERMOD exercises, a file with hourly adjusted equivalent plume temperature,  $T_p^{eq}$ , was supplied based on an exponent  $p$  equal to 2.5 and 3, respectively.

The resulting observations versus AERMOD predictions are displayed via a quantile-quantile plot using modeled plume temperatures versus the original plume exit temperature. A quantile-quantile (q-q) plot for the AERMOD predicted concentrations for the highest concentration receptor are shown in Figure 7. In this figure, it can be noted that the virtual temperature provides the smallest change (decrease) in the ground-level receptor concentration. The reduction for the highest concentration is only 6-7%. The other extreme is the AERMOIST  $T_p^{eq}$  estimator with a power law of 3 which indicates a reduction of 41-42% in the peak concentration. The intermediate power law of 2.5 provides a reduction of 33-34% while insuring that the wet rise is not overstated. For the 4<sup>th</sup> highest predicted concentration at this receptor, the difference between the power law exponents is reduced, leaving only the virtual temperature as an outlier. The AERMOIST processor gives a reduction of 25-26% in concentration while the virtual temperature gives a reduction of only 11-12%.

A similar behavior in the concentration predictions made by AERMOD is shown at other receptors. The q-q plot for the 4<sup>th</sup> highest concentration receptor is displayed in Figure 8. This figure shows that the differences in ground-level concentrations between the various plume exit temperatures has the same relation for the highest concentration as for the prior receptor displayed in Figure 7. The major difference is that at the 4<sup>th</sup> highest predicted concentration, there is still a significant difference between the predicted concentrations for the 2.5 and 3 power law exponent cases with the  $p = 2.5$  providing the intermediate ground-level concentration estimate.

Figure 7. A quantile-quantile plot of AERMOD predicted ground level concentrations at the receptor where the highest concentrations for the point source example occur.

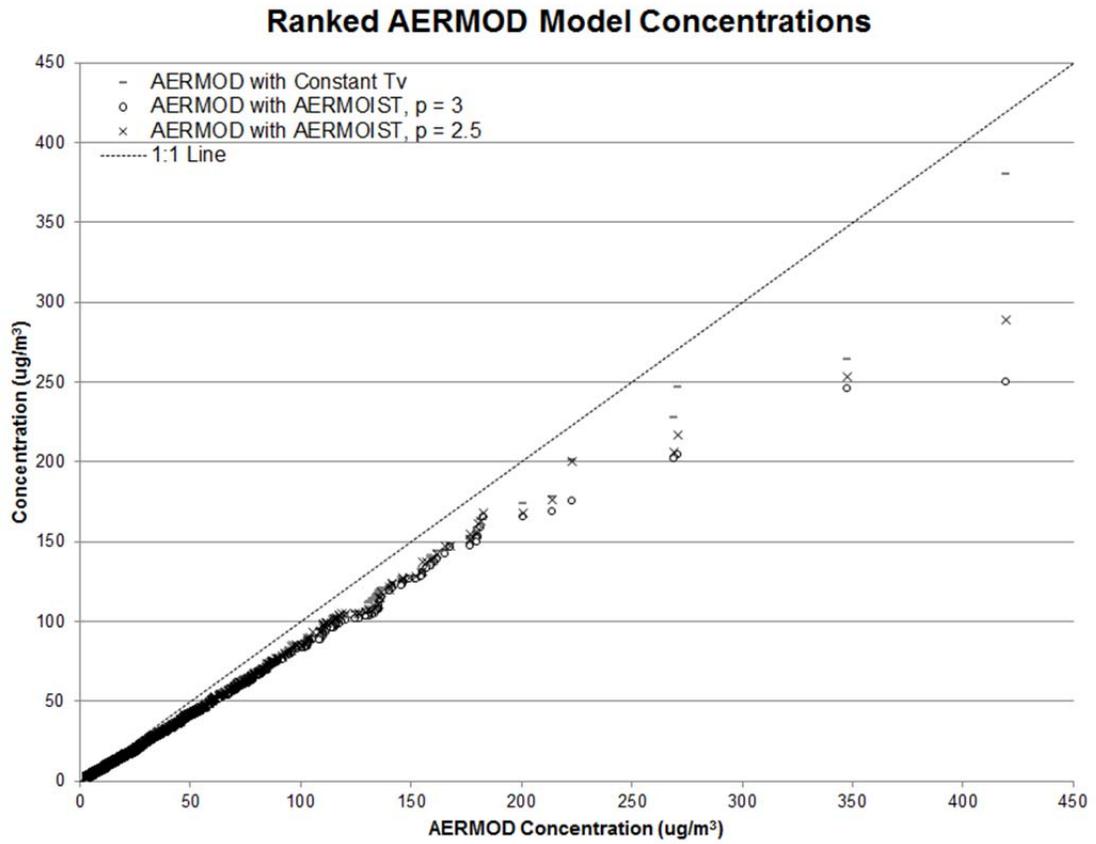
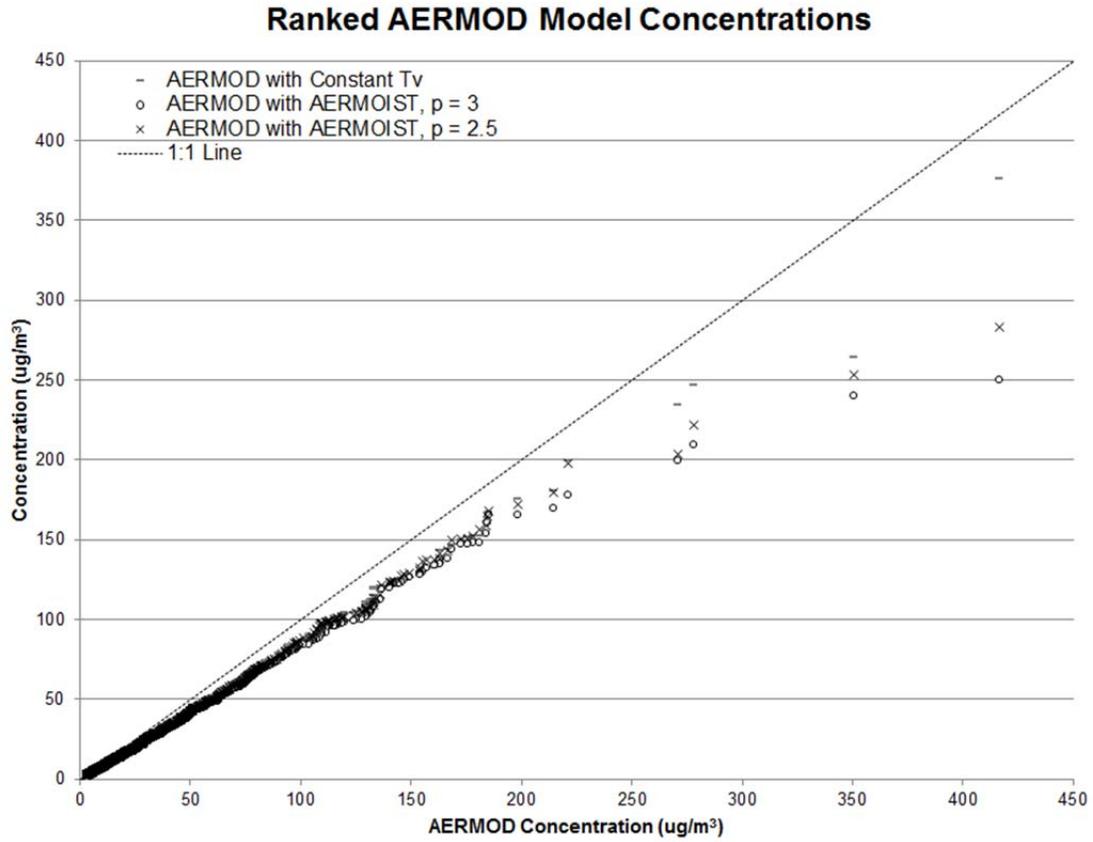


Figure 8. A quantile-quantile plot of AERMOD predicted ground level concentrations at the receptor where the fourth highest concentrations for the point source example occur.



## Summary and Conclusions

In this document, we describe a method by which the under prediction of moist plumes made by AERMOD may be externally addressed. Moist parcel thermodynamics are described and the simplistic use of virtual rather than actual plume exit temperature is discussed. This virtual temperature method fails to account for the thermodynamic efficiency of latent heat buoyancy production as the relative humidity and temperature of the ambient environment changes. This environmental dependency requires hourly ambient meteorology and a fully consistent moist plume set of dynamic equations in order to accurately estimate the additional final plume rise that can be obtained from the net latent heating buoyancy production.

The IBJpluris model version 2.7 by Janicke and Janicke (2001) was reviewed and selected as a technically complete and evaluated plume rise model to make estimates of Briggs (1984) equivalent moist and dry plume rise. This model was applied to estimate the ratio of dry to moist plume rise. A derivation is presented which relates the ratio, the ambient surface temperature and relative humidity, and the plume exit temperature to an equivalent plume exit temperature. The equivalent temperature is designed to reproduce the IBJpluris moist plume rise as a function of its dry plume rise.

A pre-processor called "AERMOIST" has been developed with uses a bivariate linear temperature and relative humidity fit of the moist to dry ratio plume rise ratio. A modest set of RH values and temperatures are used as points from which the linear piece-wise is used to interpolate the plume rise ratio to hourly observed ambient RH and temperature. This model accounts for the ever changing sensitivity of plume rise with the exception of days when the environment is so moist (RH > 95%) that instability can occur and a plume lifts to the cloud condensation level. This condition is avoided by truncation of the ambient RH to 95%.

An analysis was made of the plume rise for a typical large, scrubbed stack plume that is fully saturated. A set of temperature and RH ranges were used by the AERMOIST processor to automatically build a stack-specific wet plume rise model based on IBJpluris predictions. These were used to develop hourly equivalent plume temperatures for use direct use by AERMOD. The AERMOIST processor has an evaluation process that compares several hundred final plume rise estimates made by:

- $H_d$  - Dry IBJpluris with original plume exit temperature
- $H_{Tv}$  - Dry IBJpluris with plume constant exit virtual temperature
- $H_{T_{peq}}$  - Dry IBJpluris with equivalent plume temperature using  $p = 3.0$
- $H_{T_{peq}}$  - Dry IBJpluris with equivalent plume temperature using  $p = 2.5$
- $H_w$  - Moist plume model (IBJpluris)

A series of statistical metrics was estimated including linear models of the dry plume rise estimates versus the moist estimates. The results found that:

- The linear model slope for the  $p = 3$  model has an R squared of 0.93 and a slope of 0.98 against the moist plume model.
- The residual differences of  $H_w - H_{T_{peq}}$  display a curvilinear relation with outliers corresponding to hours when the RH is truncated to 95%.
- The box whisker plots indicate that the  $p = 2.5$  case retains most of the plume rise increase without producing plume rises greater than the wet model.
- For the  $p = 3$  case, the AERMOIST algorithm produces some rather large equivalent plume temperatures at the extreme tail of the histogram.

These direct plume rise comparisons suggest that the  $p = 2.5$  case seems to offer the best model for the equivalent plume temperature.

A direct comparison of AERMOD ground-level concentrations was made for a 5-year run of the example source. The q-q plots presented suggest that for the largest concentrations at a receptor, the  $p=2.5$  appears to give significant reduction of the ground-level concentration over the use of just the virtual temperature. While the  $p = 3$  provides a larger reduction in surface predicted concentration, there is no guarantee that overall reduction retains a conservative tendency.

## **Appendix B**

### **Alternative Model Justification for EPA-Proposed Low Wind Options in AERMET and AERMOD Version 15181**

**Alternative Model Justification for Low Wind Speed Beta Options:  
AERMET and AERMOD**

Appendix W, Section 3.2.2 provides an approach for approval of an alternative model to determine whether it is more appropriate for this modeling application. The principle sources involve tall stack buoyant releases.

EPA indicates that for this purpose, an alternative refined model may be used provided that:

1. The model has received a scientific peer review;
2. The model can be demonstrated to be applicable to the problem on a theoretical basis;
3. The data bases which are necessary to perform the analysis are available and adequate;
4. Appropriate performance evaluations of the model have shown that the model is not biased toward underestimates; and
5. A protocol on methods and procedures to be followed has been established.

These five points are discussed below.

The model selected for this modeling application is the EPA-proposed updates to the AERMOD modeling system version 15181, including the AERMET ADJ\_U\* option, combined with the AERMOD LOWWIND3 option. EPA has indicated support for these changes in the Appendix W proposal and in the Roger Brode presentation made at the 11<sup>th</sup> Modeling Conference on August 12, 2015 (see presentation at [http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5\\_Proposed\\_Updates\\_AERMOD\\_System.pdf](http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5_Proposed_Updates_AERMOD_System.pdf)).

**1. The model has received a scientific peer review**

The AERMET changes reference a Boundary-Layer Meteorology peer-reviewed paper<sup>1</sup> that is the source of the AERMET formulation for changes in the friction velocity computation for low wind speeds. The combination of the AERMET changes and the AERMOD changes (version 14134 LOWWIND2, similar to version 15181 LOWWIND3) has been evaluated and the study<sup>2</sup> will be published in a forthcoming issue of the Journal of the Air & Waste Management Association (JAWMA). The manuscript associated with the JAWMA article is provided in Appendix B. A supplemental evaluation exercise with AERMET/AERMOD version 15181 is provided in Appendix C that shows consistent evaluation results (with a slight improvement) for the proposed AERMOD modeling application.

**2. The model can be demonstrated to be applicable to the problem on a theoretical basis.**

There is no theoretical limitation to the application of the AERMET and AERMOD low wind changes – they are generally applicable. The current default algorithm in AERMET has been demonstrated to be

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<sup>1</sup> Qian, W., and A. Venkatram. Performance of Steady-State Dispersion Models Under Low Wind-Speed Conditions. *Boundary-Layer Meteorology* 138:475–491. (2011)

<sup>2</sup> Paine, R., Samani, O., Kaplan, M. Knipping, E., and Kumar, N. Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases. Pending publication (as of August, 2015) in the *Journal of Air & Waste Management Association*.

faulty and needs to be replaced by the ADJ\_U\* approach. The improvements due to the LOWWIND3 algorithm are demonstrated with the low wind model evaluations reported by the presentations<sup>3</sup> at the 11<sup>th</sup> EPA modeling conference

**3. The data bases which are necessary to perform the analysis are available and adequate.**

Routine meteorological databases that are already available are sufficient for exercising this low wind options. There are no special database requirements for the use of these options.

**4. Appropriate performance evaluations of the model have shown that the model is not biased toward underestimates.**

The studies cited above by EPA and AECOM provide this demonstration.

**5. A protocol on methods and procedures to be followed has been established.**

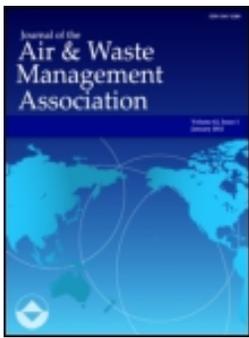
This report documents the methods and procedures to be followed.

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<sup>3</sup> [http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5\\_Proposed\\_Updates\\_AERMOD\\_System.pdf](http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5_Proposed_Updates_AERMOD_System.pdf) and [http://www.epa.gov/ttn/scram/11thmodconf/presentations/2-3\\_Low\\_Wind\\_Speed\\_Evaluation\\_Study.pdf](http://www.epa.gov/ttn/scram/11thmodconf/presentations/2-3_Low_Wind_Speed_Evaluation_Study.pdf).

## **Appendix C**

**Peer-Reviewed Paper on Low Wind  
Evaluation Study for Tall Stacks  
Published by Journal of the Air &  
Waste Management Association**



## Evaluation of low wind modeling approaches for two tall-stack databases

Robert Paine, Olga Samani, Mary Kaplan, Eladio Knipping & Naresh Kumar

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# Evaluation of low wind modeling approaches for two tall-stack databases

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*The performance of the AERMOD air dispersion model under low wind speed conditions, especially for applications with only one level of meteorological data and no direct turbulence measurements or vertical temperature gradient observations, is the focus of this study. The analysis documented in this paper addresses evaluations for low wind conditions involving tall stack releases for which multiple years of concurrent emissions, meteorological data, and monitoring data are available. AERMOD was tested on two field-study databases involving several SO<sub>2</sub> monitors and hourly emissions data that had sub-hourly meteorological data (e.g., 10-min averages) available using several technical options: default mode, with various low wind speed beta options, and using the available sub-hourly meteorological data. These field study databases included (1) Mercer County, a North Dakota database featuring five SO<sub>2</sub> monitors within 10 km of the Dakota Gasification Company's plant and the Antelope Valley Station power plant in an area of both flat and elevated terrain, and (2) a flat-terrain setting database with four SO<sub>2</sub> monitors within 6 km of the Gibson Generating Station in southwest Indiana. Both sites featured regionally representative 10-m meteorological databases, with no significant terrain obstacles between the meteorological site and the emission sources. The low wind beta options show improvement in model performance helping to reduce some of the overprediction biases currently present in AERMOD when run with regulatory default options. The overall findings with the low wind speed testing on these tall stack field-study databases indicate that AERMOD low wind speed options have a minor effect for flat terrain locations, but can have a significant effect for elevated terrain locations. The performance of AERMOD using low wind speed options leads to improved consistency of meteorological conditions associated with the highest observed and predicted concentration events. The available sub-hourly modeling results using the Sub-Hourly AERMOD Run Procedure (SHARP) are relatively unbiased and show that this alternative approach should be seriously considered to address situations dominated by low-wind meander conditions.*

*Implications:* AERMOD was evaluated with two tall stack databases (in North Dakota and Indiana) in areas of both flat and elevated terrain. AERMOD cases included the regulatory default mode, low wind speed beta options, and use of the Sub-Hourly AERMOD Run Procedure (SHARP). The low wind beta options show improvement in model performance (especially in higher terrain areas), helping to reduce some of the overprediction biases currently present in regulatory default AERMOD. The SHARP results are relatively unbiased and show that this approach should be seriously considered to address situations dominated by low-wind meander conditions.

## Introduction

During low wind speed (LWS) conditions, the dispersion of pollutants is limited by diminished fresh air dilution. Both monitoring observations and dispersion modeling results of this study indicate that high ground-level concentrations can occur in these conditions. Wind speeds less than 2 m/sec are generally considered to be “low,” with steady-state modeling assumptions compromised at these low speeds (Pasquill et al., 1983). Pasquill and Van der Hoven (1976) recognized that for such low wind speeds, a plume is unlikely to have any definable travel. Wilson et al. (1976) considered this wind speed (2 m/sec) as the upper limit for conducting tracer experiments in low wind speed conditions.

Anfossi et al. (2005) noted that in LWS conditions, dispersion is characterized by meandering horizontal wind oscillations.

They reported that as the wind speed decreases, the standard deviation of the wind direction increases, making it more difficult to define a mean plume direction. Sagendorf and Dickson (1974) and Wilson et al. (1976) found that under LWS conditions, horizontal diffusion was enhanced because of this meander and the resulting ground-level concentrations could be much lower than that predicted by steady-state Gaussian plume models that did not account for the meander effect.

A parameter that is used as part of the computation of the horizontal plume spreading in the U.S. Environmental Protection Agency (EPA) preferred model, AERMOD (Cimorelli et al., 2005), is the standard deviation of the crosswind component,  $\sigma_v$ , which can be parameterized as being proportional to the friction velocity,  $u_*$  (Smedman, 1988; Mahrt, 1998). These investigators

found that there was an elevated minimum value of  $\sigma_v$  that was attributed to meandering. While at higher wind speeds small-scale turbulence is the main source of variance, lateral meandering motions appear to exist in all conditions. Hanna (1990) found that  $\sigma_v$  maintains a minimum value of about 0.5 m/sec even as the wind speed approaches zero. Chowdhury et al. (2014) noted that a minimum  $\sigma_v$  of 0.5 m/s is a part of the formulation for the SCICHEM model. Anfossi (2005) noted that meandering exists under all meteorological conditions regardless of the stability or wind speed, and this phenomenon sets a lower limit for the horizontal wind component variances as noted by Hanna (1990) over all types of terrain.

An alternative method to address wind meander was attempted by Sagendorf and Dickson (1974), who used a Gaussian model, but divided each computation period into sub-hourly (2-min) time intervals and then combined the results to determine the total hourly concentration. This approach directly addresses the wind meander during the course of an hour by using the sub-hourly wind direction for each period modeled. As we discuss later, this approach has some appeal because it attempts to use direct wind measurements to account for sub-hourly wind meander. However, the sub-hourly time interval must not be so small as to distort the basis of the horizontal plume dispersion formulation in the dispersion model (e.g., AERMOD). Since the horizontal dispersion shape function for stable conditions in AERMOD is formulated with parameterizations derived from the 10-min release and sampling times of the Prairie Grass experiment (Barad, 1958), it is appropriate to consider a minimum sub-hourly duration of 10 minutes for such modeling using AERMOD. The Prairie Grass formulation that is part of AERMOD may also result in an underestimate of the lateral plume spread shape function in some cases, as reported by Irwin (2014) for Kincaid SF<sub>6</sub> releases. From analyses of hourly samples of SF<sub>6</sub> taken at Kincaid (a tall stack source), Irwin determined that the lateral dispersion simulated by AERMOD could underestimate the lateral dispersion (by 60%) for near-stable conditions (conditions for which the lateral dispersion formulation that was fitted to the Project Prairie Grass data could affect results).

It is clear from the preceding discussion that the simulation of pollutant dispersion in LWS conditions is challenging. In the United States, the use of steady-state plume models before the introduction of AERMOD in 2005 was done with the following rule implemented by EPA: “When used in steady-state Gaussian plume models, measured site-specific wind speeds of less than 1 m/sec but higher than the response threshold of the instrument should be input as 1 m/sec” (EPA, 2004).

With EPA’s implementation of a new model, AERMOD, in 2005 (EPA, 2005), input wind speeds lower than 1 m/sec were allowed due to the use of a meander algorithm that was designed to account for the LWS effects. As noted in the AERMOD formulation document (EPA, 2004), “AERMOD accounts for meander by interpolating between two concentration limits: the coherent plume limit (which assumes that the wind direction is distributed about a well-defined mean direction with variations due solely to lateral turbulence) and the random plume limit (which assumes an equal probability of any wind direction).”

A key aspect of this interpolation is the assignment of a time scale (= 24 hr) at which mean wind information at the source is no longer correlated with the location of plume material at a

downwind receptor (EPA, 2004). The assumption of a full diurnal cycle relating to this time scale tends to minimize the weighting of the random plume component relative to the coherent plume component for 1-hr time travel. The resulting weighting preference for the coherent plume can lead to a heavy reliance on the coherent plume, ineffective consideration of plume meander, and a total concentration overprediction.

For conditions in which the plume is emitted aloft into a stable layer or in areas of inhomogeneous terrain, it would be expected that the decoupling of the stable boundary layer relative to the surface layer could significantly shorten this time scale. These effects are discussed by Brett and Tuller (1991), where they note that lower wind autocorrelations occur in areas with a variety of roughness and terrain effects. Perez et al. (2004) noted that the autocorrelation is reduced in areas with terrain and in any terrain setting with increasing height in stable conditions when decoupling of vertical motions would result in a “loss of memory” of surface conditions. Therefore, the study reported in this paper has reviewed the treatment of AERMOD in low wind conditions for field data involving terrain effects in stable conditions, as well as for flat terrain conditions, for which convective (daytime) conditions are typically associated with peak modeled predictions.

The computation of the AERMOD coherent plume dispersion and the relative weighting of the coherent and random plumes in stable conditions are strongly related to the magnitude of  $\sigma_v$ , which is directly proportional to the magnitude of the friction velocity. Therefore, the formulation of the friction velocity calculation and the specification of a minimum  $\sigma_v$  value are also considered in this paper. The friction velocity also affects the internally calculated vertical temperature gradient, which affects plume rise and plume–terrain interactions, which are especially important in elevated terrain situations.

Qian and Venkatram (2011) discuss the challenges of LWS conditions in which the time scale of wind meandering is large and the horizontal concentration distribution can be non-Gaussian. It is also quite possible that wind instrumentation cannot adequately detect the turbulence levels that would be useful for modeling dispersion. They also noted that an analysis of data from the Cardington tower indicates that Monin–Obukhov similarity theory underestimates the surface friction velocity at low wind speeds. This finding was also noted by Paine et al. (2010) in an independent investigation of Cardington data as well as data from two other research-grade databases. Both Qian and Venkatram and Paine et al. proposed similar adjustments to the calculation of the surface friction velocity by AERMET, the meteorological processor for AERMOD. EPA incorporated the Qian and Venkatram suggested approach as a “beta option” in AERMOD in late 2012 (EPA, 2012). The same version of AERMOD also introduced low wind modeling options affecting the minimum value of  $\sigma_v$  and the weighting of the meander component that were used in the Test Cases 2–4 described in the following.

AERMOD’s handling of low wind speed conditions, especially for applications with only one level of meteorological data and no direct turbulence measurements or vertical temperature gradient observations, is the focus of this study. Previous evaluations of AERMOD for low wind speed conditions (e.g., Paine et al., 2010) have emphasized low-level tracer release

studies conducted in the 1970s and have utilized results of researchers such as Luhar and Rayner (2009). The focus of the study reported here is a further evaluation of AERMOD, but focusing upon tall-stack field databases. One of these databases was previously evaluated (Kaplan et al., 2012) with AERMOD Version 12345, featuring a database in Mercer County, North Dakota. This database features five SO<sub>2</sub> monitors in the vicinity of the Dakota Gasification Company plant and the Antelope Valley Station power plant in an area of both flat and elevated terrain. In addition to the Mercer County, ND, database, this study considers an additional field database for the Gibson Generating Station tall stack in flat terrain in southwest Indiana.

EPA released AERMOD version 14134 with enhanced low wind model features that can be applied in more than one combination. There is one low wind option (beta u\*) applicable to the meteorological preprocessor, AERMET, affecting the friction velocity calculation, and a variety of options available for the dispersion model, AERMOD, that focus upon the minimum  $\sigma_v$  specification. These beta options have the potential to reduce the overprediction biases currently present in AERMOD when run for neutral to stable conditions with regulatory default options (EPA, 2014a, 2014b). These new low wind options in AERMET and AERMOD currently require additional justification for each application in order to be considered for use in the United States. While EPA has conducted evaluations on low-level, nonbuoyant studies with the AERMET and AERMOD low wind speed beta options, it has not conducted any new evaluations on tall stack releases (U.S. EPA, 2014a, 2014b). One of the purposes of this study was to augment the evaluation experiences for the low wind model approaches for a variety of settings for tall stack releases.

This study also made use of the availability of sub-hourly meteorological observations to evaluate another modeling approach. This approach employs AERMOD with sub-hourly meteorological data and is known as the Sub-Hourly AERMOD Run Procedure or SHARP (Electric Power Research Institute [EPRI], 2013). Like the procedure developed by Sagendorf and Dickson as described earlier, SHARP merely subdivides each hour's meteorology (e.g., into six 10-min periods) and AERMOD is run multiple times with the meteorological input data (e.g., minutes 1–10, 11–20, etc.) treated as “hourly” averages for each run. Then the results of these runs are combined (averaged). In our SHARP runs, we did not employ any observed turbulence data as input. This alternative modeling approach (our Test Case 5 as discussed later) has been compared to the standard hourly AERMOD modeling approach for default and low wind modeling options (Test Cases 1–4 described later, using hourly averaged meteorological data) to determine whether it should be further considered as a viable technique. This study provides a discussion of the various low wind speed modeling options and the field study databases that were tested, as well as the modeling results.

## Modeling Options and Databases for Testing

Five AERMET/AERMOD model configurations were tested for the two field study databases, as listed in the following. All model applications used one wind level, a minimum wind speed

of 0.5 m/sec, and also used hourly average meteorological data with the exception of SHARP applications. As already noted, Test Cases 1–4 used options available in the current AERMOD code. The selections for Test Cases 1–4 exercised these low wind speed options over a range of reasonable choices that extended from no low wind enhancements to a full treatment that incorporates the Qian and Venkatram (2011) u\* recommendations as well as the Hanna (1990) and Chowdhury (2014) minimum  $\sigma_v$  recommendations (0.5 m/sec). Test Case 5 used sub-hourly meteorological data processed with AERMET using the beta u\* option for SHARP applications. We discuss later in this document our recommendations for SHARP modeling without the AERMOD meander component included.

Test Case 1: AERMET and AERMOD in default mode.

Test Case 2: Low wind beta option for AERMET and default options for AERMOD (minimum  $\sigma_v$  value of 0.2 m/sec).

Test Case 3: Low wind beta option for AERMET and the LOWWIND2 option for AERMOD (minimum  $\sigma_v$  value of 0.3 m/sec).

Test Case 4: Low wind beta option for AERMET and the LOWWIND2 option for AERMOD (minimum  $\sigma_v$  value of 0.5 m/sec).

Test Case 5: Low wind beta option for AERMET and AERMOD run in sub-hourly mode (SHARP) with beta u\* option.

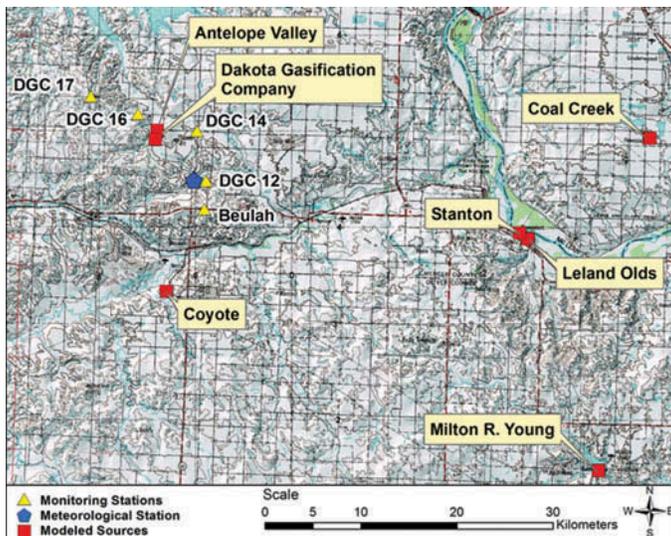
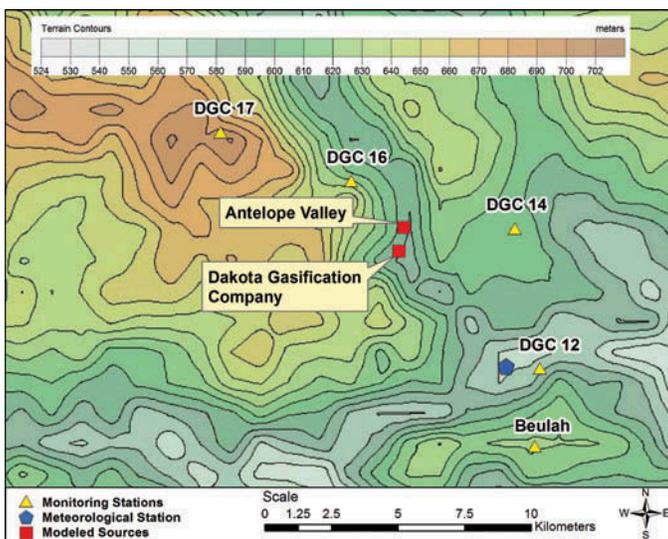
The databases that were selected for the low wind model evaluation are listed in Table 1 and described next. They were selected due to the following attributes:

- They feature multiple years of hourly SO<sub>2</sub> monitoring at several sites.
- Emissions are dominated by tall stack sources that are available from continuous emission monitors.
- They include sub-hourly meteorological data so that the SHARP modeling approach could be tested as well.
- There are representative meteorological data from a single-level station typical of (or obtained from) airport-type data.

*Mercer County, North Dakota.* An available 4-year period of 2007–2010 was used for the Mercer County, ND, database with five SO<sub>2</sub> monitors within 10 km of two nearby emission facilities (Antelope Valley and Dakota Gasification Company), site-specific meteorological data at the DGC#12 site (10-m level data in a low-cut grassy field in the location shown in Figure 1), and hourly emissions data from 15 point sources. The terrain in the area is rolling and features three of the monitors (Beulah, DGC#16, and especially DGC#17) being above or close to stack top for some of the nearby emission sources; see Figure 2 for more close-up terrain details. Figure 1 shows a layout of the sources, monitors, and the meteorological station. Tables 2 and 3 provide details about the emission sources and the monitors. Although this modeling application employed sources as far away as 50 km, the proximity of the monitors to the two nearby emission facilities meant that emissions from those facilities dominated the impacts. However, to avoid criticism from reviewers that other regional sources that

**Table 1.** Databases selected for the model evaluation.

	Mercer County, North Dakota	Gibson Generating Station, Indiana
Number of emission sources modeled	15	5
Number of SO <sub>2</sub> monitors	5 (one above stack top for several sources)	4 (all below stack top)
Type of terrain	Rolling	Flat
Meteorological years and data source	2007–2010 Local 10-m tower data	2008–2010 Evansville airport
Meteorological data time step	Hourly and sub-hourly	Hourly and sub-hourly
Emissions and exhaust data	Actual hourly variable emissions and velocity, fixed temperature	Actual hourly variable emissions and velocity, fixed temperature

**Figure 1.** Map of North Dakota model evaluation layout.**Figure 2.** Terrain around the North Dakota monitors.

should have been modeled were omitted, other regional lignite-fired power plants were included in the modeling.

**Gibson Generating Station, Indiana.** An available 3-year period of 2008–2010 was used for the Gibson Generating Station in southwest Indiana with four SO<sub>2</sub> monitors within 6 km of the plant, airport hourly meteorological data (from Evansville, IN, 1-min data, located about 40 km SSE of the plant), and hourly emissions data from one electrical generating station (Gibson). The terrain in the area is quite flat and the stacks are tall. Figure 3 depicts the locations of the emission source and the four SO<sub>2</sub> monitors. Although the plant had an on-site meteorological tower, EPA (2013a) noted that the tower's location next to a large lake resulted in nonrepresentative boundary-layer conditions for the area, and that the use of airport data would be preferred. Tables 2 and 3 provide details about the emission sources and the monitors. Due to the fact that there are no major SO<sub>2</sub> sources within at least 30 km of Gibson, we modeled emissions from only that plant.

## Meteorological Data Processing

For the North Dakota and Gibson database evaluations, the hourly surface meteorological data were processed with AERMET, the meteorological preprocessor for AERMOD. The boundary layer parameters were developed according to the guidance provided by EPA in the current AERMOD Implementation Guide (EPA, 2009). For the first modeling evaluation option, Test Case 1, AERMET was run using the default options. For the other four model evaluation options, Test Cases 2 to 5, AERMET was run with the beta  $u^*$  low wind speed option.

### North Dakota meteorological processing

Four years (2007–2010) of the 10-m meteorological data collected at the DGC#12 monitoring station (located about 7 km SSE of the central emission sources) were processed with AERMET. The data measured at this monitoring station were wind direction, wind speed, and temperature. Hourly cloud

**Table 2.** Source information.

Database	Source ID	UTM X (m)	UTM Y (m)	Base elevation (m)	Stack height (m)	Exit temperature (K)	Stack diameter (m)
ND	Antelope Valley	285920	5250189	588.3	182.9	Vary	7.0
ND	Antelope Valley	285924	5250293	588.3	182.9	Vary	7.0
ND	Leland Olds	324461	5239045	518.3	106.7	Vary	5.3
ND	Leland Olds	324557	5238972	518.3	152.4	Vary	6.7
ND	Milton R Young	331870	5214952	597.4	171.9	Vary	6.2
ND	Milton R Young	331833	5214891	600.5	167.6	Vary	9.1
ND	Coyote	286875	5233589	556.9	151.8	Vary	6.4
ND	Stanton	323642	5239607	518.2	77.7	Vary	4.6
ND	Coal Creek	337120	5249480	602.0	201.2	Vary	6.7
ND	Coal Creek	337220	5249490	602.0	201.2	Vary	6.7
ND	Dakota Gasification Company	285552	5249268	588.3	119.8	Vary	7.0
ND	Dakota Gasification Company	285648	5249553	588.3	68.6	Vary	0.5
ND	Dakota Gasification Company	285850	5248600	588.3	76.2	Vary	1.0
ND	Dakota Gasification Company	285653	5249502	588.3	30.5	Vary	0.5
Gibson	Gibson 1	432999	4247189	119.0	189.0	327.2	7.6
Gibson	Gibson 2	432999	4247189	119.0	189.0	327.2	7.6
Gibson	Gibson 3	432923	4247251	118.5	189.0	327.2	7.6
Gibson	Gibson 4	432886	4247340	117.9	152.4	327.2	7.2
Gibson	Gibson 5	432831	4247423	116.3	152.4	327.2	7.2

Notes: SO<sub>2</sub> emission rate and exit velocity vary on hourly basis for each modeled source. Exit temperature varies by hour for the ND sources. UTM zones are 14 for North Dakota and 16 for Gibson.

**Table 3.** Monitor locations.

Database	Monitor	UTM X (m)	UTM Y (m)	Monitor elevation (m)
ND	DGC#12	291011	5244991	593.2
ND	DGC#14	290063	5250217	604.0
ND	DGC#16	283924	5252004	629.1
ND	DGC#17 <sup>a</sup>	279025	5253844	709.8
ND	Beulah	290823	5242062	627.1
Gibson	Mt. Carmel	432424	4250202	119.0
Gibson	East Mt. Carmel	434654	4249666	119.3
Gibson	Shrodt	427175	4247182	138.0
Gibson	Gibson Tower	434792	4246296	119.0

Note: <sup>a</sup>This monitor's elevation is above stack top for several of the ND sources.

cover data from the Dickinson Theodore Roosevelt Regional Airport, North Dakota (KDIK) ASOS station (85 km to the SW), were used in conjunction with the monitoring station data. Upper air data were obtained from the Bismarck Airport, North Dakota (KBIS; about 100 km to the SE), twice-daily soundings.

In addition, the sub-hourly (10-min average) 10-m meteorological data collected at the DGC#12 monitoring station were also processed with AERMET. AERMET was set up to read six 10-min average files with the tower data and output six 10-min average surface and profile files for use in SHARP. SHARP then used the sub-hourly output of AERMET to

calculate hourly modeled concentrations, without changing the internal computations of AERMOD. The SHARP user's manual (EPRI, 2013) provides detailed instructions on processing sub-hourly meteorological data and executing SHARP.

### Gibson meteorological processing

Three years (2008–2010) of hourly surface data from the Evansville Airport, Indiana (KEVV), ASOS station (about 40 km SSE of Gibson) were used in conjunction with the

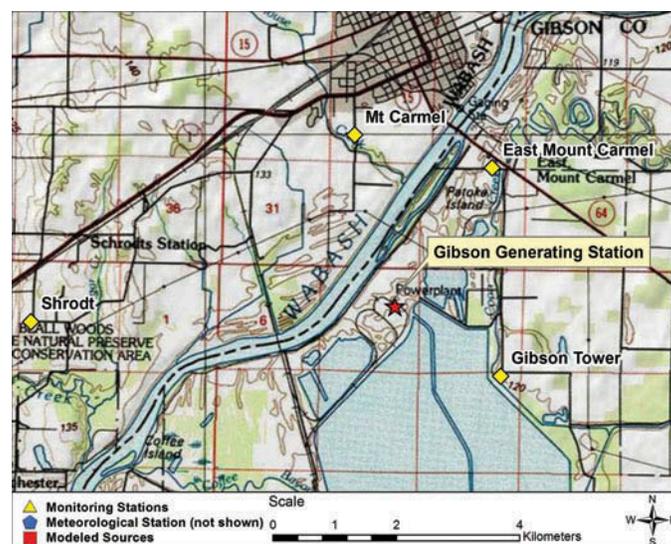


Figure 3. Map of Gibson model evaluation layout.

twice-daily soundings upper air data from the Lincoln Airport, Illinois (KILX, about 240 km NW of Gibson). The 10-min sub-hourly data for SHARP were generated from the 1-min meteorological data collected at Evansville Airport.

## Emission Source Characteristics

Table 2 summarizes the stack parameters and locations of the modeled sources for the North Dakota and Gibson databases. Actual hourly emission rates, stack temperatures, and stack gas exit velocities were used for both databases.

## Model Runs and Processing

For each evaluation database, the candidate model configurations were run with hourly emission rates provided by the plant operators. In the case of rapidly varying emissions (startup and shutdown), the hourly averages may average intermittent conditions occurring during the course of the hour. Actual stack heights were used, along with building dimensions used as input to the models tested. Receptors were placed only at the location of each monitor to match the number of observed and predicted concentrations.

The monitor (receptor) locations and elevations are listed in Table 3. For the North Dakota database, the DGC#17 monitor is located in the most elevated terrain of all monitors. The monitors for the Gibson database were located at elevations at or near stack base, with stack heights ranging from 152 to 189 m.

## Tolerance Range for Modeling Results

One issue to be aware of regarding SO<sub>2</sub> monitored observations is that they can exhibit over- or underprediction tendencies up to 10% and still be acceptable. This is related to the tolerance in the EPA procedures (EPA, 2013b) associated with quality control checks and span checks of ambient measurements. Therefore, even ignoring uncertainties in model input parameters and other contributions (e.g., model science errors and random variations) that can also lead to modeling uncertainties, just the uncertainty in measurements indicates that modeled-to-monitored ratios between 0.9 and 1.1 can be considered “unbiased.” In the discussion that follows, we consider model performance to be “relatively unbiased” if its predicted model to monitor ratio is between 0.75 and 1.25.

## Model Evaluation Metrics

The model evaluation employed metrics that address three basic areas, as described next.

### The 1-hr SO<sub>2</sub> NAAQS design concentration

An operational metric that is tied to the form of the 1-hour SO<sub>2</sub> National Ambient Air Quality Standards (NAAQS) is the “design concentration” (99th percentile of the peak daily 1-hr maximum values). This tabulated statistic was developed for

each modeled case and for each individual monitor for each database evaluated.

### Quantile–quantile plots

Operational performance of models for predicting compliance with air quality regulations, especially those involving a peak or near-peak value at some unspecified time and location, can be assessed with quantile–quantile (Q-Q) plots (Chambers et al., 1983), which are widely used in AERMOD evaluations. Q-Q plots are created by independently ranking (from largest to smallest) the predicted and the observed concentrations from a set of predictions initially paired in time and space. A robust model would have all points on the diagonal (45-degree) line. Such plots are useful for answering the question, “Over a period of time evaluated, does the distribution of the model predictions match those of observations?” Therefore, the Q-Q plot instead of the scatterplot is a pragmatic procedure for demonstrating model performance of applied models, and it is widely used by EPA (e.g., Perry et al. 2005). Venkatram et al. (2001) support the use of Q-Q plots for evaluating regulatory models. Several Q-Q plots are included in this paper in the discussion provided in the following.

### Meteorological conditions associated with peak observed versus modeled concentrations

Lists of the meteorological conditions and hours/dates of the top several predictions and observations provide an indication as to whether these conditions are consistent between the model and monitoring data. For example, if the peak observed concentrations generally occur during daytime hours, we would expect that a well-performing model would indicate that the peak predictions are during the daytime as well. Another meteorological variable of interest is the wind speed magnitudes associated with observations and predictions. It would be expected, for example, that if the wind speeds associated with peak observations are low, then the modeled peak predicted hours would have the same characteristics. A brief qualitative summary of this analysis is included in this paper, and supplemental files contain the tables of the top 25 (unpaired) predictions and observations for all monitors and cases tested.

## North Dakota Database Model Evaluation Procedures and Results

AERMOD was run for five test cases to compute the 1-hr daily maximum 99th percentile averaged over 4 years at the five ambient monitoring locations listed in Table 3. A regional background of 10 µg/m<sup>3</sup> was added to the AERMOD modeled predictions. The 1-hr 99th percentile background concentration was computed from the 2007–2010 lowest hourly monitored concentration among the five monitors so as to avoid double-counting impacts from sources already being modeled.

The ratios of the modeled (including the background of 10 µg/m<sup>3</sup>) to monitored design concentrations are summarized in

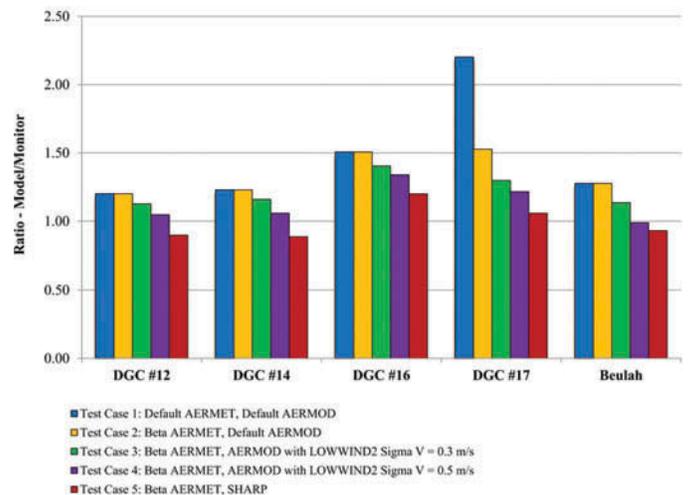
**Table 4.** North Dakota ratio of monitored to modeled design concentrations.

Test case	Monitor	Observed	Predicted	Ratio
Test Case 1 (Default AERMET, Default AERMOD)	DGC#12	91.52	109.96	1.20
	DGC#14	95.00	116.84	1.23
	DGC#16	79.58	119.94	1.51
	DGC#17	83.76	184.48	2.20
	Beulah	93.37	119.23	1.28
Test Case 2 (Beta AERMET, Default AERMOD)	DGC#12	91.52	109.96	1.20
	DGC#14	95.00	116.84	1.23
	DGC#16	79.58	119.94	1.51
	DGC#17	83.76	127.93	1.53
	Beulah	93.37	119.23	1.28
Test Case 3 (Beta AERMET, AERMOD with LOWWIND2 $\sigma_v = 0.3$ m/sec)	DGC#12	91.52	103.14	1.13
	DGC#14	95.00	110.17	1.16
	DGC#16	79.58	111.74	1.40
	DGC#17	83.76	108.69	1.30
	Beulah	93.37	106.05	1.14
Test Case 4 (Beta AERMET, AERMOD with LOWWIND2 $\sigma_v = 0.5$ m/sec)	DGC#12	91.52	95.86	1.05
	DGC#14	95.00	100.50	1.06
	DGC#16	79.58	106.65	1.34
	DGC#17	83.76	101.84	1.22
	Beulah	93.37	92.32	0.99
Test Case 5 (SHARP)	DGC#12	91.52	82.18	0.90
	DGC#14	95.00	84.24	0.89
	DGC#16	79.58	95.47	1.20
	DGC#17	83.76	88.60	1.06
	Beulah	93.37	86.98	0.93

Notes: \*Design concentration: 99th percentile peak daily 1-hr maximum, averaged over the years modeled and monitored.

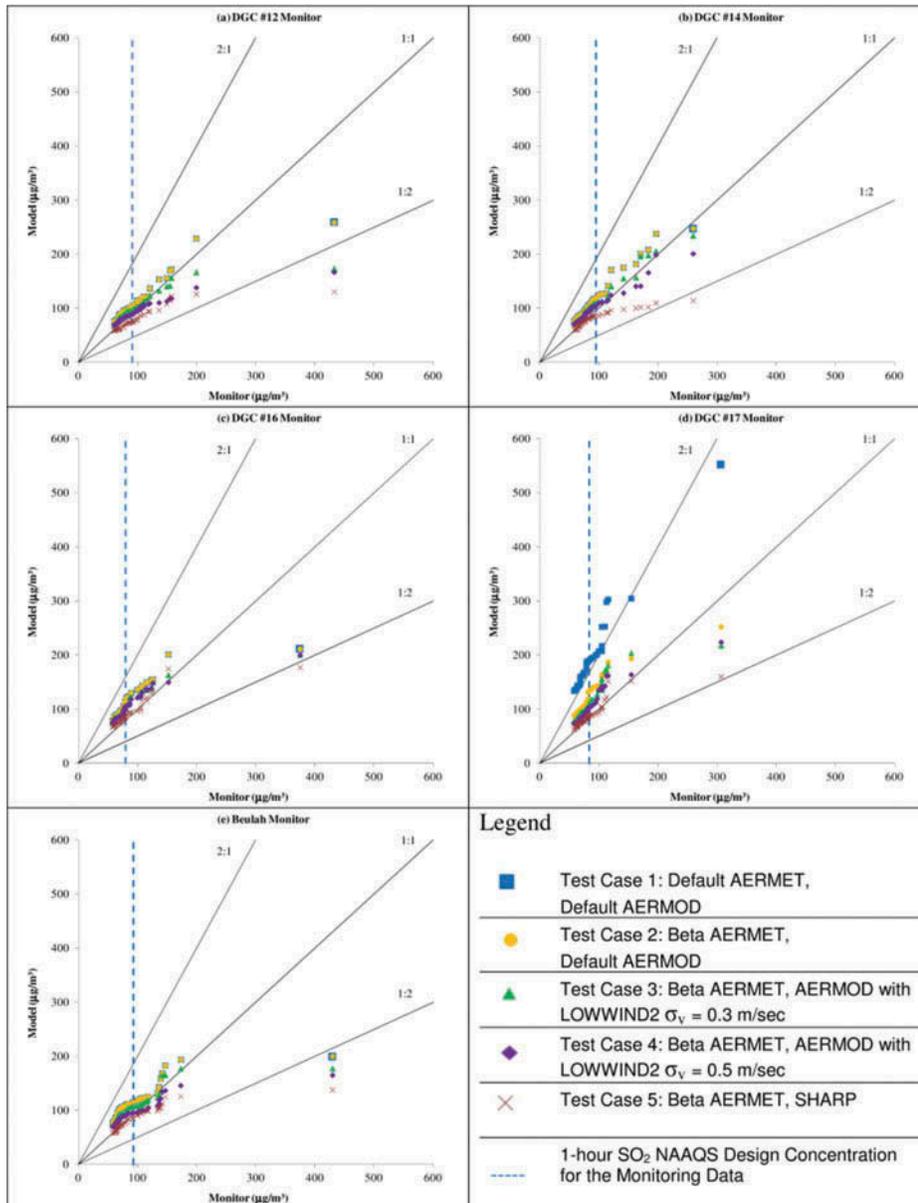
Table 4 and graphically plotted in Figure 4 and are generally greater than 1. (Note that the background concentration is a small fraction of the total concentration, as shown in Table 4.) For the monitors in simple terrain (DGC#12, DGC#14, and Beulah), the evaluation results are similar for both the default and beta options and are within 5–30% of the monitored concentrations depending on the model option. The evaluation result for the monitor in the highest terrain (DGC#17) shows that the ratio of modeled to monitored concentration is more than 2, but when this location is modeled with the AERMET and AERMOD low wind beta options, the ratio is significantly better, at less than 1.3. It is noteworthy that the modeling results for inclusion of just the beta  $u^*$  option are virtually identical to the default AERMET run for the simple terrain monitors, but the differences are significant for the higher terrain monitor (DGC#17). For all of the monitors, it is evident that further reductions of AERMOD’s overpredictions occur as the minimum  $\sigma_v$  in AERMOD is increased from 0.3 to 0.5 m/sec. For a minimum  $\sigma_v$  of 0.5 m/sec at all the monitors, AERMOD is shown to be conservative with respect to the design concentration.

The Q-Q plots of the ranked top fifty daily maximum 1-hr SO<sub>2</sub> concentrations for predictions and observations are shown in Figure 5. For the convenience of the reader, a vertical dashed line is included in each Q-Q plot to indicate the observed design concentration. In general, the Q-Q plots indicate the following:



**Figure 4.** North Dakota ratio of monitored to modeled design concentration values at specific monitors.

- For all of the monitors, to the left of the design concentration line, the AERMOD hourly runs all show ranked predictions at or higher than observations. To the right of the design concentration line, the ranked modeled values for specific



**Figure 5.** North Dakota Q-Q plots: top 50 daily maximum 1-hr SO<sub>2</sub> concentrations: (a) DGC #12 Monitor. (b) DGC#14 monitor. (c) DGC#16 monitor. (d) DGC#17 monitor. (e) Beulah monitor.

test cases and monitors are lower than the ranked observed levels, and the slope of the line formed by the plotted points is less than the slope of the 1:1 line. For model performance goals that would need to predict well for the peak concentrations (rather than the 99th percentile statistic), this area of the Q-Q plots would be of greater importance.

- The very highest observed value (if indeed valid) is not matched by any of the models for all of the monitors, but since the focus is on the 99th percentile form of the United States ambient standard for SO<sub>2</sub>, this area of model performance is not important for this application.
- The ranked SHARP modeling results are lower than all of the hourly AERMOD runs, but at the design concentration level, they are, on average, relatively unbiased over all of the

monitors. The AERMOD runs for SHARP included the meander component, which probably contributed to the small underpredictions noted for SHARP. In future modeling, we would advise users of SHARP to employ the AERMOD LOWWIND1 option to disable the meander component.

## Gibson Generating Station Database Model Evaluation Procedures and Results

AERMOD was run for five test cases for this database as well in order to compute the 1-hr daily maximum 99th

percentile averaged over three years at the four ambient monitoring locations listed in Table 3. A regional background of  $18 \mu\text{g}/\text{m}^3$  was added to the AERMOD modeled predictions. The 1-hr 99th percentile background concentration was computed from the 2008–2010 lowest hourly monitored concentration among the four monitors so as to avoid impacts from sources being modeled.

The ratio of the modeled (including the background of  $18 \mu\text{g}/\text{m}^3$ ) to monitored concentrations is summarized in Table 5 and graphically plotted in Figure 6 and are generally greater than 1.0. (Note that the background concentration is a small fraction of the total concentration, as shown in Table 5.) Figure 6 shows that AERMOD with hourly averaged meteorological data overpredicts by about 40–50% at Mt. Carmel and Gibson Tower monitors and by about 9–31% at East Mt. Carmel and Shrodt monitors. As expected (due to dominance of impacts with convective conditions), the AERMOD results do not vary much with the various low wind speed options in this flat terrain setting. AERMOD with sub-hourly meteorological data (SHARP) has the best (least biased predicted-to-observed ratio of design concentrations) performance among the five cases modeled. Over the four monitors, the range of predicted-to-observed ratios for SHARP is a narrow one, ranging from a slight underprediction by 2% to an overprediction by 14%.

The Q-Q plots of the ranked top fifty daily maximum 1-hr  $\text{SO}_2$  concentrations for predictions and observations are shown in Figure 7. It is clear from these plots that the SHARP results parallel and are closer to the 1:1 line for a larger portion of the concentration range than any other model tested. In general,

AERMOD modeling with hourly data exhibits an overprediction tendency at all of the monitors for the peak ranked concentrations at most of the monitors. The AERMOD/SHARP models predicted lower relative to observations at the East Mt. Carmel monitor for the very highest values, but match well for the 99th percentile peak daily 1-hr maximum statistic.

## Evaluation Results Discussion

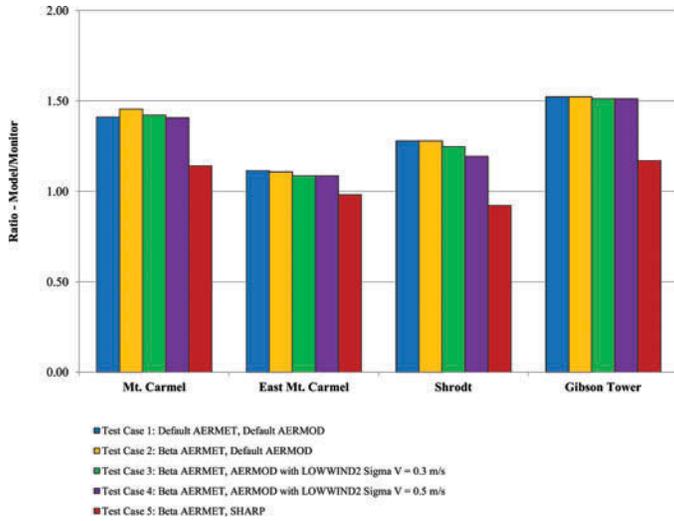
The modeling results for these tall stack releases are sensitive to the source local setting and proximity to complex terrain. In general, for tall stacks in simple terrain, the peak ground-level impacts mostly occur in daytime convective conditions. For settings with a mixture of simple and complex terrain, the peak impacts for the higher terrain are observed to occur during both daytime and nighttime conditions, while AERMOD tends to favor stable conditions only without low wind speed enhancements. Exceptions to this “rule of thumb” can occur for stacks with aerodynamic building downwash effects. In that case, high observed and modeled predictions are likely to occur during high wind events during all times of day.

The significance of the changes in model performance for tall stacks (using a 90th percentile confidence interval) was independently tested for a similar model evaluation conducted for Eastman Chemical Company (Paine et al., 2013; Szembek et al., 2013), using a modification of the Model Evaluation Methodology (MEM) software that computed estimates of the hourly stability class (Strimaitis et al., 1993). That study indicated that relative to a perfect model, a model that

**Table 5.** Gibson ratio of monitored to modeled design concentrations\*.

Test case	Monitor	Observed	Predicted	Ratio
Test Case 1 (Default AERMET, Default AERMOD)	Mt. Carmel	197.25	278.45	1.41
	East Mt. Carmel	206.89	230.74	1.12
	Shrodt	148.16	189.63	1.28
	Gibson Tower	127.12	193.71	1.52
Test Case 2 (Beta AERMET, Default AERMOD)	Mt. Carmel	197.25	287.16	1.46
	East Mt. Carmel	206.89	229.22	1.11
	Shrodt	148.16	189.63	1.28
	Gibson Tower	127.12	193.71	1.52
Test Case 3 (Beta AERMET, AERMOD with LOWWIND2 $\sigma_v = 0.3$ m/sec)	Mt. Carmel	197.25	280.32	1.42
	East Mt. Carmel	206.89	224.65	1.09
	Shrodt	148.16	184.82	1.25
	Gibson Tower	127.12	192.22	1.51
Test Case 4 (Beta AERMET, AERMOD with LOWWIND2 $\sigma_v = 0.5$ m/sec)	Mt. Carmel	197.25	277.57	1.41
	East Mt. Carmel	206.89	224.65	1.09
	Shrodt	148.16	176.81	1.19
	Gibson Tower	127.12	192.22	1.51
Test Case 5 (SHARP)	Mt. Carmel	197.25	225.05	1.14
	East Mt. Carmel	206.89	202.82	0.98
	Shrodt	148.16	136.41	0.92
	Gibson Tower	127.12	148.64	1.17

Notes: \*Design Concentration: 99<sup>th</sup> percentile peak daily 1-hr maximum, averaged over the years modeled and monitored.



**Figure 6.** Gibson ratio of monitored to modeled design concentration values at specific monitors.

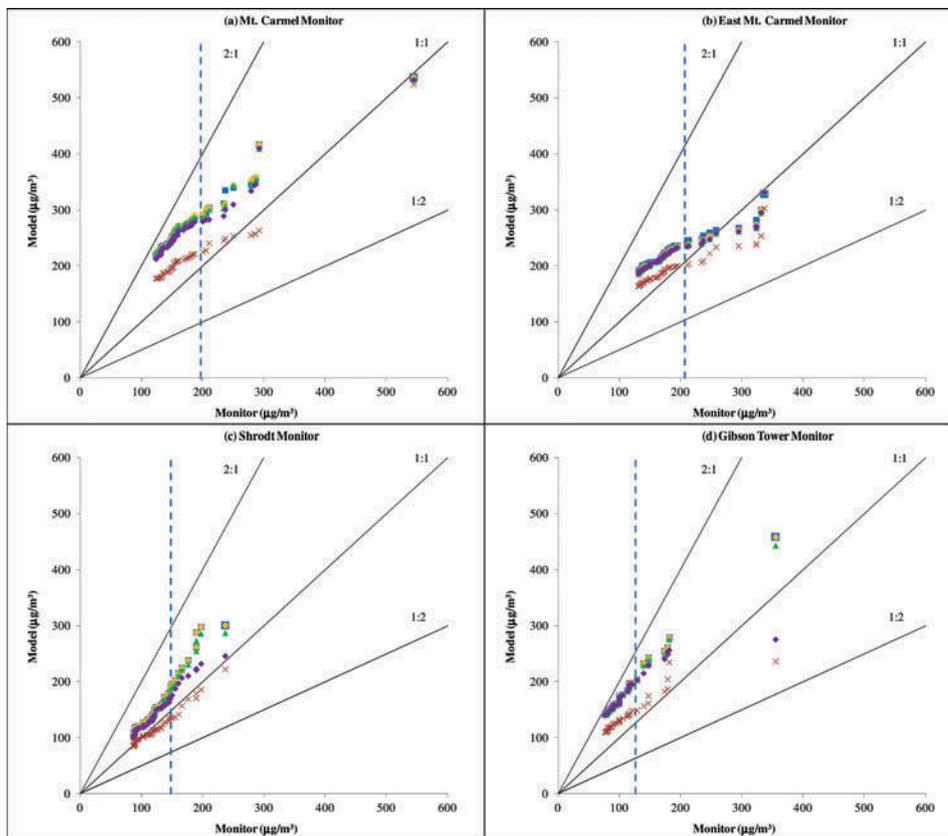
overpredicted or underpredicted by less than about 50% would likely show a performance level that was not significantly different. For a larger difference in bias, one could expect a statistically significant difference in model performance. This finding has been adopted as an indicator of the significance of different modeling results for this study.

A review of the North Dakota ratios of monitored to modeled values in Figure 4 generally indicates that for DGC#12, DGC#14, and Beulah, the model differences were not significantly different. For DGC#16, it could be concluded that the SHARP results were significantly better than the default AERMOD results, but other AERMOD variations were not significantly better. For the high terrain monitor, DGC#17, it is evident that all of the model options departing from default were significantly better than the default option, especially the SHARP approach.

For the Gibson monitors (see Figure 6), the model variations did not result in significantly different performance except for the Gibson Tower (SHARP vs. the hourly modes of running AERMOD).

General conclusions from the review of meteorological conditions associated with the top observed concentrations at the North Dakota monitors, provided in the supplemental file called “North Dakota Meteorological Conditions Resulting in Top 25 Concentrations,” are as follows:

- A few peak observed concentrations occur at night with light winds. The majority of observations for the DGC#12 monitor are mostly daytime conditions with moderate to strong winds.
- Peak observations for the DGC#14 and Beulah monitors are mostly daytime conditions with a large range of wind speeds. Once again, a minority of the peak concentrations occur at night with a large range of wind speeds.



**Figure 7.** Gibson Q-Q plots: top 50 daily maximum 1-hour SO<sub>2</sub> concentrations. (a) Mt. Carmel monitor. (b) East Mt. Carmel monitor. (c) Shrodt monitor. (d) Gibson tower monitor. For the legend, see Figure 5.

- Peak observed concentrations for the DGC#16 and DGC#17 monitors occur at night with light winds. Majority of observations are mixed between daytime and nighttime conditions with a large range of wind speeds for both. The DGC#17 monitor is located in elevated terrain.

The conclusions from the review of the meteorological conditions associated with peak AERMOD or SHARP predictions are as follows:

- AERMOD hourly peak predictions for the DGC#12 and Beulah monitors are consistently during the daytime with light to moderate wind speeds and limited mixing heights. This is a commonly observed situation that is further discussed later.
- There are similar AERMOD results for DGC#14, except that there are more periods with high winds and higher mixing heights.
- The AERMOD results for DGC#16 still feature mostly daytime hours, but with more high wind conditions.
- The default AERMOD results for DGC#17 are distinctly different from the other monitors, with most hours featuring stable, light winds. There are also a few daytime hours of high predictions with low winds and low mixing heights. This pattern changes substantially with the beta  $u^*$  options employed, when the majority of the peak prediction hours are daytime periods with light to moderate wind speeds. This pattern is more consistent with the peak observed concentration conditions.
- The SHARP peak predictions at the North Dakota monitors were also mostly associated with daytime hours with a large range of wind speeds for all of the monitors.

The North Dakota site has some similarities due to a mixture of flat and elevated terrain to the Eastman Chemical Company model evaluation study in Kingsport, TN (this site features three coal-fired boiler houses with tall stacks). In that study (Paine et al. 2013; Szembek et al., 2013), there was one monitor in elevated terrain and two monitors in flat terrain with a full year of data. Both the North Dakota and Eastman sites featured observations of the design concentration being within about 10% of the mean design concentration over all monitors. Modeling results using default options in AERMOD for both of these sites indicated a large spread of the predictions, with predictions in high terrain exceeding observations by more than a factor of 2. In contrast, the predictions in flat terrain, while higher than observations, showed a lower overprediction bias. The use of low wind speed improvements in AERMOD (beta  $u^*$  in AERMET and an elevated minimum  $\sigma_v$  value) did improve model predictions for both databases.

The conclusions from the review of the meteorological conditions associated with peak observations, provided in the supplemental file called “Gibson Meteorological Conditions Resulting in Top 25 Concentrations,” are as follows:

- Peak observations for the Mt. Carmel and East Mt. Carmel monitors occur during both light wind convective conditions and strong wind conditions (near neutral, both daytime and nighttime).

- Nighttime peaks that are noted at Mt. Carmel and East Mt. Carmel could be due to downwash effects with southerly winds.
- Gibson Tower and Shrodt monitors were in directions with minimal downwash effects; therefore, the peak impacts at these monitors occur with convective conditions.
- The Gibson Tower and Shrodt monitor peak observation conditions were similarly mixed for wind speeds, but they were consistently occurring during the daytime only.

AERMOD (hourly) modeling runs and SHARP runs are generally consistent with the patterns of observed conditions for Shrodt and Gibson Tower monitors. Except for downwash effects, the peak concentrations were all observed and predicted during daytime hours. There are similar AERMOD results for Mt. Carmel and East Mt. Carmel, except that there are more nighttime periods and periods with strong wind conditions.

As noted earlier, AERMOD tends to focus its peak predictions for tall stacks in simple terrain (those not affected by building downwash) for conditions with low mixing heights in the morning. However, a more detailed review of these conditions indicates that the high predictions are not simply due to plumes trapped within the convective mixed layer, but instead due to plumes that initially penetrate the mixing layer, but then emerge (after a short travel time) into the convective boundary layer in concentrated form with a larger-than-expected vertical spread. Tests of this condition were undertaken by Dr. Ken Rayner of the Western Australia Department of Environmental Regulation (2013), who found the same condition occurring for tall stacks in simple terrain for a field study database in his province. Rayner found that AERMOD tended to overpredict peak concentrations by a factor of about 50% at a key monitor, while with the penetrated plume removed from consideration, AERMOD would underpredict by about 30%. Therefore, the correct treatment might be a more delayed entrainment of the penetrated plume into the convective mixed layer. Rayner's basic conclusions were:

- A plume penetrates and disperses within a 1-hr time step in AERMOD, while in the real world, dispersion of a penetrated puff may occur an hour or more later, after substantial travel time.
- A penetrated plume initially disperses via a vertical Gaussian formula, not a convective probability density function. Because penetrated puffs typically have a very small vertical dispersion, they are typically fully entrained (in AERMOD) in a single hour by a growing mixed layer, and dispersion of a fully entrained puff is via convective mixing, with relatively rapid vertical dispersion, and high ground-level concentrations.

## Conclusions and Recommendations for Further Research

This study has addressed additional evaluations for low wind conditions involving tall stack releases for which multiple

years of concurrent emissions, meteorological data, and monitoring data were available. The modeling cases that were the focus of this study involved applications with only one level of meteorological data and no direct turbulence measurements or vertical temperature gradient observations.

For the North Dakota evaluation, the AERMOD model overpredicted, using the design concentration as the metric for each monitor. For the relatively low elevation monitors, the results were similar for both the default and beta options and are within 5–30% of the monitored concentrations depending on the model option. The modeling result for the elevated DGC#17 monitor showed that this location is sensitive to terrain, as the ratio of modeled to monitored concentration is over 2. However, when this location was modeled with the low wind beta option, the ratio was notably better, at less than 1.3. Furthermore, the low wind speed beta option changed the AERMOD's focus on peak predictions conditions from mostly nighttime to mostly daytime periods, somewhat more in line with observations. Even for a minimum  $\sigma_v$  as high as 0.5 m/sec, all of the AERMOD modeling results were conservative or relatively unbiased (for the design concentration). The North Dakota evaluation results for the sub-hourly (SHARP) modeling were, on average, relatively unbiased, with a predicted-to-observed design concentration ratio ranging from 0.89 to 1.2. With a 10% tolerance in the SO<sub>2</sub> monitored values, we find that the SHARP performance is quite good. Slightly higher SHARP predictions would be expected if AERMOD were run with the LOWWIND1 option deployed.

For the Gibson flat terrain evaluation, AERMOD with hourly averaged meteorological data overpredicted at three of the four monitors between 30 and 50%, and about 10% at the fourth monitor. The AERMOD results did not vary much with the various low wind speed options in this flat terrain setting. AERMOD with sub-hourly meteorological data (SHARP) had the best (least biased predicted-to-observed ratio of design concentrations) performance among the five cases modeled. Over the four monitors, the range of predicted-to-observed ratios for SHARP was a narrow one, ranging from a slight underprediction by 2% to an overprediction by 14%. All other modeling options had a larger range of results.

The overall findings with the low wind speed testing on these tall stack databases indicate that:

- The AERMOD low wind speed options have a minor effect for flat terrain locations.
- The AERMOD low wind speed options have a more significant effect with AERMOD modeling for elevated terrain locations, and the use of the LOWWIND2 option with a minimum  $\sigma_v$  on the order of 0.5 m/sec is appropriate.
- The AERMOD sub-hourly modeling (SHARP) results are mostly in the unbiased range (modeled to observed design concentration ratios between 0.9 and 1.1) for the two databases tested with that option.
- The AERMOD low wind speed options improve the consistency of meteorological conditions associated with the highest observed and predicted concentration events.

Further analysis of the low wind speed performance of AERMOD with either the SHARP procedure or the use of

the minimum  $\sigma_v$  specifications by other investigators is encouraged. However, SHARP can only be used if sub-hourly meteorological data is available. For Automated Surface Observing Stations (ASOS) with 1-min data, this option is a possibility if the 1-min data are obtained and processed.

Although the SHARP results reported in this paper are encouraging, further testing is recommended to determine the optimal sub-hourly averaging time (no less than 10 min is recommended) and whether other adjustments to AERMOD (e.g., total disabling of the meander option) are recommended. Another way to implement the sub-hourly information in AERMOD and to avoid the laborious method of running AERMOD several times for SHARP would be to include a distribution, or range, of the sub-hourly wind directions to AERMOD so that the meander calculations could be refined.

For most modeling applications that use hourly averages of meteorological data with no knowledge of the sub-hourly wind distribution, it appears that the best options with the current AERMOD modeling system are to implement the AERMET beta  $u_*$  improvements and to use a minimum  $\sigma_v$  value on the order of 0.5 m/sec/sec.

It is noteworthy that EPA has recently approved (EPA, 2015) as a site-specific model for Eastman Chemical Company the use of the AERMET beta  $u_*$  option as well as the LOWWIND2 option in AERMOD with a minimum  $\sigma_v$  of 0.4 m/sec. This model, which was evaluated with site-specific meteorological data and four SO<sub>2</sub> monitors operated for 1 year, performed well in flat terrain, but overpredicted in elevated terrain, where a minimum  $\sigma_v$  value of 0.6 m/sec actually performed better. This would result in an average value of the minimum  $\sigma_v$  of about 0.5 m/sec, consistent with the findings of Hanna (1990).

The concept of a minimum horizontal wind fluctuation speed on the order of about 0.5 m/sec is further supported by the existence of vertical changes (shears) in wind direction (as noted by Etling, 1990) that can result in effective horizontal shearing of a plume that is not accounted for in AERMOD. Although we did not test this concept here, the concept of vertical wind shear effects, which are more prevalent in decoupled stable conditions than in well-mixed convective conditions, suggests that it would be helpful to have a “split minimum  $\sigma_v$ ” approach in AERMOD that enables the user to specify separate minimum  $\sigma_v$  values for stable and unstable conditions. This capability would, of course, be backward-compatible to the current minimum  $\sigma_v$  specification that applies for all stability conditions in AERMOD now.

## Supplemental Material

Supplemental data for this article can be accessed at the [publisher's website](#)

## References

- Anfossi, D., D. Oetli, G. Degrazia, and A. Goulart. 2005. An analysis of sonic anemometer observations in low wind speed conditions. *Boundary Layer Meteorol.* 114:179–203. doi:10.1007/s10546-004-1984-4

- Barad, M.L. 1958. Project Prairie Grass, a field program in diffusion. *Geophys. Res. Pap.* 59. Bedford, MA: Air Force Cambridge Centre.
- Brett, A.C., and S.E. Tuller. 1991. The autocorrelation of hourly wind speed observations. *J. Appl. Meteorol.* 30:823–33. doi:10.1175/1520-0450(1991)030%3C0823:TAOHWS%3E2.0.CO;2
- Chambers, J.M., W.S. Cleveland, B. Kleiner, and P.A. Tukey. 1983. Comparing data distributions. Graphical methods for data analysis. Pacific Grove, CA: Bell Laboratories. Wadsworth International Group and Duxbury Press.
- Chowdhury, B., R.I. Sykes, D. Henn, and P. Karamchandani. 2014. SCICHEM Version 3.0 (Beta 2) technical documentation. <http://sourceforge.net/projects/epri-dispersion/files/SCICHEM/SCICHEM3.0b2.zip/download>
- Cimorelli, A.J., S.G. Perry, A. Venkatram, J.C. Weil, R.J. Paine, R.B. Wilson, R.F. Lee, W.D. Peters, and R.W. Brode. 2005. AERMOD: A dispersion model for industrial source applications. Part I: General model formulation and boundary layer characterization. *J. Appl. Meteorol.* 44:682–93. doi:10.1175/JAM2227.1
- Electric Power Research Institute. 2013. Sub Hourly AERMOD Run Procedure (SHARP), version 13011 user's guide. Research project 1025622. <http://sourceforge.net/projects/epri-dispersion/files/SHARP> (accessed June 10, 2015).
- Etling, D. 1990. On plume meandering under stable stratification. *Atmos. Environ.* 8:1979–85. doi:10.1016/0960-1686(90)90232-C
- Hanna, S.R. 1990. Lateral dispersion in light-wind stable conditions. *Nuovo Cimento* 13:889–94. doi:10.1007/BF02514777
- Irwin, J.S. 2014. A suggested method for dispersion model evaluation. *J. Air Waste Manage. Assoc.* 64(3):255–64. doi:10.1080/10962247.2013.833147
- Kaplan, M., and R.J. Paine. 2012. Comparison of AERMOD modeled 1-hour SO<sub>2</sub> concentrations to observations at multiple monitoring stations in North Dakota. Presented at the 105th Annual Conference and Exhibition of the Air & Waste Management Association, June 2012, San Antonio, TX.
- Luhar, A.K., and K.N. Rayner. 2009. Methods to estimate surface fluxes of momentum and heat from routine weather observations for dispersion applications under stable stratification. *Boundary Layer Meteorol.* 132:437–54. doi:10.1007/s10546-009-9409-z
- Mahrt, L. 1998. Stratified atmospheric boundary layers and breakdown of models. *Theor. Comput. Fluid Dynam.* 11:263–79. doi:10.1007/s001620050093
- Paine, R., J.A. Connors, and C.D. Szembek. 2010. AERMOD low wind speed evaluation study: Results and implementation. Paper 2010-A-631-AWMA. Presented at the 103rd Annual Conference, Air & Waste Management Association, June 2012, Calgary, Alberta, Canada.
- Paine, R., F. Tringale, and S. Gossett. 2013. Resolution of 1-hour SO<sub>2</sub> non-attainment area in Kingsport, TN: Advanced meteorological and monitoring study. Presented at the Air & Waste Management Association's Specialty Conference, Raleigh, NC, March.
- Pasquill, F., and F.B. Smith. 1983. *Atmospheric Diffusion*. Series in Environmental Science. Ellis Horwood. Chichester: John Wiley & Sons.
- Perez, I., M. Garcia, M. Sanchez, and B. De Torre. 2004. Autocorrelation analysis of meteorological data from a RASS Sodar. *J. Appl. Meteorol.*, 43:1213–23. doi:10.1175/1520-0450(2004)043%3C1213:AAOMDF%3E2.0.CO;2
- Perry, S.G., A.J. Cimorelli, R.J. Paine, R.W. Brode, J.C. Weil, A. Venkatram, R. B. Wilson, R.F. Lee, and W.D. Peters. 2005. AERMOD: A dispersion model for industrial source applications. Part II: Model performance against 17 field study databases. *J. Appl. Meteorol.* 44:694–708. doi:10.1175/JAM2228.1
- Qian, W., and A. Venkatram. 2011. Performance of steady-state dispersion models under low wind-speed conditions. *Boundary Layer Meteorol.* 138:475–91. doi:10.1007/s10546-010-9565-1
- Rayner, K. 2013. Personal communication with Robert Paine, AECOM.
- Sagendorf, J.F., and C.R. Dickson. 1974. Diffusion under low windspeed, inversion conditions. *NOAA Technical Memorandum* 52. <http://www.arl.noaa.gov/documents/reports/ARL-52.pdf> (accessed September 9, 2015).
- Smedman, A.S. 1988. Observations of a multi-level turbulence structure in a very stable atmospheric boundary layer. *Boundary Layer Meteorol.* 66:105–26. doi:10.1007/BF00116064
- Strimaitis, D., E. Insley, M. Korc, and F. Lurmann. 1993. User's guide for the Model Evaluation Methodology (MEM) system for comparing model performance, Version 1.0. STI-93261-1392-FR. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, NC.
- Szembek, C., R. Paine, and S. Gossett. 2013. Resolution of 1-hour SO<sub>2</sub> non-attainment area in Kingsport, TN: Model evaluation analysis results to date. Presented at the Air & Waste Management Association's Specialty Conference, Raleigh, NC, March.
- U.S. Environmental Protection Agency. 2004. AERMOD: Description of model formulation. EPA-454/R-03-004. [http://www.epa.gov/ttn/scram/7thconf/aermod/aermod\\_mfd.pdf](http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_mfd.pdf) (accessed June 10, 2015).
- U.S. Environmental Protection Agency. 2005. Revision to the guideline on air quality models: Adoption of a preferred general purpose (flat and complex terrain) dispersion model and other revisions. Final rule. *Fed. Reg.* 70 (216). <http://www.gpo.gov/fdsys/pkg/FR-2005-11-09/html/05-21627.htm> (accessed June 10, 2015).
- U.S. Environmental Protection Agency. 2009. AERMOD implementation guide (AIG). [http://www.epa.gov/ttn/scram/7thconf/aermod/aermod\\_implmntn\\_guide\\_19March2009.pdf](http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_implmntn_guide_19March2009.pdf) (accessed June 10, 2015).
- U.S. Environmental Protection Agency. 2012. AERMET 12345 model change bulletin MCB#3. [http://www.epa.gov/ttn/scram/7thconf/aermod/aermet\\_mcb3.txt](http://www.epa.gov/ttn/scram/7thconf/aermod/aermet_mcb3.txt) (accessed June 10, 2015).
- U.S. Environmental Protection Agency. 2013a. Personal communication from Roger Brode, EPA, to Robert Paine, AECOM.
- U.S. Environmental Protection Agency. 2013b. *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II, Ambient Air Quality Monitoring Program*. <http://www.epa.gov/ttnamti1/files/ambient/pm25/qa/QA-Handbook-Vol-II.pdf> (accessed June 10, 2015).
- U.S. Environmental Protection Agency. 2014a. Webinar: AERMOD modeling system update, January 15. [http://www.epa.gov/ttn/scram/webinar/AERMOD\\_13350\\_Update/AERMOD\\_System\\_Update\\_Webinar\\_01-14-2014\\_FINAL.pdf](http://www.epa.gov/ttn/scram/webinar/AERMOD_13350_Update/AERMOD_System_Update_Webinar_01-14-2014_FINAL.pdf) (accessed June 10, 2015).
- U.S. Environmental Protection Agency. 2014b. Webinar: AERMOD modeling system update, August 14. [http://www.epa.gov/ttn/scram/webinar/AERMOD\\_14134-NO2\\_Memo/20140812-Webinar\\_Slides.pdf](http://www.epa.gov/ttn/scram/webinar/AERMOD_14134-NO2_Memo/20140812-Webinar_Slides.pdf) (accessed June 10, 2015).
- U.S. Environmental Protection Agency. 2015. Approval of alternative model request: Modeling of sulfur dioxide emissions from Eastman Chemical Company, Sullivan County, Tennessee, 2010 Sulfur dioxide National Ambient Air Quality Standards (NAAQS) nonattainment area. Letter to Mr. Barry R. Stephens, Tennessee Department of Environment and Conservation from Beverly H. Bannister, Director of Air, Pesticides and Toxics Management Division (EPA Region 4).
- Van der Hoven, I. 1976. A survey of field measurements of atmospheric diffusion under low-wind-speed inversion conditions. *Nuclear Safety* 17:223–30.
- Venkatram, A., R.W. Brode, A.J. Cimorelli, J.T. Lee, R.J. Paine, S.G. Perry, W. D. Peters, J.C. Weil, and R.B. Wilson. 2001. A complex terrain dispersion model for regulatory applications. *Atmos. Environ.* 35:4211–21. doi:10.1016/S1352-2310(01)00186-8
- Wilson, R.B., G.E. Start, C.R. Dickson, and N.R. Ricks. 1976. Diffusion under low wind speed conditions near Oak Ridge, Tennessee. *NOAA Technical Memorandum* ERL ARL-61, 83 pp. <http://www.arl.noaa.gov/documents/reports/ARL-61.pdf> (accessed September 9, 2015).

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## **Appendix D**

### **Supplemental Evaluation of AERMOD Version 15181 Low Wind Options for the Tall Stack Evaluation Databases**

# Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases with AERMET ADJ\_U\* and AERMOD LOWWIND3 Options

Olga Samani and Robert Paine, AECOM

August 22, 2015

## Introduction

In a proposed rulemaking published in the July 29, 2015 Federal Register (80 FR 45340), the United States Environmental Protection Agency (EPA) released a revised version of AERMOD (15181), which replaces the previous version of AERMOD dated 14134. EPA proposed refinements to its preferred short-range model, AERMOD, involving low wind conditions. These refinements involve an adjustment to the computation of the friction velocity (“ADJ\_U\*”) in the AERMET meteorological pre-processor and a higher minimum lateral lateral wind speed standard deviation, sigma-v ( $\sigma_v$ ), as incorporated into the “LOWWIND3” option. The proposal indicates that “the LOWWIND3 BETA option increases the minimum value of sigma-v from 0.2 to 0.3 m/s, uses the FASTALL approach to replicate the centerline concentration accounting for horizontal meander, but utilizes an effective sigma-y and eliminates upwind dispersion”.<sup>1</sup>

This document describes the evaluation of the combined ADJ\_U\* and LOWWIND3 options as recommended by EPA for incorporated as default options in AERMOD version 15181 on two previously evaluated tall-stack databases as described by Paine et al. (2015)<sup>2</sup>. Here we compare the model evaluation results of these new options relative to the various modeling options previously tested model options in AERMOD version 14134.

## Modeling Options and Databases for Testing

The meteorological data, emissions, and receptors used in this analysis were identical to Paine et al. (2015) analysis. Two AERMET/AERMOD model configurations were tested for the two field study databases.

- AERMET and AERMOD in default mode with version 15181.
- Low wind beta option for AERMET (ADJ\_U\*) and the LOWWIND3 option for AERMOD (LOWWIND3 automatically sets minimum  $\sigma_v$  value to 0.3 m/sec) with version 15181.

The results were compared to the five AERMET/AERMOD model configurations previously tested in Paine et al. (2015) with version 13350.

- AERMET and AERMOD in default mode.

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<sup>1</sup> Addendum User’s Guide for the AMS/EPA Regulatory Model – AERMOD  
[http://www.epa.gov/ttn/scram/models/aermod/aermod\\_userguide.zip](http://www.epa.gov/ttn/scram/models/aermod/aermod_userguide.zip)

<sup>2</sup> Paine, R., Samani, O., Kaplan, M. Knipping, E., and Kumar, N. Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases. Pending publications (as of August, 2015) in the Journal of Air & Waste Management Association.

- Low wind beta option for AERMET and default options for AERMOD (minimum  $\sigma_v$  value of 0.2 m/sec).
- Low wind beta option for AERMET and the LOWWIND2 option for AERMOD (minimum  $\sigma_v$  value of 0.3 m/sec).
- Low wind beta option for AERMET and the LOWWIND2 option for AERMOD (minimum  $\sigma_v$  value of 0.5 m/sec).
- Low wind beta option for AERMET and AERMOD run in sub-hourly mode (SHARP).

All model applications used one wind level, a minimum wind speed of 0.5 m/sec, and also used hourly average meteorological data with the exception of SHARP applications.

The Mercer County, North Dakota and Gibson Generating Station, Indiana databases were selected for the low wind model evaluation due to the following attributes:

- They feature multiple years of hourly SO<sub>2</sub> monitoring at several sites.
- Emissions are dominated by tall stack sources that are available from continuous emission monitors.
- They include sub-hourly meteorological data so that the SHARP modeling approach could be tested as well.
- There is representative meteorological data from a single-level station typical of (or obtained from) airport-type data.

### **Model Evaluation Results**

The model evaluation employed metrics that address two basic areas:

- 1) 1-hour SO<sub>2</sub> NAAQS Design Concentration averaged over the years modeled at each monitor.

An operational metric that is tied to the form of the 1-hour SO<sub>2</sub> NAAQS is the “design concentration” (99<sup>th</sup> percentile of the peak daily 1-hour maximum values). This tabulated statistic was developed for each modeled case and for each individual monitor for each database evaluated.

- 2) Quantile-Quantile Plots for each monitor.

Operational performance of models for predicting compliance with air quality regulations, especially those involving a peak or near-peak value at some unspecified time and location, can be assessed with quantile-quantile (Q-Q) plots, which are widely used in AERMOD evaluations. Q-Q plots are created by independently ranking (from largest to smallest) the predicted and the observed concentrations from a set of predictions initially paired in time and space. A robust model would have all points on the diagonal (45-degree) line.

## North Dakota Database Model Evaluation Procedures and Results

AERMOD was run for the two version 15181 configurations described above to compute the 1-hour daily maximum 99<sup>th</sup> percentile averaged over four years at the five ambient monitoring locations. A regional background of 10  $\mu\text{g}/\text{m}^3$  was added to the AERMOD modeled predictions, as determined from a review of rural monitors unaffected by local sources.

The 1-hour  $\text{SO}_2$  design concentrations and ratios of the modeled (including the background of 10  $\mu\text{g}/\text{m}^3$ ) to monitored design concentrations for the North Dakota evaluation database are summarized in Table 1 and graphically plotted in Figure 2. The results of the Paine et al. (2015) model evaluation analysis for the five options (version 13350) is shown here along with the results of the new evaluation with AERMOD version 15181.

The overall results indicate that the predicted-to-observed ratios are generally greater than 1.0 and AERMOD version 15181 still over-predicts even with use of the proposed ADJ\_u\* and the LOWWIND3 options. The low wind options show improvement relative to the default options at all monitors, especially the monitor in higher terrain (DGC #17).

As shown in Figure 1, and as expected the results for the new model with low wind options are very close to the AERMOD version 14134 model with ADJ\_U\* and LOWWIND2. The results of the two model versions with default options are also very close to each other.

The Q-Q plots of the ranked top fifty daily maximum 1-hour  $\text{SO}_2$  concentrations for predictions and observations are shown in Figure 2 (a-e) for AERMOD version 15181 default and low wind options. For the convenience of the reader, a vertical dashed line is included in each Q-Q plot to indicate the observed design concentration. In general, the Q-Q plots indicate the following:

- For all of the monitors, to the left of the design concentration line, the ranked predictions are at or higher than observations.
- To the right of the design concentration line, some of the ranked modeled values are lower than the ranked observed levels (although this is not the case for DGC #17).

## **Gibson Generating Station Database Model Evaluation Procedures and Results**

AERMOD was run for the two version 15181 configurations described above to compute the 1-hour daily maximum 99<sup>th</sup> percentile averaged over three years at the four ambient monitors. A regional background of 18  $\mu\text{g}/\text{m}^3$  was added to the AERMOD modeled predictions.

The ratio of the modeled (including the background of 18  $\mu\text{g}/\text{m}^3$ ) to monitored concentrations is summarized in Table 2 and graphically plotted in Figure 3, and these ratios are generally greater than 1.0. The current version of AERMOD (version 15181) run in default mode showed no changes from the previous version's default results, still having over-predictions of about 10-50%. The proposed low wind options provided modest improvements in performance relative to the default options, while still showing an over-prediction tendency at each monitor.

The Q-Q plots of the ranked top fifty daily maximum 1-hour  $\text{SO}_2$  concentrations for predictions and observations are shown in Figure 4 (a-d). As in the case of the North Dakota evaluation results, the Gibson plots indicate the following:

- For all of the monitors, to the left of the design concentration line, the ranked predictions are at or higher than observations.
- To the right of the design concentration line, some of the ranked modeled values are lower than the ranked observed levels (although this is not the case for Shrodt or Mt. Carmel for the low wind options).

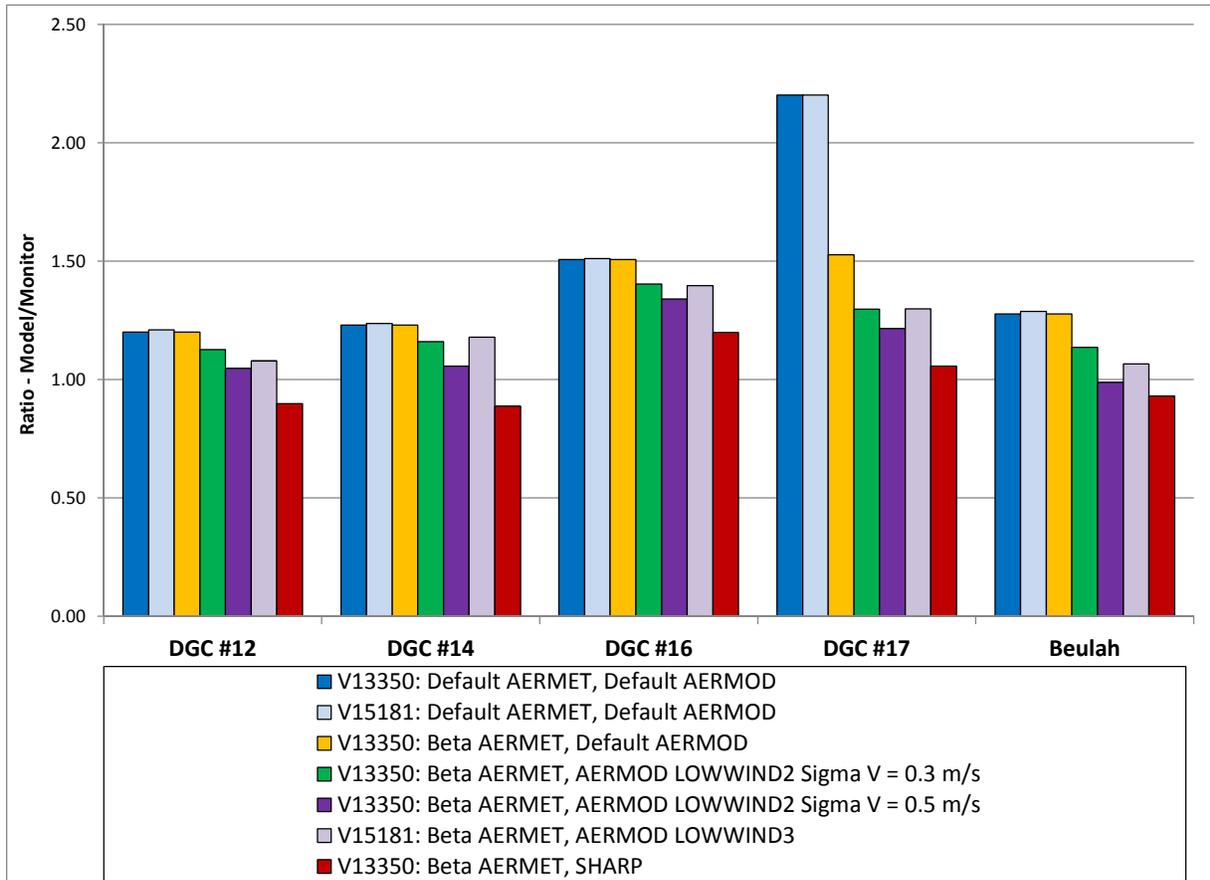
## **Conclusions**

The model evaluation results for the new version of AERMOD (version 15181) on the two databases showed that the proposed low wind options (ADJ\_U\* and LOWWIND3) perform better than the default options, while still overpredicting the design concentration at each monitor in both databases. Therefore, in conjunction with other evaluations that EPA reported at the 11<sup>th</sup> modeling conference on August 12, 2015, we recommend that EPA adopt the proposed low wind options default options, and allow their use in the interim for all modeling applications.

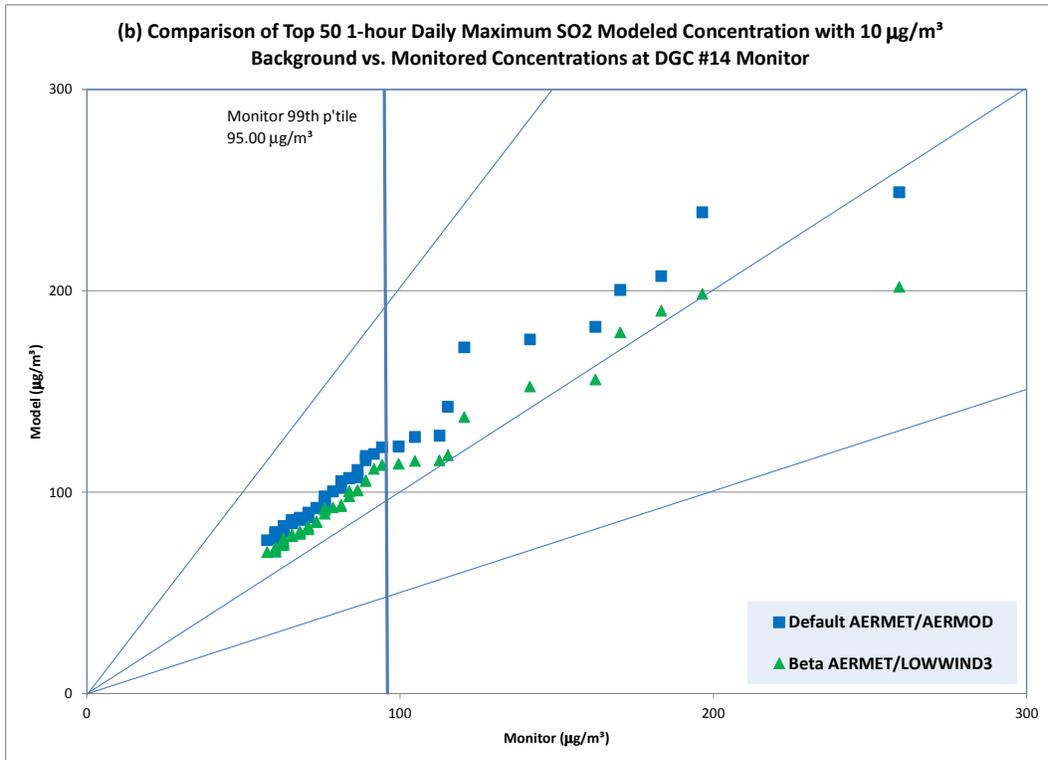
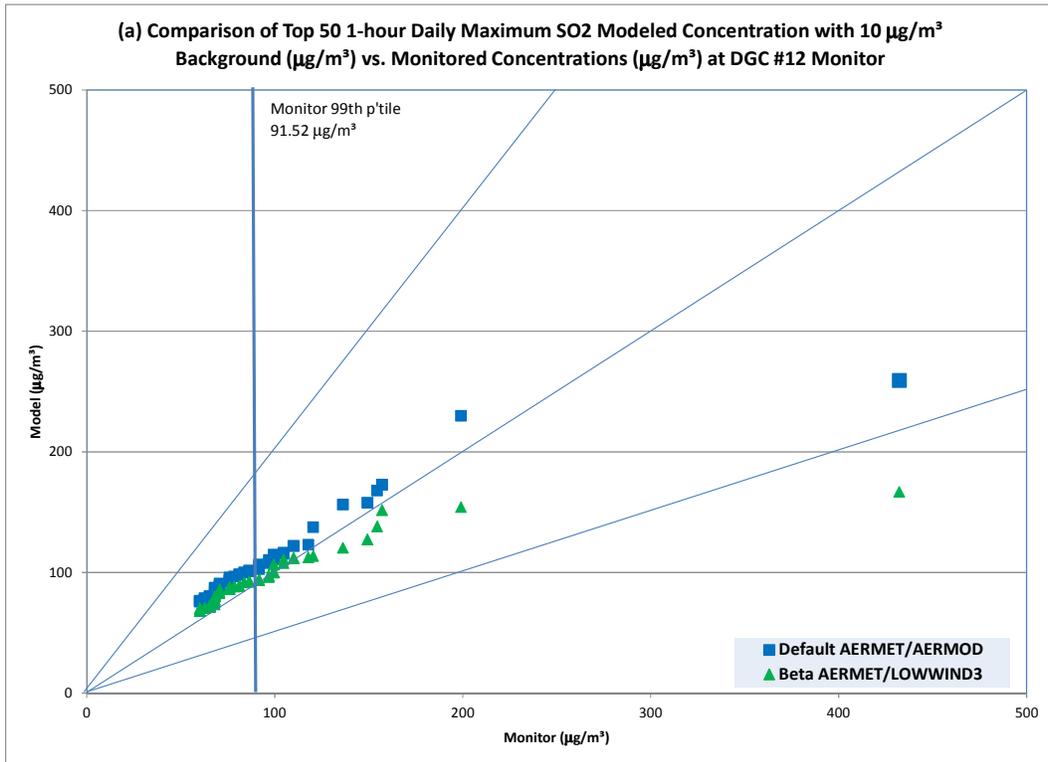
**Table 1: North Dakota Ratio of Monitored to Modeled Design Concentrations\***

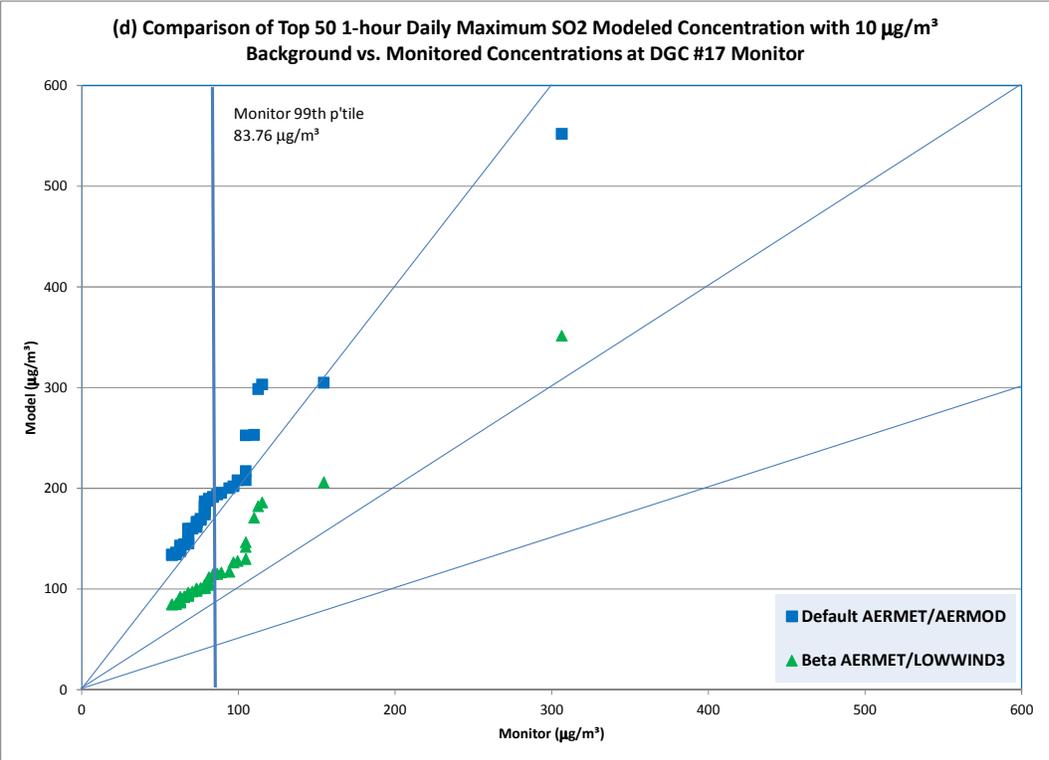
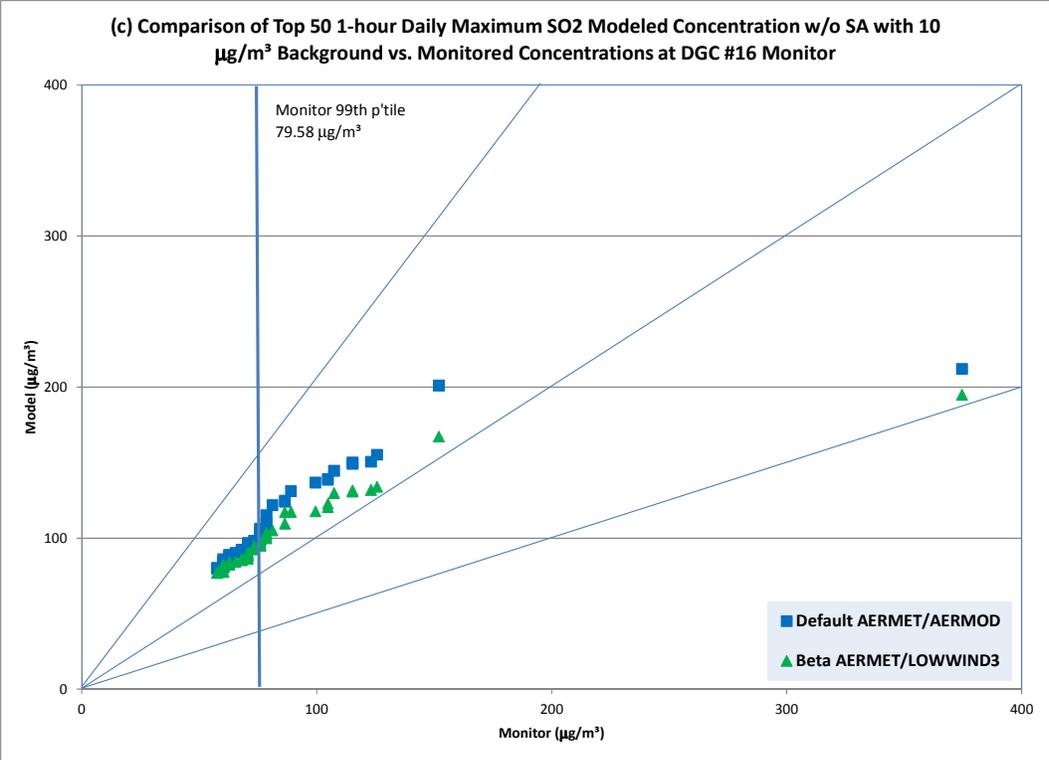
Model Version	Test Case	Monitor	Observed	Predicted	Ratio
13350 (previously reported results)	Default AERMET, Default AERMOD	DGC#12	91.52	109.96	1.20
		DGC#14	95.00	116.84	1.23
		DGC#16	79.58	119.94	1.51
		DGC#17	83.76	184.48	2.20
		Beulah	93.37	119.23	1.28
15181	Default AERMET, Default AERMOD	DGC#12	91.52	110.77	1.21
		DGC#14	95.00	117.51	1.24
		DGC#16	79.58	120.30	1.51
		DGC#17	83.76	184.49	2.20
		Beulah	93.37	120.31	1.29
13350 (previously reported results)	Beta AERMET, Default AERMOD	DGC#12	91.52	109.96	1.20
		DGC#14	95.00	116.84	1.23
		DGC#16	79.58	119.94	1.51
		DGC#17	83.76	127.93	1.53
		Beulah	93.37	119.23	1.28
13350 (previously reported results)	Beta AERMET, AERMOD with LOWWIND2 $\sigma_v =$ 0.3 m/sec	DGC#12	91.52	103.14	1.13
		DGC#14	95.00	110.17	1.16
		DGC#16	79.58	111.74	1.40
		DGC#17	83.76	108.69	1.30
		Beulah	93.37	106.05	1.14
13350 (previously reported results)	Beta AERMET, AERMOD with LOWWIND2 $\sigma_v =$ 0.5 m/sec	DGC#12	91.52	95.86	1.05
		DGC#14	95.00	100.50	1.06
		DGC#16	79.58	106.65	1.34
		DGC#17	83.76	101.84	1.22
		Beulah	93.37	92.32	0.99
15181	Beta AERMET, AERMOD with LOWWIND3	DGC#12	91.52	98.75	1.08
		DGC#14	95.00	112.09	1.18
		DGC#16	79.58	111.20	1.40
		DGC#17	83.76	108.76	1.30
		Beulah	93.37	99.54	1.07
13350 (previously reported results)	SHARP	DGC#12	91.52	82.18	0.90
		DGC#14	95.00	84.24	0.89
		DGC#16	79.58	95.47	1.20
		DGC#17	83.76	88.60	1.06
		Beulah	93.37	86.98	0.93
*Design Concentration: 99 <sup>th</sup> percentile peak daily 1-hour maximum, averaged over the years modeled and monitored.					

**Figure 1: North Dakota Ratio of Monitored to Modeled Design Concentration Values**

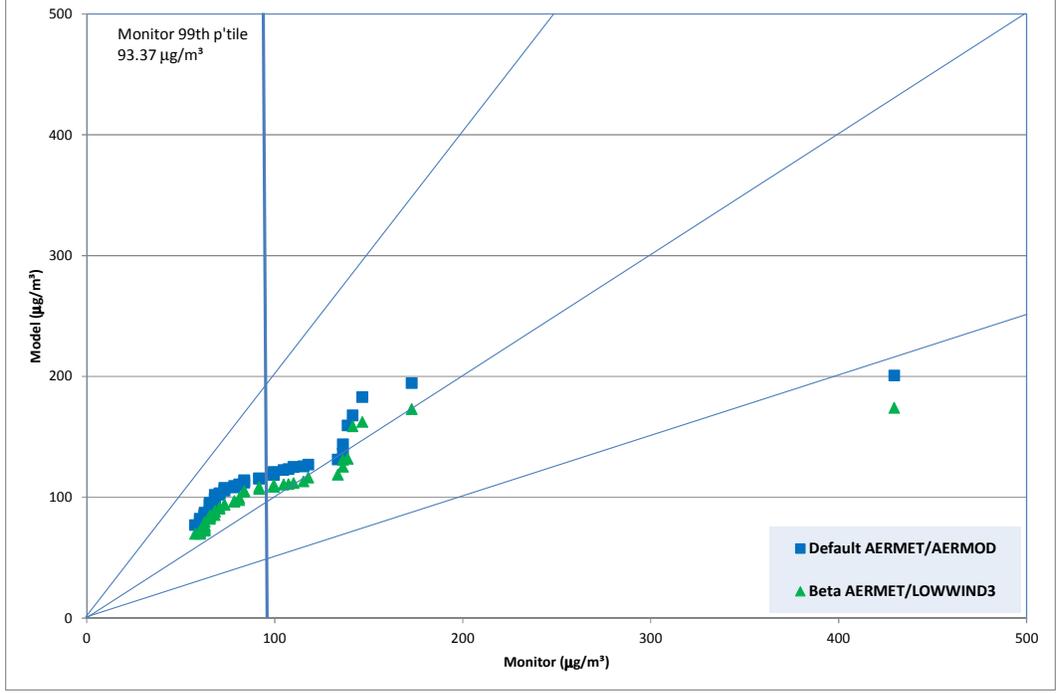


**Figure 2: North Dakota Q-Q Plots: Top 50 Daily Maximum 1-hour SO<sub>2</sub> Concentrations. (a) DGC #12 Monitor. (b) DGC#14 Monitor. (c) DGC#16 Monitor. (d) DGC#17 Monitor. (e) Beulah Monitor**





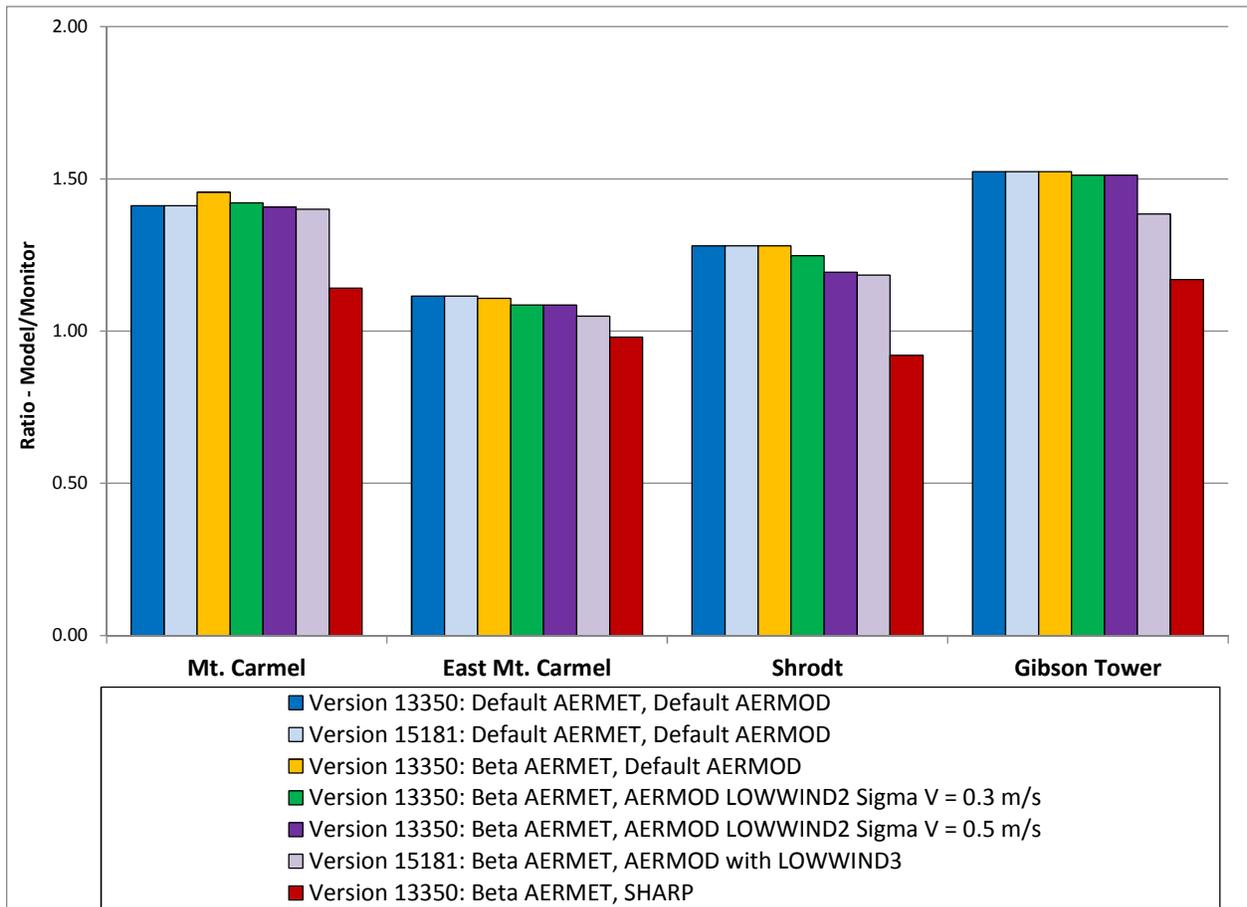
(e) Comparison of Top 50 1-hour Daily Maximum SO<sub>2</sub> Modeled Concentration with 10 µg/m<sup>3</sup> Background vs. Monitored Concentrations at Beulah Monitor



**Table 2: Gibson Ratio of Monitored to Modeled Design Concentrations\***

Model Version	Test Case	Monitor	Observed	Predicted	Ratio
13350 (previously reported results)	Default AERMET, Default AERMOD	Mt. Carmel	197.25	278.45	1.41
		East Mt.	206.89	230.74	1.12
		Shrodt	148.16	189.63	1.28
		Gibson Tower	127.12	193.71	1.52
15181	Default AERMET, Default AERMOD	Mt. Carmel	197.25	278.45	1.41
		East Mt.	206.89	230.74	1.12
		Shrodt	148.16	189.63	1.28
		Gibson Tower	127.12	193.71	1.52
13350 (previously reported results)	Beta AERMET, Default AERMOD	Mt. Carmel	197.25	287.16	1.46
		East Mt.	206.89	229.22	1.11
		Shrodt	148.16	189.63	1.28
		Gibson Tower	127.12	193.71	1.52
13350 (previously reported results)	Beta AERMET, AERMOD with LOWWIND2 $\sigma_v =$ 0.3 m/sec	Mt. Carmel	197.25	280.32	1.42
		East Mt.	206.89	224.65	1.09
		Shrodt	148.16	184.82	1.25
		Gibson Tower	127.12	192.22	1.51
13350 (previously reported results)	Beta AERMET, AERMOD with LOWWIND2 $\sigma_v =$ 0.5 m/sec	Mt. Carmel	197.25	277.57	1.41
		East Mt.	206.89	224.65	1.09
		Shrodt	148.16	176.81	1.19
		Gibson Tower	127.12	192.22	1.51
15181	Beta AERMET, AERMOD with LOWWIND3	Mt. Carmel	197.25	276.12	1.40
		East Mt.	206.89	217.05	1.05
		Shrodt	148.16	175.42	1.18
		Gibson Tower	127.12	175.92	1.38
13350 (previously reported results)	SHARP	Mt. Carmel	197.25	225.05	1.14
		East Mt.	206.89	202.82	0.98
		Shrodt	148.16	136.41	0.92
		Gibson Tower	127.12	148.64	1.17
*Design Concentration: 99 <sup>th</sup> percentile peak daily 1-hour maximum, averaged over the years modeled and monitored.					

**Figure 3: Gibson Ratio of Monitored to Modeled Design Concentration Values**



**Figure 4: Gibson Q-Q Plots: Top 50 Daily Maximum 1-hour SO<sub>2</sub> Concentrations.**  
**(a) Mt. Carmel Monitor. (b) East Mt. Carmel Monitor. (c) Shrodt Monitor. (d) Gibson Tower Monitor**

