PacifiCorp Dave Johnston Power Plant – SO_2 DRR Modeling Report

PacifiCorp

Project Number: 60446049

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Quality information

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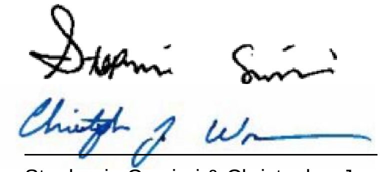		
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1. Introduction

1.1 Overview of the SO_2 Data Requirements Rule

In August 2015, the U.S. Environmental Protection Agency (EPA) issued the SO_2 Data Requirements Rule[1] (DRR), which directs state and tribal air agencies in "an orderly process" to identify maximum ambient air 1-hour SO_2 concentrations in areas with large sources of SO_2 emissions.

The purpose of the DRR is to identify large SO_2-emitting sources, generally those with annual emissions greater than 2,000 tons for the most recent year for which emissions data are available and to characterize SO_2 concentrations in the vicinity of these sources. The affected sources are those that have not been previously captured as part of the initial non-attainment area designations for the 1-hour SO_2 National Ambient Air Quality Standard (NAAQS) in August 2013 or with the sources identified by the March 2015 Consent Decree between the EPA and the Sierra Club and National Resources Defense Council.

The Wyoming Department of Environmental Quality (WDEQ) is consulting with the owners or operators of the DRR-identified sources in Wyoming to identify the means for determining whether the area surrounding each identified source is in attainment with the SO_2 NAAQS for area designation purposes. This report addresses one of the sources identified as being subject to these requirements: the Dave Johnston Power Plant located near Glenrock, Wyoming, which is owned and operated by PacifiCorp.

According to the DRR, the method of characterizing the SO_2 concentrations around each source can be done by either:

1) installing and operating an ambient air monitoring network; or
2) performing an air dispersion modeling study to characterize the SO_2 concentration pattern in areas beyond the secured industrial boundary where monitors could be placed.

Alternatively, instead of a source characterization, each identified source can modify its air operating permit prior to January 13, 2017 such that the DRR-identified source either:

3) limits annual SO_2 emissions to less than 2,000 tons, or
4) limits short-term (1-hour) and/or longer-term (up to 30-day average) SO_2 emissions that, based on the results of an air dispersion modeling study, demonstrate that the area surrounding the source is in attainment with the SO_2 NAAQS, allowing the state air agency to provide a recommendation for a designation of attainment with the NAAQS.

Although PacifiCorp has adopted Option 1 to satisfy the DRR requirements, this document provides a supplemental analysis using air quality modeling procedures and results of an air dispersion modeling demonstration that was performed to characterize SO_2 concentrations around the Dave Johnston Power Plant.

A draft dispersion modeling protocol for Dave Johnston was submitted to WDEQ and EPA Region 8 dated February 12, 2016. WDEQ and EPA Region 8 provided written comments on the draft modeling protocol on June 28, 2016. Comments were addressed in a subsequent revised draft dispersion modeling protocol for Dave Johnston submitted to WDEQ and EPA Region 8 on December 13, 2016. This dispersion modeling report is consistent with the modeling protocol submitted on December 13, 2016.

The current version of the TAD references other EPA modeling guidance documents, including the following clarification memos (1) the August 23, 2010 "Applicability of Appendix W Modeling Guidance for the 1-hour SO_2 NAAQS" and (2) the March 1, 2011 "Additional Clarification Regarding Application W Modeling Guidance for the 1-hour NO_2 National Ambient Air Quality Standard" (hereafter referred to as the "additional clarification memo"). In the March 1, 2011 clarification memo, EPA declares that the memo applies equally to the 1-hour SO_2 NAAQS even though it was prepared primarily for the 1-hour NO_2 NAAQS.

[1] Docket ID No. EPA–HQ–OAR–2013–0711, August 10, 2015. http://www.epa.gov/oaqps001/sulfurdioxide/pdfs/so2_drr__final_081215.pdf.

1.2 Report Organization

This report consists of five sections. **Section 1** provides this introductory discussion. **Section 2** provides a description of the PacifiCorp Dave Johnston facility. That section also includes a topographic map centered at the source, and tables of emission points (and stack parameters). **Section 3** provides the general modeling approach and technical options used. **Section 4** discusses the model configuration, including model domain, nearby sources, receptors, ambient background, and meteorological data. **Section 5** discusses the procedures that were used to characterize SO_2 concentrations in the vicinity of the Dave Johnston plant and the modeling results.

2. Description of PacifiCorp's Dave Johnston Facility

PacifiCorp's Dave Johnston Power Plant is located about 5 miles southeast of Glenrock, Wyoming in Converse County. Dave Johnston has four existing coal-fired boilers and based on the current stack configuration, flues for Boilers 1 and 2 exhaust through a combined 496-foot stack. Similarly, flues for Boilers 3 and 4 exhaust through a second combined 497-foot stack. For the combined flues, the modeling was conducted with a single merged stack, consistent with EPA precedent established with Model Clearinghouse Memo 91-II-01[2].

The location of the plant is shown in **Figure 2-1**. A topographic map of the area surrounding Dave Johnston is provided in **Figure 2-2**. As shown in **Figure 2-2**, there is "complex" terrain (with elevations above stack top) within 10 kilometers of the plant. In addition, as shown in **Figures 2-1** and **2-2**, the area in the immediate vicinity (i.e., within 3 km) of Dave Johnston can be characterized as having a rural land use type.

The modeling was performed with the actual stack heights in accordance with recommendations in the DRR and TAD. **Table 2-1** shows the physical stack parameters that were used in the modeling. The hourly exhaust flow rates, temperatures, and emission rates were based on the actual data available from the continuous emission monitor (CEM) systems. The emissions for modeling consist of actual hourly data for the most recent 36-month period (November 2013-October 2016).

The four coal-fired boilers are the major sources of SO_2 emissions at Dave Johnston. There are other small insignificant sources of SO_2 at Dave Johnston; however, these sources are either emergency in nature and thus do not operate routinely or have very low actual SO_2 emissions. In either case, these small sources of SO_2 do not have an impact on the results of the 1-hour SO_2 modeling and were not included in the modeling consistent with guidance provided by EPA's March 1, 2011 Clarification Memo[3]. As such, the four coal-fired boilers are the only emission sources from the Dave Johnston Power Plant that were included in the 1-hour SO_2 modeling.

Table 2-1: Dave Johnston – Physical Stack Parameters(1)

Unit	Description	Stack Base Elevation (feet msl)	Stack Height (feet)	Flue Diameter (feet)
Unit 1	Tangential Coal Fired Boiler	4954	496	16 (effective)
Unit 2	Tangential Coal Fired Boiler			
Unit 3	Tangential Coal Fired Boiler	4956	497	25 (effective)
Unit 4	Tangential Coal Fired Boiler			

(1) Emission rates, exhaust temperature, and exhaust flow rate were based on hourly CEMs data.

[2] Available at http://cfpub.epa.gov/oarweb/MCHISRS/index.cfm?fuseaction=main.resultdetails&recnum=91-II%20%20-01.
[3] Available at http://www3.epa.gov/scram001/guidance/clarification/Additional_Clarifications_AppendixW_Hourly-NO2-NAAQS_FINAL_03-01-2011.pdf.

Figure 2-1: Location of the Dave Johnston Power Plant

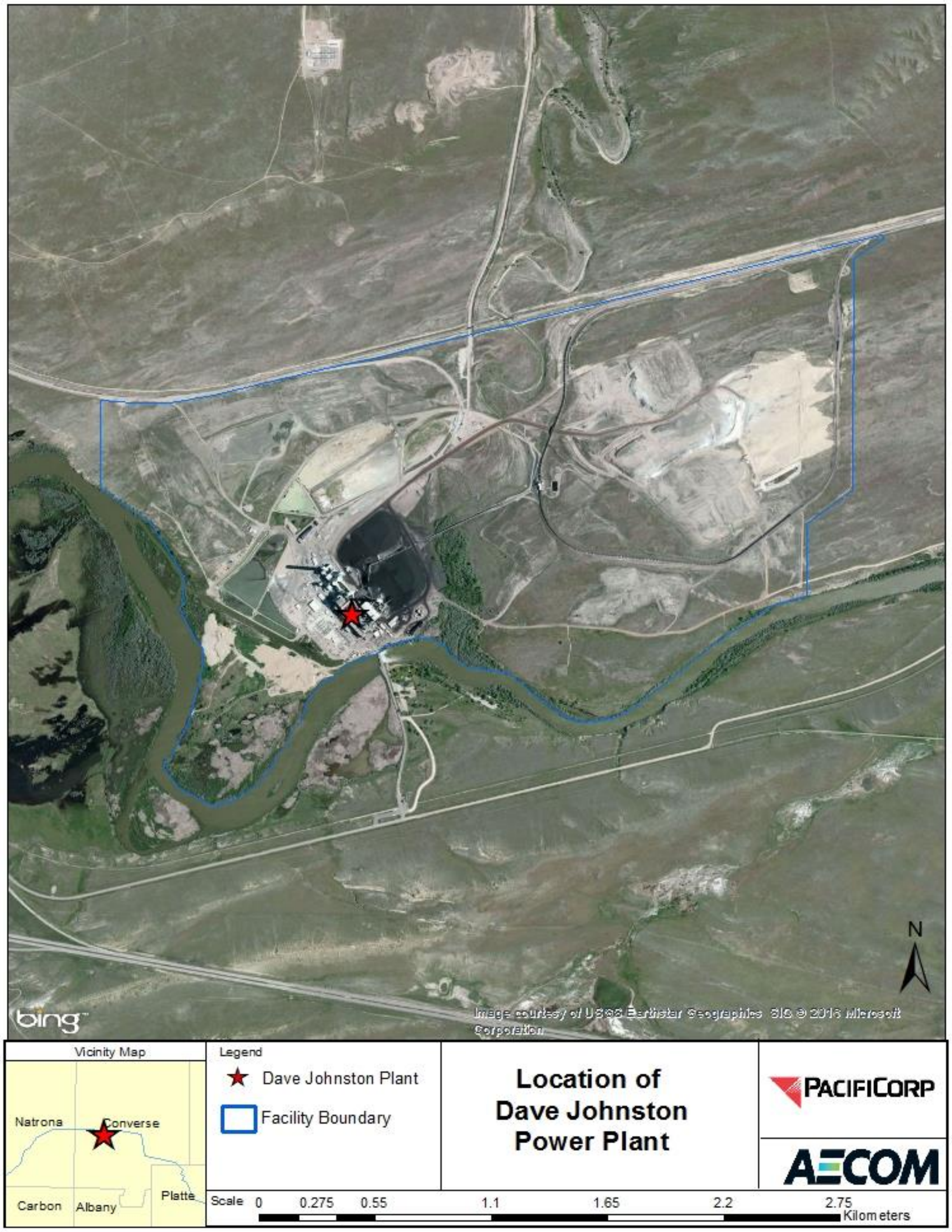
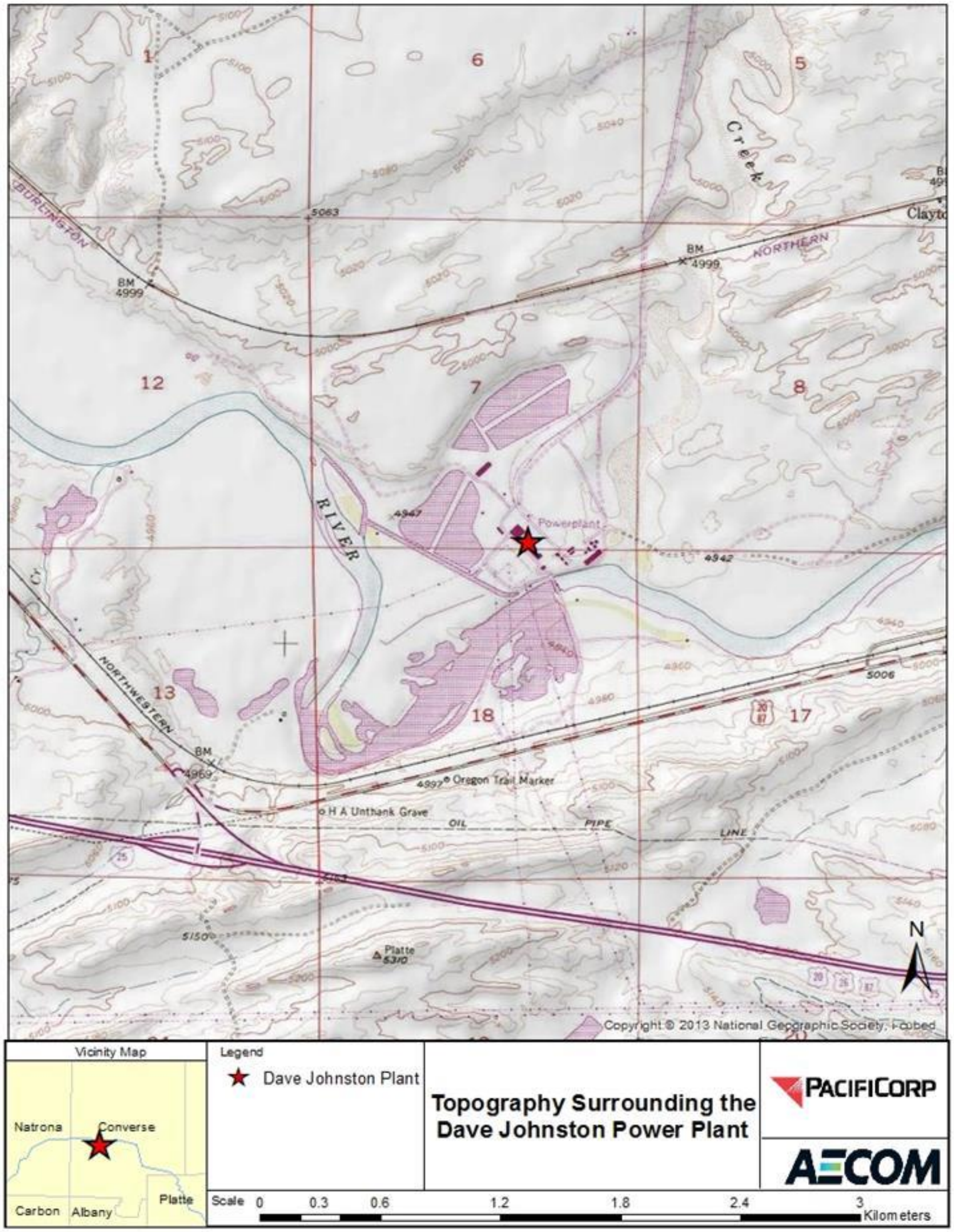


Figure 2-2: Topography in the Vicinity of Dave Johnston Power Plant



3. Dispersion Modeling Selection and Options

The EPA Guideline on Air Quality Models (Appendix W[4]) prescribes a set of approved models for regulatory applications for a wide range of source types and dispersion environments. Based on a review of the factors discussed below, the latest version[5] of AERMOD (15181) was used in the DRR modeling for the PacifiCorp Dave Johnston facility.

In a proposed rulemaking published in the July 29, 2015 Federal Register (80 FR 45340), the USEPA released a revised version of AERMOD (15181), which replaces the previous version of AERMOD dated 14134. The rulemaking included proposed refinements to EPA's 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. At present, ADJ_U* remains a non-guideline beta option, the use of which requires EPA concurrence. It is anticipated that the ADJ_U* option will become a guideline option when the upcoming Appendix W update is release, thus no longer requiring EPA concurrence. Recent examples of such concurrence are found in EPA's February 10, 2016 and April 29, 2016 release of the Model Clearinghouse Review of the Use of ADJ_U* Beta Option,[6, 7] each of which supports the use of this non-guideline beta option.

On September 28, 2016, PacifiCorp submitted an alternate model justification package consistent with Appendix W, Section 3.2.2 for the use of the non-regulatory ADJ_U* option. This alternate model justification package, along with supporting documentation, is provided in Appendices A, B, and C.

Another technical option that was ultimately not used due to lack of time for requesting its use, but would make the modeling more accurate, is a source characterization approach[8] called "AERMOIST". This approach does not change the model, but rather accounts more appropriately for the increased heat of condensation inherent in these plumes (under certain atmospheric conditions) that results in more accurate plume rise calculations. Since this approach was not used in the modeling, the modeling results are conservatively high due to the lack of consideration of the moist plume effect in AERMOD.

Based on EPA guidance provided in the modeling Technical Assistance Document (TAD), all stacks were modeled with their actual physical stack height. In addition, EPA's Building Profile Input Program (BPIP-Version 04274) version that is appropriate for use with PRIME algorithms in AERMOD was used to incorporate downwash effects in the model for all modeled point sources. The building dimensions of nearby building structures were input to the BPIPPRM program to determine direction-specific building data for input to AERMOD, as shown in **Figure 3-1**.

Consistent with the updated modeling TAD guidance for characterizing SO_2 concentrations due to existing emissions, actual hourly emission rates (as well as hourly stack temperature and exit velocity) from a recent 36-month period (November 2013- October 2016) were used.

For SO_2 designations modeling, the areas to consider for receptor placement are those areas that would be considered ambient air relative to each modeled facility, including other facilities' property. However, for some limited ambient air locations, such as water bodies, receptors can be excluded or ignored in analyses as monitors could not feasibly be placed in those areas. For the purposes of modeling for designations, power inaccessibility or locations in areas located near roadways are not appropriate rationales for excluding receptors."

Consistent with the updated TAD guidance, receptors used in the modeling were excluded only from the following areas that are not considered ambient air, or where a monitor could not be feasibly placed or maintained, including areas subject to the threat of disruption or removal by industrial processes (e.g., strip mines):

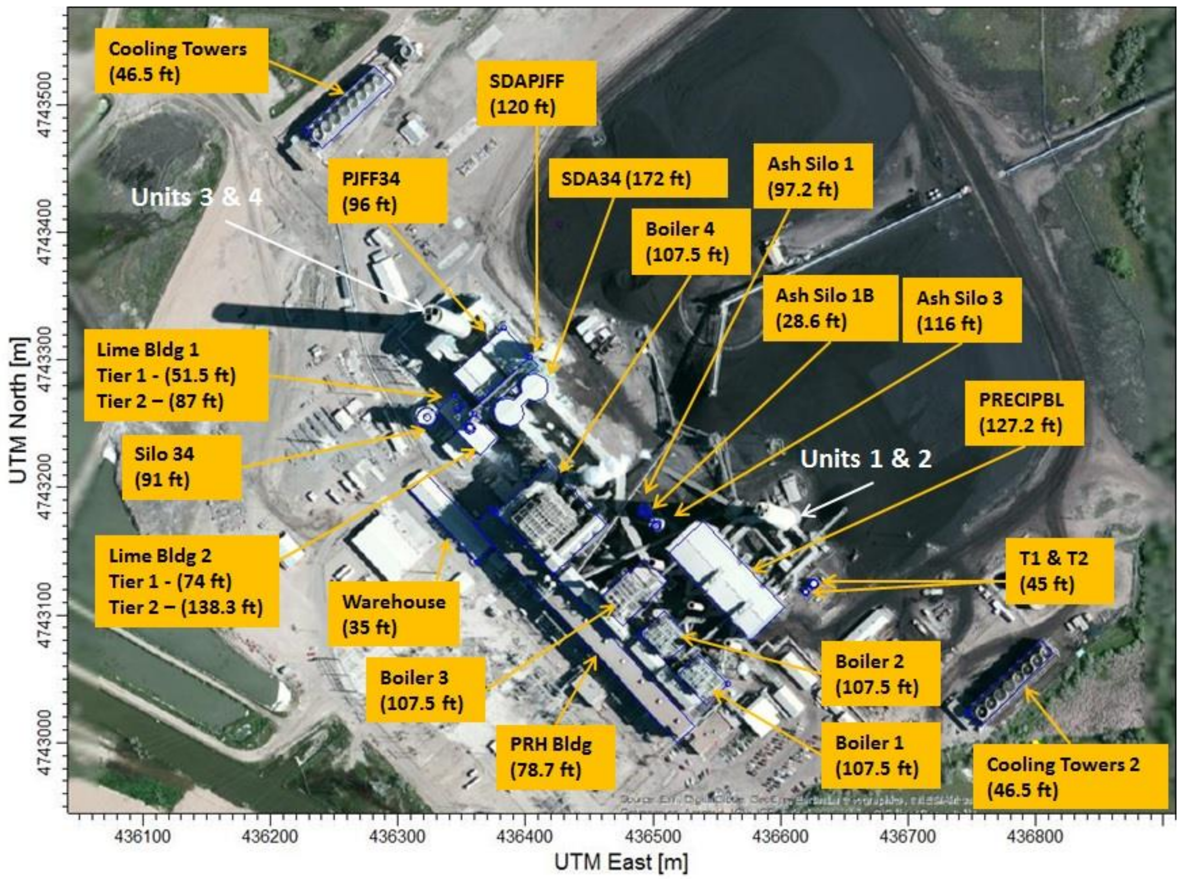
5) over water (rivers, lakes, ponds, and swamps), and

6) on the secured property of PacifiCorp.

[4] Available at http://www3.epa.gov/ttn/scram/guidance/guide/appw_05.pdf.
[5] As of December 20, 2016.
[6] Available at http://www3.epa.gov/ttn/scram/guidance/mch/new_mch/16-X-01_MCResponse_Region10_Donlin-02102016.pdf
[7] Available at https://www3.epa.gov/ttn/scram/guidance/mch/new_mch/16-I-01_MCResponse_Region1_Schiller-04292016.pdf
[8] Described in the peer-reviewed journal article: Paine, R., Warren, L.L., Moore, G.E., Source Characterization Refinements for Routine Modeling Applications, *Atm. Env.* 129 (2016), 55-67. doi:10.1016/j.atmosenv.2016.01.003.

For this application, no receptors were actually excluded from water bodies, but receptors were excluded from the secured property within the Dave Johnston Power Plant. Receptor spacing used in the modeling was consistent with WDEQ guidelines[9] and features the most closely spaced receptors close to the Dave Johnston facility.

Figure 3-1: Stacks and Buildings in the GEP Analysis for Dave Johnston Power Plant



[9] http://deq.wyoming.gov/aqd/new-source-review/resources/guidance-documents/.

4. Modeling Configuration

4.1 Modeling Domain

The Dave Johnston Power Plant is a relatively isolated facility with little to no industrial development nearby. The modeling domain established was based on the area necessary to include all modeled sources (primary plus background) and all modeled receptor points. The modeling domain was set to 25 km, which is consistent with guidance from WDEQ[10].

4.2 Receptor Grid

The modeling analysis was conducted using the following Cartesian receptor grid design.

7) 50-m receptor spacing along the ambient air boundary for the SO_2 characterization,

8) 100-m receptor spacing extending out 1.8 kilometers from the grid center,

9) 250-m receptor spacing between 1.8 and 3.0 kilometers from the grid center,

10) 500-m receptor spacing between 3.0 and 10 kilometers from the grid center, and

11) 1000-m receptor spacing beyond 10 kilometers (out to 25 km).

The receptor grid used in the modeling analysis can be seen in **Figures 4-1 and 4-2** for near-field and far-field views, respectively. It was based on Universal Transverse Mercator (UTM) coordinates referenced to NAD 83 datum and in zone 13. The receptor grid was centered at the approximate mid-point of the modeled facility based on WDEQ Guidance Document. In consultation with the agency reviewers, receptors were only excluded from the secured area of Dave Johnston.

The latest version of AERMAP (version 15181), the AERMOD terrain preprocessor program, was used to calculate terrain elevations and critical hill heights for the modeled receptors at each of the project facilities using National Elevation Data (NED). The dataset was downloaded from the USGS website (http://viewer.nationalmap.gov/viewer/) and consisted of 1/3 arc second (~10 m resolution) NED. As per the AERMAP User's Guide, the domain was sufficient to ensure all significant nodes are included such that all terrain features exceeding a 10% elevation slope from any given receptor were considered.

[10] Wyoming Department of Environmental Quality/Air Quality Division Guidance for Submitting Major Source/PSD Modeling Analyses.

Figure 4-1: Near-Field Receptor Grid for Dave Johnston Power Plant

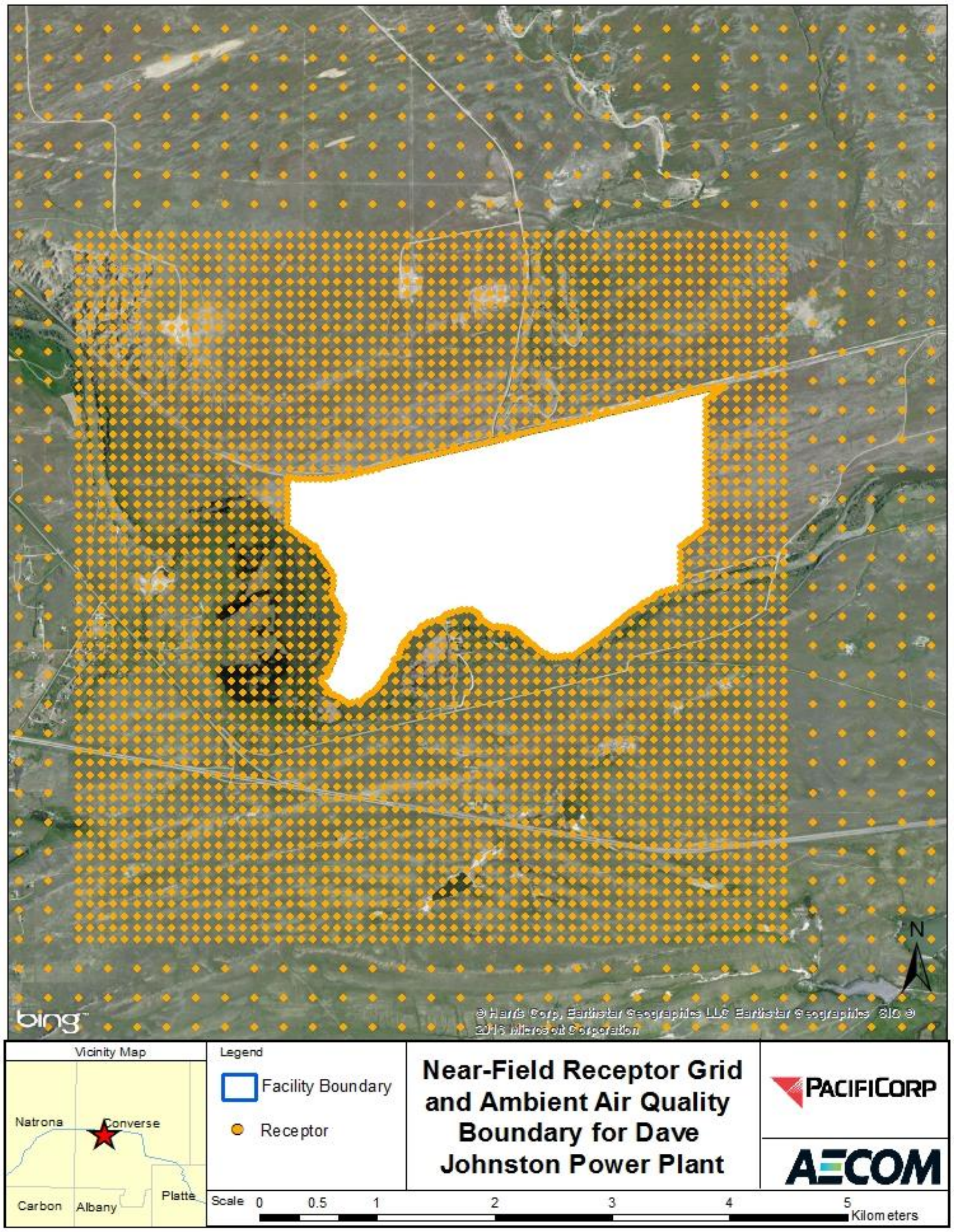
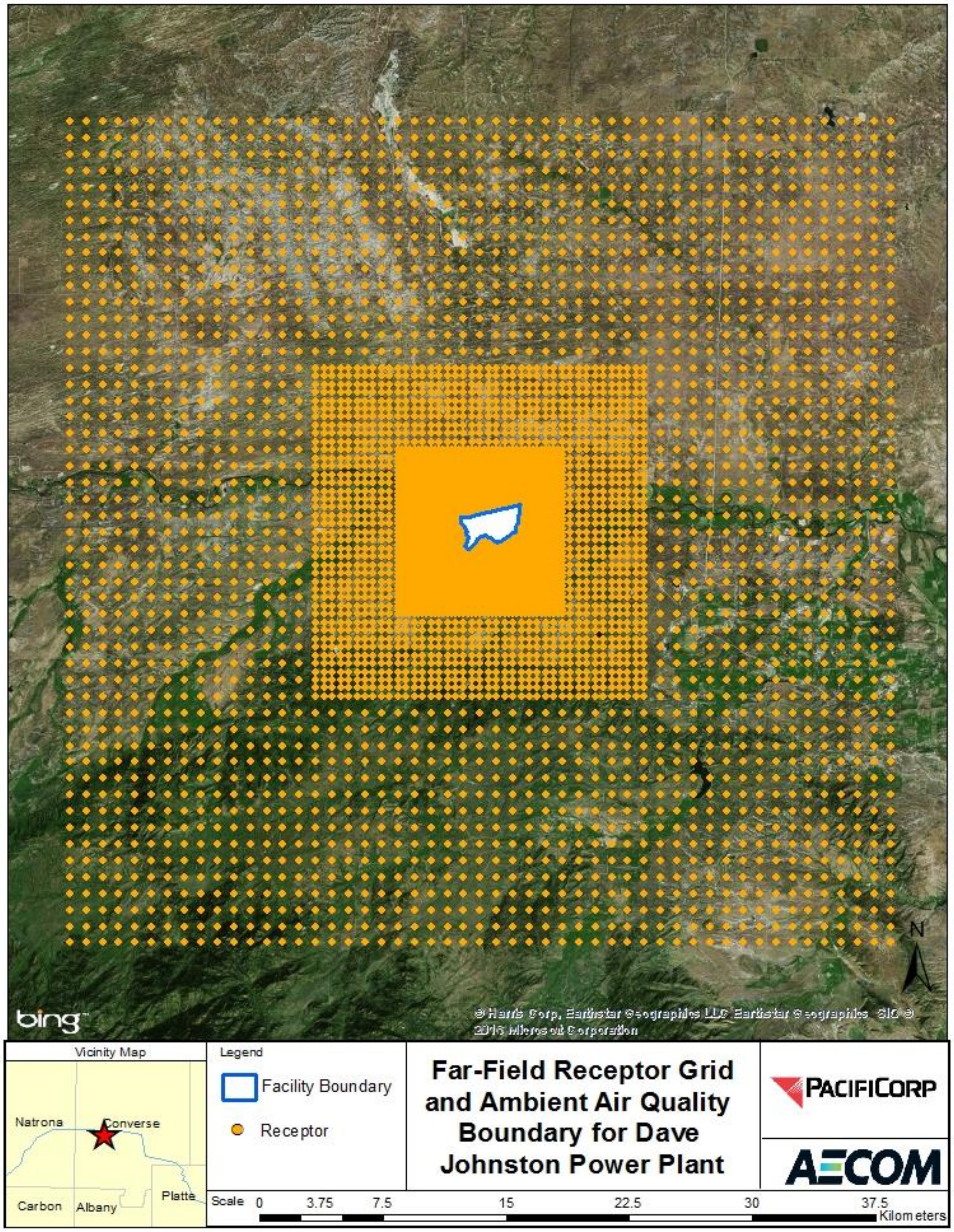


Figure 4-2: Far-Field Receptor Grid for Dave Johnston Power Plant



4.3 Meteorological Data for Modeling

Meteorological data required for AERMOD include hourly values of wind speed, wind direction, and ambient temperature. Since the AERMOD dispersion algorithms are based on atmospheric boundary layer dispersion theory, additional boundary layer variables are derived by parameterization formulas, which are computed by the AERMOD meteorological preprocessor, AERMET. These parameters include sensible heat flux, surface friction velocity, convective velocity scale, vertical potential temperature gradient, convective and mechanical mixing heights, Monin-Obukhov length, surface roughness length, Bowen ratio, and albedo.

Hourly surface observations (including 1-minute and 5-minute ASOS) were processed from Converse County Airport (Douglas, WY). Concurrent upper-air data was obtained from the closest or most representative National Weather Service site, which was determined to be Riverton, WY. Additional details are provided in the following sections.

4.3.1 Available Onsite Meteorological Data and Upper-Air Data

The hourly meteorological data for Dave Johnston was processed with the latest version of AERMET (Version 15181). AERMET was run utilizing three concurrent years (November 2013-October 2016) of hourly surface observations from Converse County Airport in Douglas, WY along with concurrent upper air data from Riverton, WY. In 2016 (May 25 – July 29), the Converse County airport ASOS experienced a prolonged data outage. Therefore, ASOS data from Torrington Municipal Airport was substituted during this outage period. **Figure 4-3** shows the location of the meteorological stations in relationship to the Dave Johnston Plant. A comparison of 2013-2015 wind roses from Converse County Airport **(Figure 4-4)** and Torrington Municipal Airport **(Figure 4-5)** located in Torrington, WY shows that they are very similar. **Figure 4-6** shows the wind rose for the Converse County Airport (augmented with backup data from Torrington during the May 25, 2016 – July 29, 2016 period) for the November 2013- October 2016 modeling period.

The AERMET inputs were based on surface meteorological data from the National Climatic Data Center's (NCDC) Integrated Surface Hourly (ISH) database along with both 1-minute and concurrent 5-minute Automated Surface Observing System (ASOS) data. The latest version of AERMINUTE (version 15272) was used to process this data. The upper air data input to AERMET was downloaded from the NOAA/ESRL/GSD - RAOB database (http://esrl.noaa.gov/raobs/). **Table 4-1** gives the site location and information on the meteorological datasets. The surface wind data are measured 10 meters above ground level. The temperature and relative humidity are measured 2 meters above ground level. **Table 4-2** provides the meteorological data capture percentages for the November 2013-October 2016 modeling period, showing data capture above 94% per quarter.

Table 4-1: Meteorological Data Used in AERMET for Dave Johnston

Met Site	Latitude	Longitude	Base Elevation (m)	Data Source	Data Format
Converse Airport - Douglas, WY	42.800	-105.380	1504.5	NCDC	ISHD, 1-min, 5-min ASOS
Torrington Airport - Torrington, WY	42.065	-104.150	1282.0	NCDC	ISHD, 1-min, 5-min ASOS
Riverton, WY	43.060	-108.470	1684	FSL	FSL

Table 4-2: Meteorological Data Capture Percentages Per Quarter for Converse County Airport Met Data Augmented with Torrington Airport[1]

Year	Q1	Q2	Q3	Q4
2013	Period Not Modeled			99.9%
2014	98.9%	98.8%	99.0%	94.4%
2015	98.1%	97.4%	97.9%	99.3%
2016[2]	99.5%	99.1%	95.7%	99.2%

[1] The percentage of hours available for modeling, as determined by AERMOD V. 15181. Note that Quarter 4 for 2013 consists of November and December, and the Quarter 4 for 2016 consists of only October.
[2] Torrington meteorology data used to fill in missing Converse AP only during May 25 – July 29, 2016 period.

Figure 4-3: Location of Meteorological Stations Relative to Dave Johnston Plant

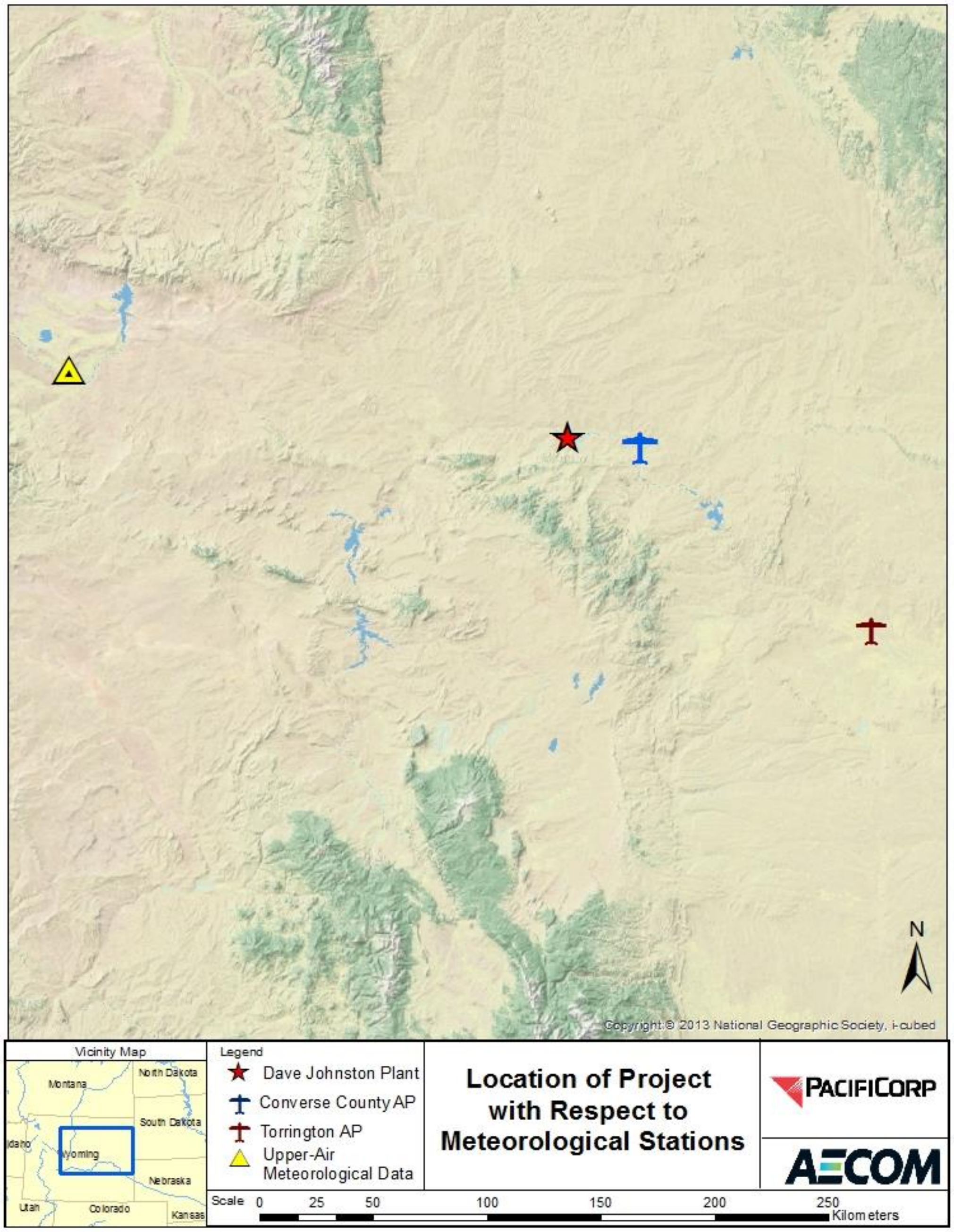


Figure 4-4: Wind Rose for Converse County Airport 2013-2015

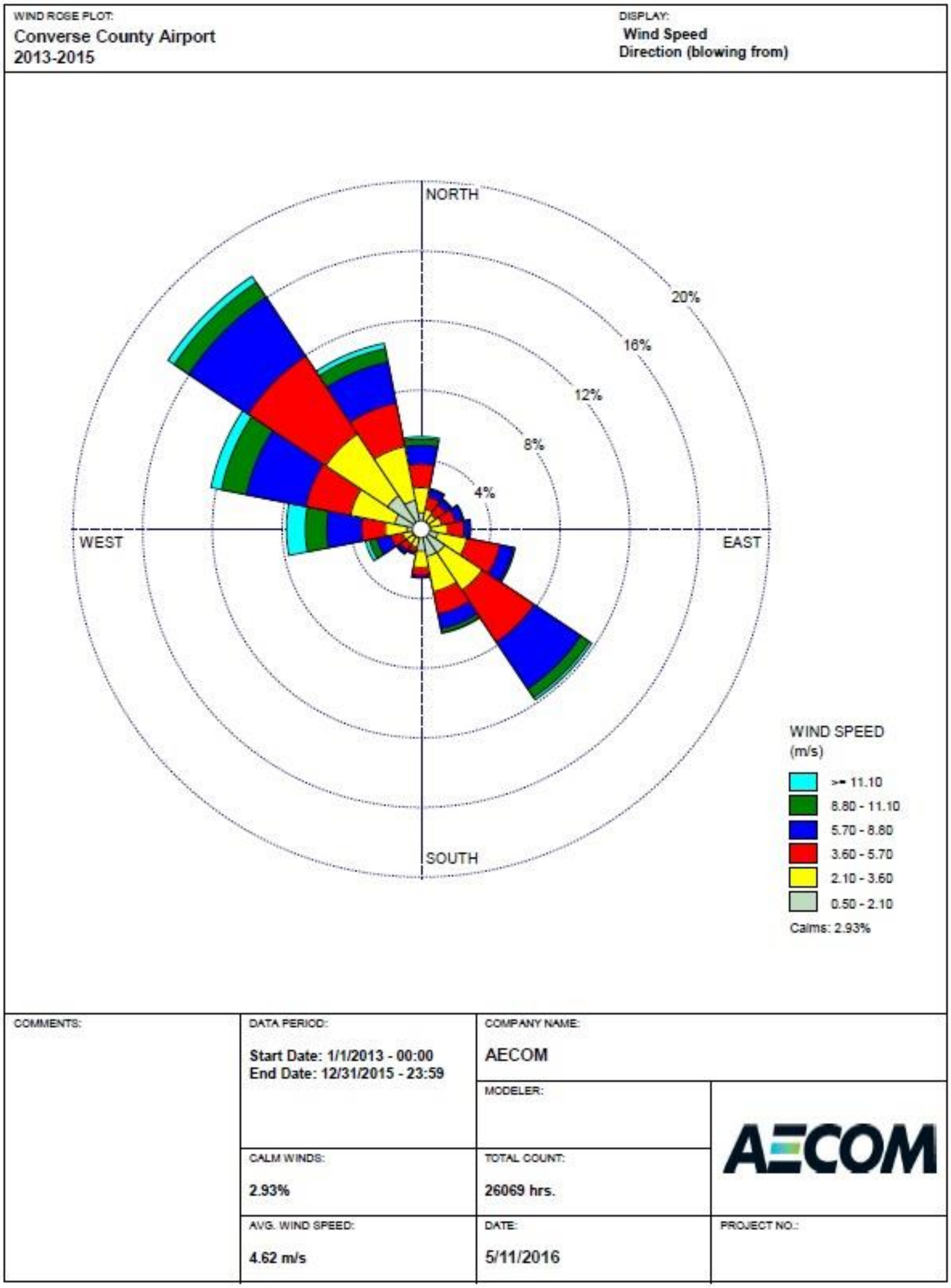
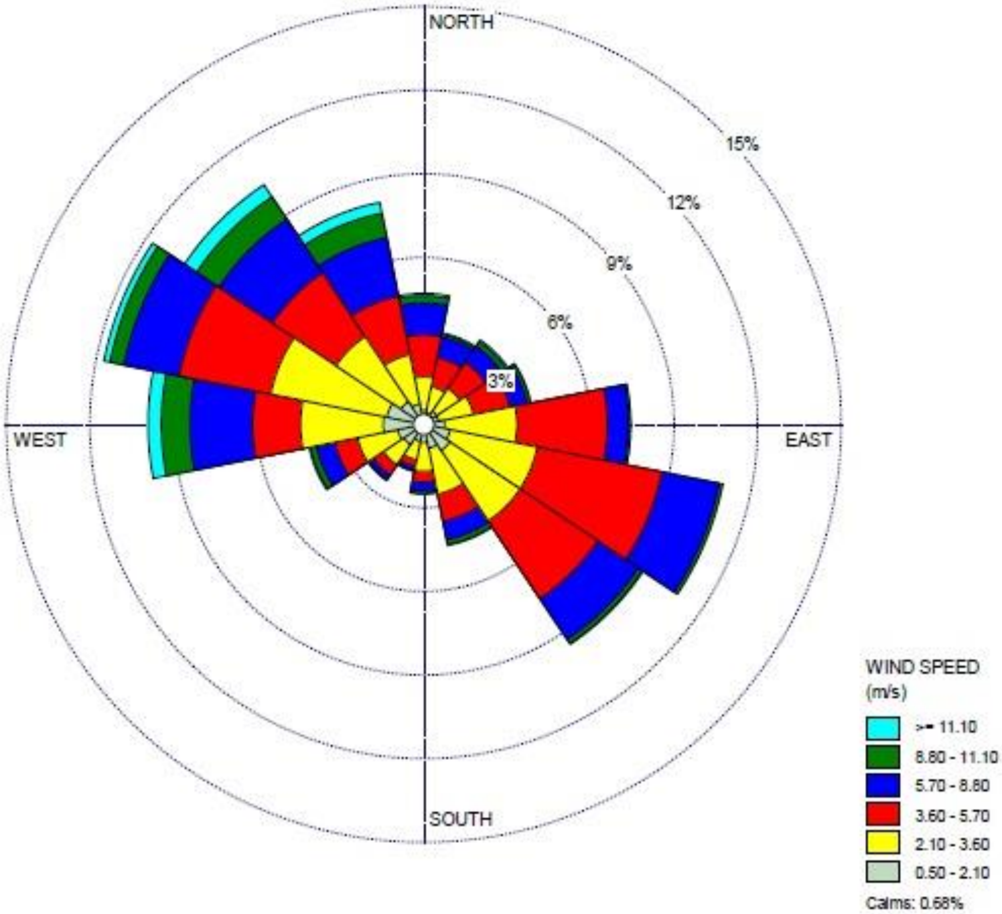


Figure 4-5: Wind Rose for Torrington Municipal Airport 2013-2015

WIND ROSE PLOT:
Torrington AP
2013-2015

DISPLAY:
Wind Speed
Direction (blowing from)



COMMENTS:

DATA PERIOD:
Start Date: 1/1/2013 - 00:00
End Date: 12/31/2015 - 23:59

COMPANY NAME:
AECOM

CALM WINDS:
0.68%

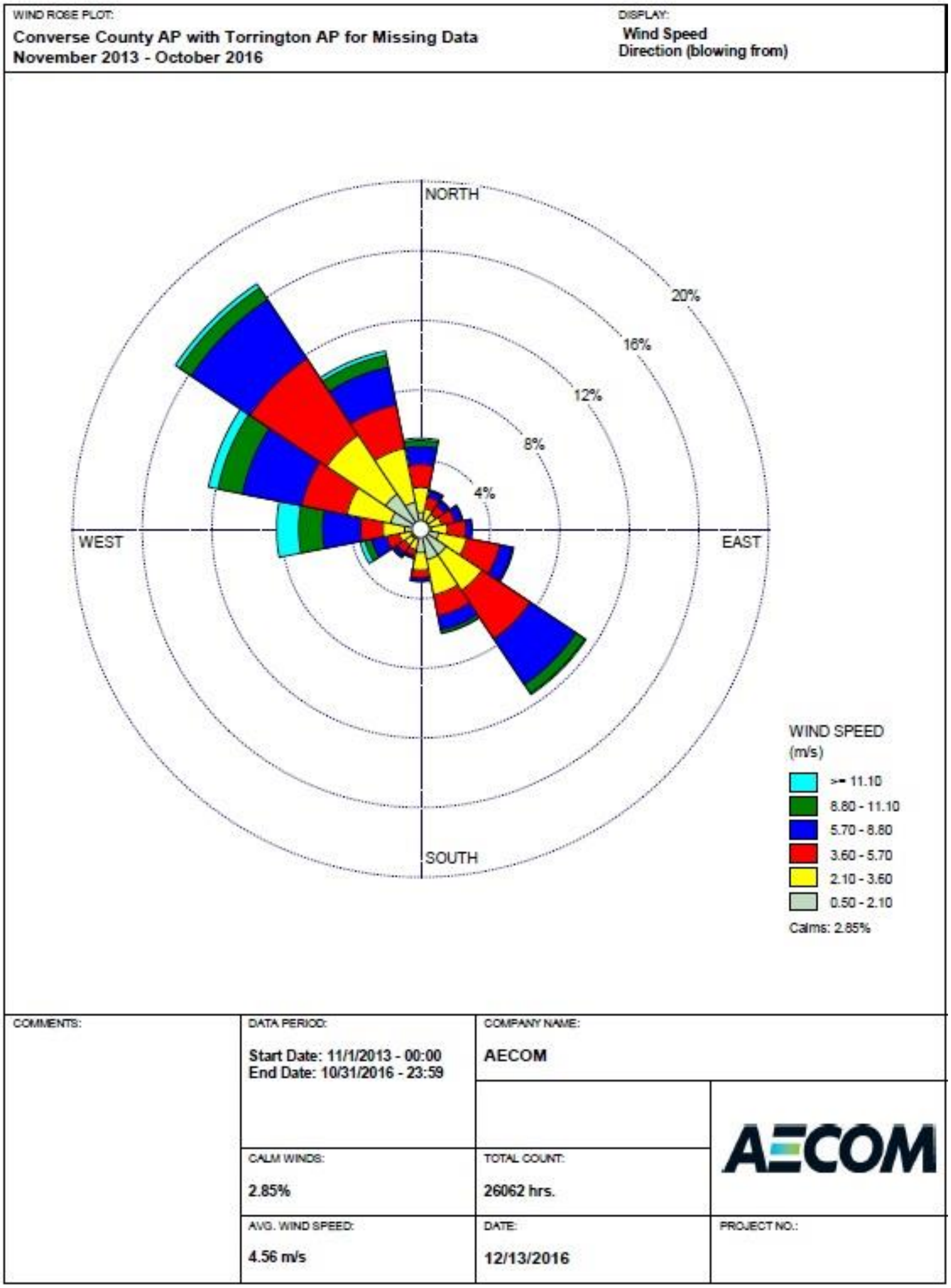
TOTAL COUNT:
26120 hrs.

AVG. WIND SPEED:
4.46 m/s

DATE:
12/13/2016

PROJECT NO.:

Figure 4-6: Wind Rose from Converse County Airport (Nov 2013 – Oct 2016) at 10-m Level with Torrington Data (May 25, 2016 – July 29, 2016)



4.3.2 AERSURFACE Analysis – Meteorological Site Land Use Characteristics

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 EPA in the recently revised AERMOD Implementation Guide (AIG)[11].

The revised 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. The EPA has developed a tool called AERSURFACE[12] 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 incorporates look-up tables of representative surface characteristic values by land cover category and seasonal category. The latest version of AERSURFACE (13016) version was applied with the instructions provided in the AERSURFACE User's Guide.

The current version of AERSURFACE supports the use of land cover data from the USGS National Land Cover Data 1992 archives[13] (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; each chosen sector has a mix of land uses that is different from that of other selected sectors. Sectors used to define the meteorological surface characteristics for the airport anemometer sites are shown in **Figures 4-7** and **4-8**, for Converse County Airport and Torrington Municipal Airport, respectfully.

4.3.2.1 Seasonal Classification

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. Each month was assigned to its default season unless evidence of snow cover changes the default season to winter with snow. The following five seasonal categories, as offered by AERSURFACE, include:

- Midsummer with lush vegetation;
- Autumn with un-harvested cropland;
- Late autumn after frost and harvest, or winter with no snow;
- Winter with continuous snow on ground; and
- Transitional spring with partial green coverage or short annuals.

The following seasonal classifications were used:

[11] Available at http://www3.epa.gov/ttn/scram/7thconf/aermod/aermod_implmtn_guide_3August2015.pdf.
[12] Available at http://www3.epa.gov/ttn/scram/dispersion_related.htm#aersurface.
[13] Available at http://edcftp.cr.usgs.gov/pub/data/landcover/states/.

June, July, August = Midsummer with lush vegetation;

September, October = Autumn with un-harvested cropland;

April, May = Transitional spring with partial green coverage or short annuals;

November, December, January, February, March = Late autumn after frost and harvest, or winter with no snow; and

November, December, January, February, March = Winter with continuous snow on ground.

For the months of November, December, January, February, and March, locally-representative snow cover data records was reviewed for sites near the plant. For each month, if the month had more than 50% of the days with a measurable snow depth, then the month was considered "Winter with continuous snow on ground". Otherwise, the month was considered "Late autumn after frost and harvest, or winter with no snow".

4.3.2.2 Surface Moisture Determination

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 will 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 recommended in AERSURFACE User's Guide, the surface moisture condition for each month 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 30th-percentile, "dry" conditions if precipitation is in the lower 30th-percentile, and "average" conditions if precipitation is in the middle 40th-percentile. The 30-year precipitation data set used in this modeling was taken from the Converse County Airport (1986 – 1994, 2000 – 2016) and Converse 1 SE (1996 – 1999). When Torrington Municipal Airport was used, the 30-year precipitation data set was taken from the Torrington Experimental Farm (1980 – 1997) and Torrington Municipal Airport (1998 – 2016). A summary of the precipitation data is provided in Appendix D.

4.3.3 AERMET Data Processing

AERMET (Version 15181) and AERMINUTE (Version 15272) were used to process data required for input to AERMOD. Boundary layer parameters used by AERMOD, which also are required as input to the AERMET processor, include albedo, Bowen ratio, and surface roughness. The land classifications and associated boundary layer parameters were determined following procedures outlined below. In running AERMET, the observed airport hourly wind directions (if used to substitute for missing AERMINUTE data) were randomized based on guidance from USEPA's March 8, 2013 Use of ASOS Meteorological Data in AERMOD Dispersion Modeling memo[14] using the "WIND_DIR RANDOM" keyword in AERMET. The randomization method addresses the lack of precision in the NWS wind direction observations, which are reported to the nearest 10 degrees. If the randomization method is not used, the potential exists for overly conservative model impacts to occur. Due to the improved model performance for the low wind options as documented in PacifiCorp's alternative model justification[15], the ADJ_U* option was used in the AERMET processing.

AERMET was applied to create two meteorological data files required 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 (σ_θ) and sigma-w (σ_w) when such data are available. For Dave Johnston, the profile

[14] Available at https://www3.epa.gov/scram001/guidance/clarification/20130308_Met_Data_Clarification.pdf
[15] The alternative model justification package, for the use of ADJ_U* for Dave Johnston Power Plant, is provided in Appendix A of this modeling report. This appendix references additional information provided in Appendices B and C.

file contains a single level of wind data (10 meters) and the temperature data only, corresponding to the Converse County Airport or Torrington Municipal Airport (May 25, 2016 – July 29, 2016) observations.

Figure 4-7: Sectors Used for Surface Characteristics at the Converse Airport

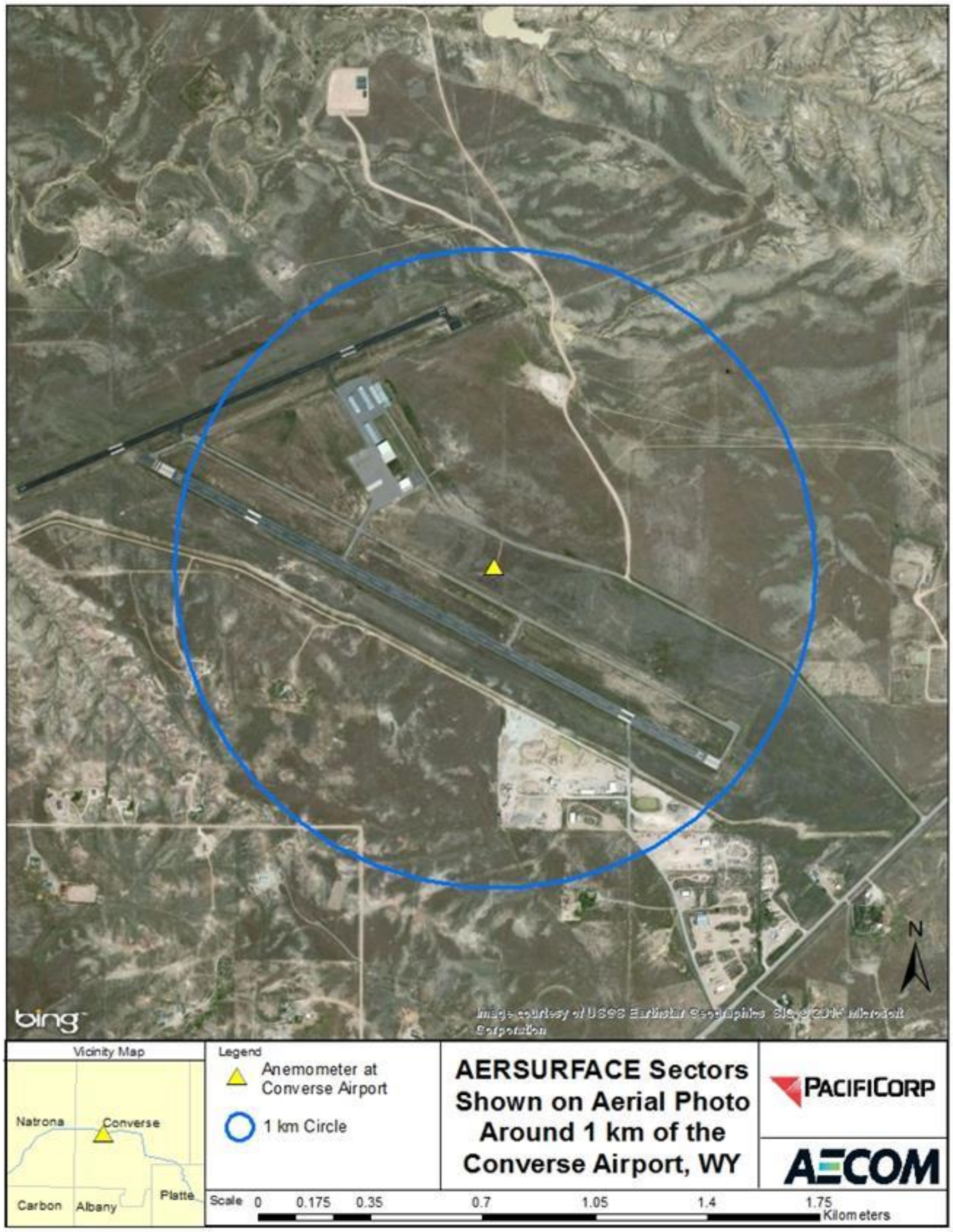
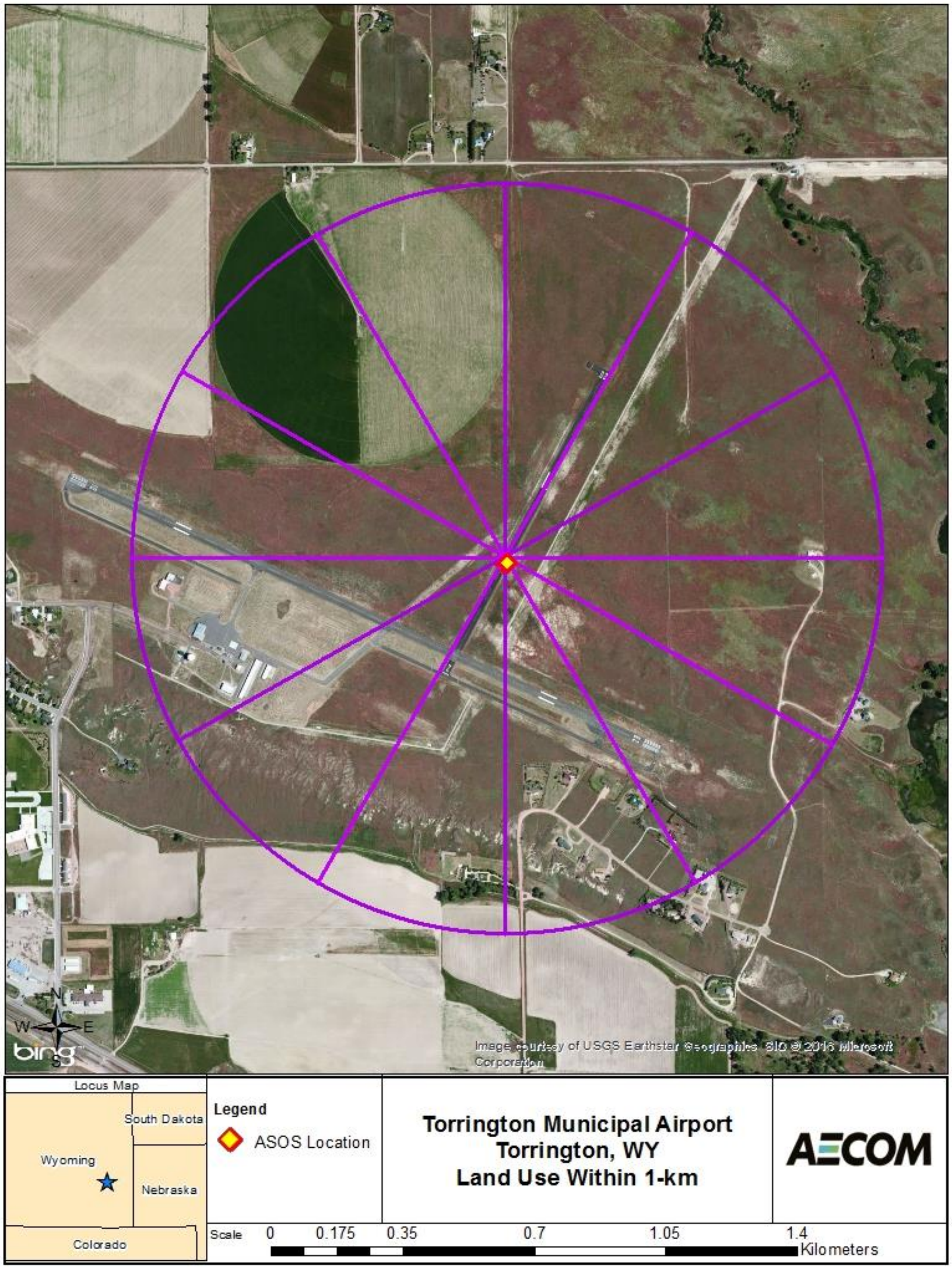


Figure 4-8: Sectors Used for Surface Characteristics at the Torrington Airport



4.4 Merged Stack Methodology

As stated in **Section 2.0**, Boilers 1 and 2 exhaust through a combined 496-foot stack and Boilers 3 and 4 exhaust through a combined 497-foot stack. Effective stack diameters were determined for each of the two merged stack flues by adding together the flue release area for each of the individual flues to get an effective release area. The effective release areas were then used to calculate an effective stack diameter for each merged stack. This effective diameter was used to determine stack velocity for all hours in the hourly data, regardless of whether both units were operating. Stack diameter and area information is presented in **Table 4-3**. The hourly exhaust temperature data for merged stacks was based on weighted averages using the individual flues' exit temperatures, multiplied by the fraction of each flue's exhaust flow to total exhaust flow coming out of the merged stack. Stack velocities for each hour were calculated using the total exhaust from both flues and the effective stack diameter.

Table 4-3 : Stack Information Used to Determine Effective Stack Diameters for Merged Stacks at Dave Johnston Power Plant

	Stack Diameter (m)	Stack Area (m^2)
Unit 1	3.4	29.0
Unit 2	3.4	29.0
Unit 1 & 2 Merged Stack (effective)	4.7	57.9
Unit 3	5.5	77.4
Unit 4	5.5	77.4
Unit 3 & 4 Merged Stack (effective)	7.8	154.8

4.5 Nearby Sources and Ambient Background Concentrations

4.5.1 Nearby Sources to be Modeled

WDEQ identified a number of SO_2 emission sources from the nearby Sinclair Casper Refinery for the DRR modeling of Dave Johnston. These SO_2 emissions from nearby background sources at the Sinclair Casper Refinery were explicitly modeled at current allowable emission rates as part of the cumulative modeling with Dave Johnston Power Plant. A summary of these background, provided by WDEQ are listed in **Table 4-4**.

Table 4-4: Summary of SO_2 Background Sources

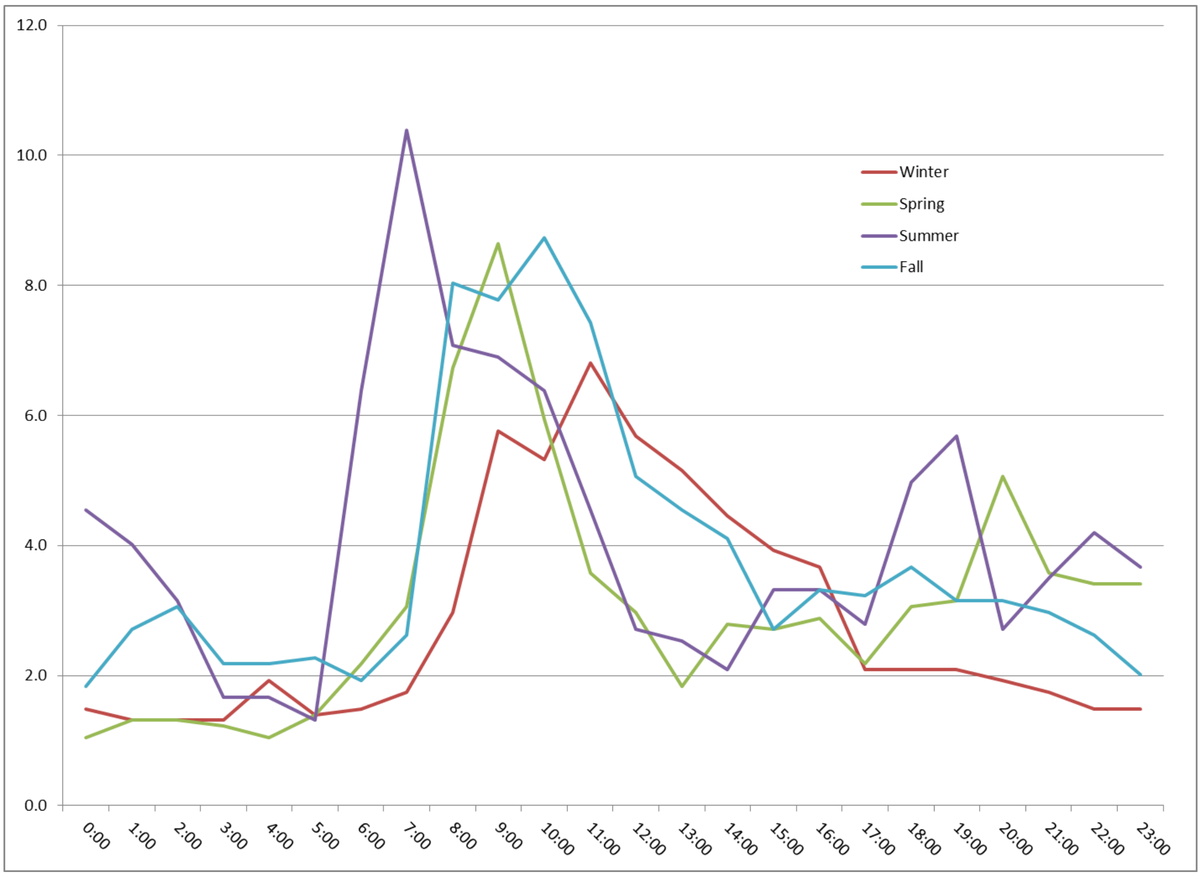
Company Name	Source Description	UTM Easting (Zone 13)	UTM Northing (Zone 13)	Base Elevation (ft)	Stack Height (ft)	Temperature (F)	Exit Velocity (ft/sec)	Stack Diameter (ft)	Short-term Limit (lbs/hr)
Sinclair Casper Refining Company	HDS Reactor Feed Heater	399586	4745740	5119.91	60.7	800	28	2	0.21
Sinclair Casper Refining Company	Asphalt Heater	399586	4745740	5116.11	34.12	1000	31.57	1.7	0.11
Sinclair Casper Refining Company	TGTU	399586	4745740	5118.54	100	167	17.48	2.5	4.63
Sinclair Casper Refining Company	Stabilizer Reboiler	399586	4745740	5119.85	60.7	800	24.9	2	0.19
Sinclair Casper Refining Company	B-2 #3 Crude Heater	399586	4745740	5117.91	60	900	43.38	3	0.47
Sinclair Casper Refining Company	34 Tank Farm Combustor Emissions	399586	4745740	5105	200	1400	66	2	3.20
Sinclair Casper Refining Company	#4 Vacuum Heater	399586	4745740	5117.91	60	950	26.64	3	0.55
Sinclair Casper Refining Company	B-2 Splitter Reboiler Heater	399586	4745740	5119.95	60.2	1010	29.94	3	0.30
Sinclair Casper Refining Company	#7 Boiler	399586	4745740	5117.68	58	510	88.18	3	1.30
Sinclair Casper Refining Company	#5 Crude Heater	399586	4745740	5119.75	60	1000	40.58	5	1.10
Sinclair Casper Refining Company	99.2 MMBtu/hr fuel gas fired Boiler #2	398430	4745881	5126	75	288	49	3.17	0.80
Sinclair Casper Refining Company	#2 Reformer (Reformer Heater #1, Reformer Heater #2, Reformer Heater #3)	399586	4745740	5117.98	80	700	58.3	4	1.90
Sinclair Casper Refining Company	B-1 #4 Crude Heater	399586	4745740	5118.01	135.8	593	42.5	4.5	52.80
Sinclair Casper Refining Company	FCCU Regenerator Stack	399586	4745740	5118.04	150	743	84.93	4.3	12.50
Sinclair Casper Refining Company	B-3 #4 Crude Heater	399586	4745740	5117.85	135	575	45.27	3	23.90
Sinclair Casper Refining Company	B-1 Pretreater Heater	399586	4745740	5120.08	60.3	980	25.86	4	0.47
Sinclair Casper Refining Company	B-201 CHD Heater	399586	4745740	5120.11	60	800	36.77	3.25	0.60
Sinclair Casper Refining Company	F-202 FCCU Feed Heater	399586	4745740	5118.11	79.99	900	48.56	4.17	1.03
Sinclair Casper Refining Company	Refinery Flare	399586	4745740	5114.86	200	1831	66.25	3.1	7.42

4.5.2 Regional Background Concentrations

Ambient air quality data was used to represent the contribution of non-modeled sources to the total ambient air pollutant concentrations. In order to characterize SO_2 concentrations in the vicinity of each plant, the modeled design concentration must be added to a measured ambient background concentration to estimate the total design concentration. This total design concentration is then compared to the 1-hour SO_2 NAAQS.

Use of seasonal and hour-of-day varying background concentrations consistent with EPA guidance in their March 1, 2011 clarification memo[16] were used. The NCORE (Cheyenne) monitoring station concentrations observed during the 2012-2014 three-year period are displayed in **Figure 4-6**.

Figure 4-9: 2012-2014 Average 99th Percentile Concentration at NCORE SO_2 Monitor



[16] http://www.epa.gov/ttn/scram/guidance/clarification/Additional_Clarifications_AppendixW_Hourly-NO2-NAAQS_FINAL_03-01-2011.pdf

5. SO_2 Characterization Assessment Results

The 1-hour SO_2 characterization modeling for the Dave Johnston Power Plant adheres to the following guidance documents (where applicable): (1) the August 2016 "SO_2 NAAQS Designations Modeling Technical Assistance Document" (TAD) issued in draft form by the USEPA, (2) the final DDR for the 2010 1-hour SO_2 primary NAAQS, (3) the final PacifiCorp modeling protocol (December 12, 2016), and (4) direction received from the WDEQ Modeling Staff. A recent 3-year period was included in the modeling (November 2013 – October 2016).

The 1-hour SO_2 characterization modeling was conducted using AERMET (version 15181) beta ADJ_U* option and AERMOD (version 15181) with default model options, the meteorological data described in **Section 4.3**, and the emission rates discussed in **Section 2** and **Section 4.5.1** for Dave Johnston and nearby sources respectfully. We expect with the impending release of Appendix W updates that the ADJ_U* option will be elevated to default status. Modeled concentrations were predicted over the receptor grids described in **Section 4.2**.

The modeled concentrations from AERMOD were calculated based on the form of the 1-hour SO_2 NAAQS and include ambient background concentrations from the NCORE (Cheyenne) monitoring station as described in **Section 4.5.2**. The total design concentration was then compared to the 1-hour SO_2 primary NAAQS.

A summary of the 1-hour SO_2 modeling results is presented in **Table 5-1**. **Figure 5-1** illustrates the overall pattern of the total SO_2 concentrations along with the location of the total maximum design concentrations. The maximum total design concentration on the 20-kilometer receptor grid occurs approximately 8.7 kilometers to the south of the main plant near Brighton Canyon.

Additional 100-meter spaced receptors were placed around the maximum impact area, located in the vicinity of an elevated terrain feature. The area of elevated terrain has peak elevations rising above the stack tops of Dave Johnston. **Figure 5-2** illustrates the location and magnitude of the final concentration on the 100-meter spaced receptor grid. The coordinates of the receptor showing the maximum impact was located at 428200.00 Easting and 4734600.00 Northing, which places it on a relative peak along Brighton Canyon, as shown in **Figure 5-3**.

As shown in **Table 5-1**, the modeled concentrations of 1-hour SO_2 are less than the NAAQS. The most refined receptor spacing produced an impact that is less than the NAAQS. The modeling results indicate that all areas surrounding the facility are in compliance with the applicable NAAQS standard.

Table 5-1: Summary of 1-hour SO_2 Modeling Analysis

Pollutant	Averaging Period	Total Predicted Concentration[1, 2] ($\mu g/m^3$)	NAAQS ($\mu g/m^3$)
SO_2 *Full Receptor Grid*	1-Hour	193.7	196.5

Figure 5-1: Full Receptor Grid 1-hour SO_2 Model Concentrations

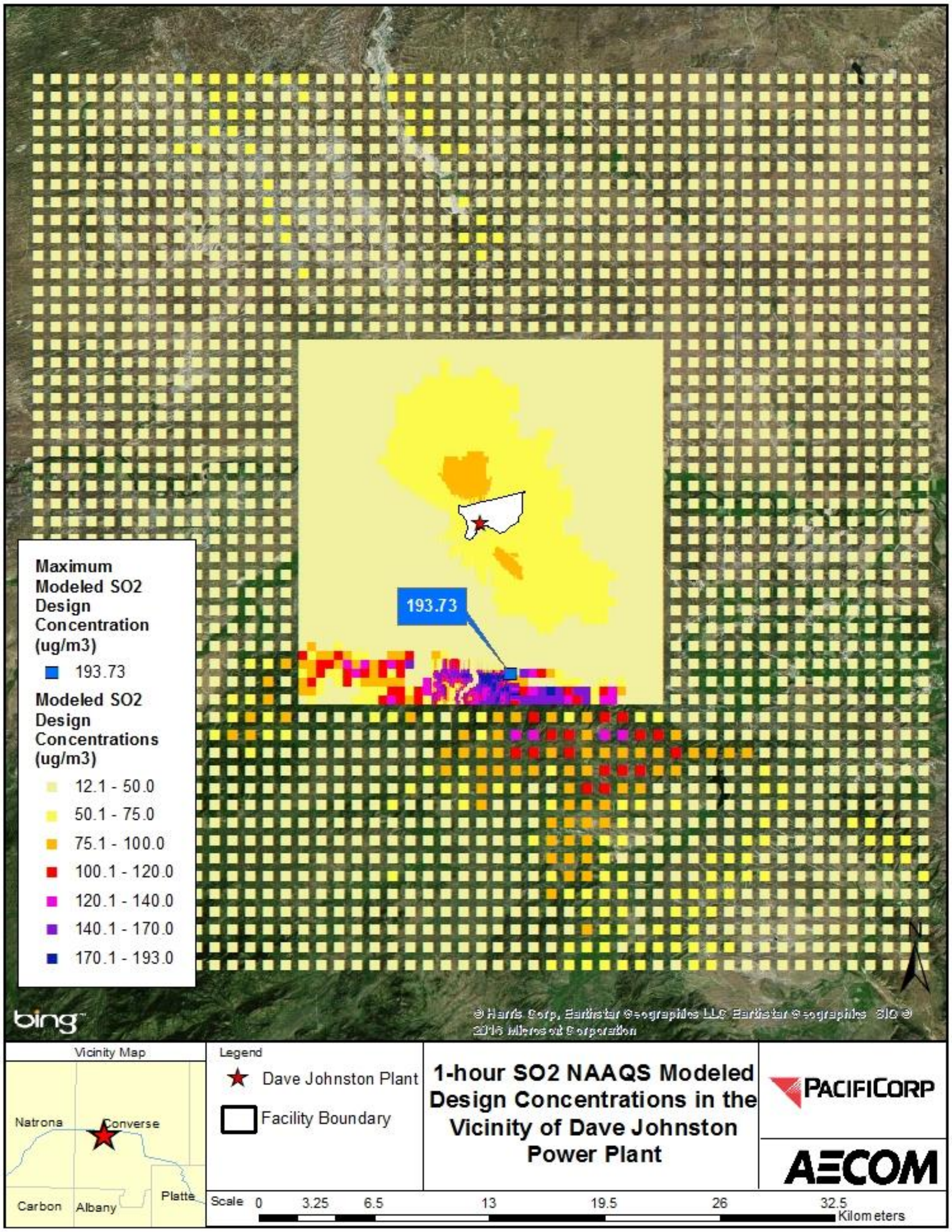


Figure 5-2: Maximum Impact of 1-hour SO_2 Model Concentrations within 100-m Spaced Receptor Grid

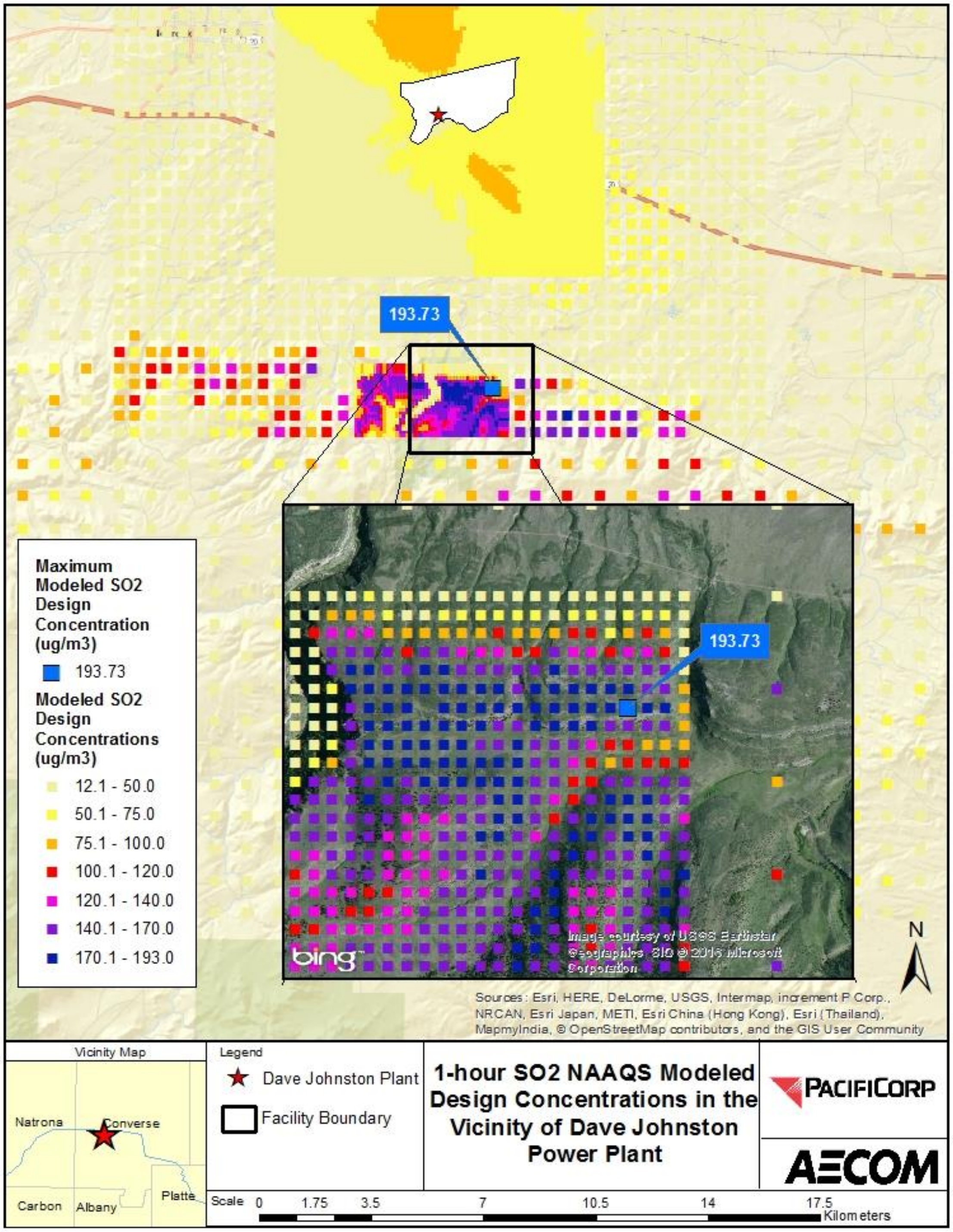
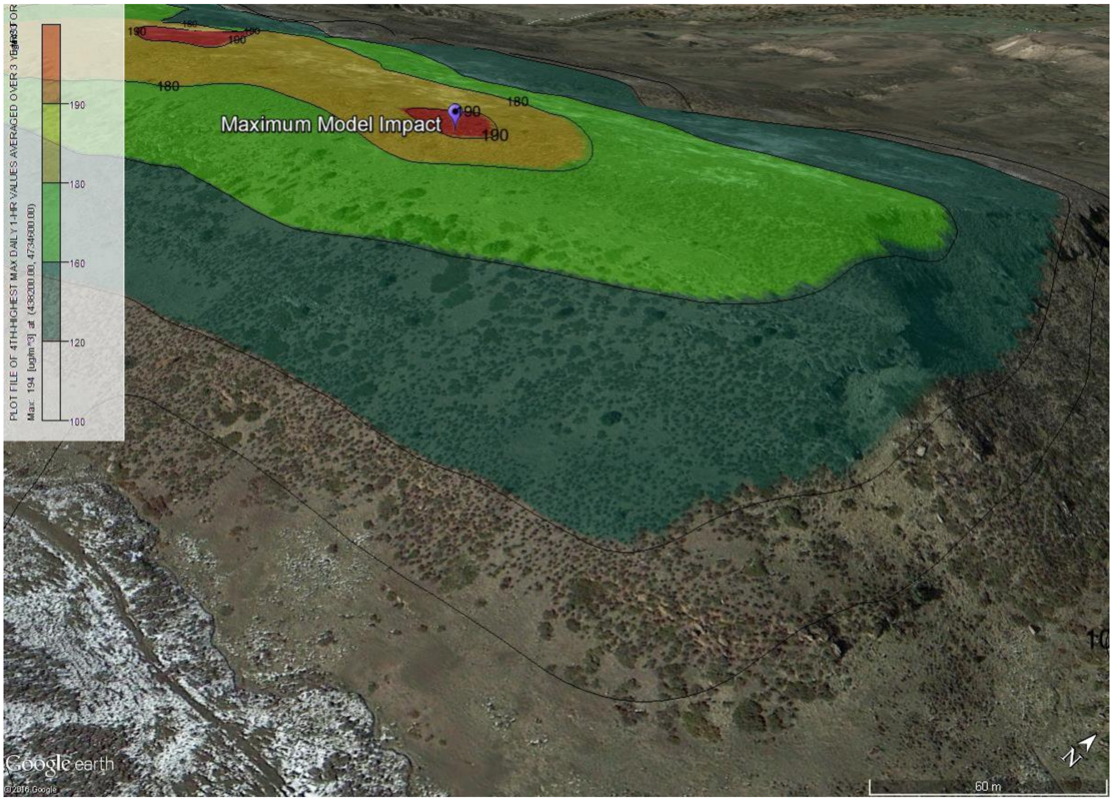


Figure 5-3: Maximum Modeled Impact Receptor Location Relative to Nearby Terrain



Appendix A

Additional Support Documentation for the Use of AERMOD Low Wind Options for Dave Johnston Power Plant

Additional Support Documentation for the Use of AERMOD Low Wind Options for Dave Johnston Power Plant

1.0 Introduction

1.1 Introduction and Overview

In 2010, the results of an evaluation[1] 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 limited AERMOD 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 10th 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.

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

[1] 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.

"Modified subroutine UCALST to incorporate AECOM's recommended corrections to theta-star under the ADJ_U* beta option, based on Qian and Venkatram[2], 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[3], as well as at the EPA's 11th modeling conference[4], 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. In conjunction with EPA's proposed changes to its modeling guidelines (40 CFR Part 51, Appendix W; see 80 FR 45340), EPA has now released AERMET/AERMOD version 15181 that incorporates low wind options that are proposed as default techniques. Based upon this action, we are proposing in this SO_2 Data Requirements Rule modeling protocol the new version of AERMET and AERMOD with the default low wind options, with accompanying technical support provided in this appendix. This technical support is needed at this time because EPA has not finalized the proposed rule, so that interim use of the low wind options is subject to case-specific EPA approval. This appendix 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 the supporting information provided by EPA as noted above, AECOM has conducted additional testing of the low wind options for tall stack databases and has provided a scientific basis for the use of these options. This scientific discussion and the results of the testing were published as a peer-reviewed paper[5] in the Journal of the Air & Waste Management Association, provided in Appendix B. The favorable results of supplemental testing using the LOWWIND3 option with these databases are presented in Appendix C.

EPA received an adverse comment (submitted to the Appendix W docket) from the Sierra Club[6] relative to the proposed inclusion of the low wind options as default options for AERMOD in Appendix W. The Sierra Club report indicated underpredictions in 3 of 5 selected AERMOD evaluation databases (Lovett, Kincaid, and Tracy showed underpredictions, Baldwin showed an overprediction, and Prairie Grass showed either overpredictions or results within 5% of being unbiased). However, the Sierra Club's study results were based on the 100th percentile (Robust Highest Concentration) model concentrations rather than the 99th percentile model concentrations

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[2] Qian, W., and A. Venkatram, 2011: "Performance of Steady-State Dispersion Models Under Low Wind-Speed Conditions", *Boundary Layer Meteorology*, 138:475-491.

[3] Available at http://www.epa.gov/ttn/scram/.

[4] Available at http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5_Proposed_Updates_AERMOD_System.pdf.

[5] 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.

[6] Available at http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2015-0310-0114.

that would be used for 1-hour SO_2 modeling. AECOM prepared an alternative evaluation study[7] and A&WMA paper in Appendix H on full-year databases (Lovett and Clifty Creek) that showed unbiased or conservative 99th percentile results with the low wind options. An additional evaluation study for the Tracy Power Plant Tracer Experiment is presented in Appendix I.

In recent communications between George Bridgers of the Office of Air Quality Planning and Standards (OAQPS) and EPA Region 8 regarding EPA approval of the LOWWIND3 option, EPA indicated that the ideal alternative model demonstration would include the type described in Section 3.2.2(b)(2) of Appendix W; i.e., a statistical performance evaluation using site-specific monitored data that would show no underprediction tendency. However, if site-specific studies are not available, a sensitivity study that shows similar modeled results when compared to those from a similar site with an evaluation against monitored data would add support to the use of the LOWWIND3 option. Since a site-specific study is not available in this case, we have found that a similar site with a model performance evaluation is the Mercer County North Dakota Evaluation Study that was included in the peer-reviewed evaluation paper by Paine et al. (2015)[5].

1.2 Description of Field Study Setting for Mercer County, North Dakota

An available 4-year period of 2007-2010 was used for the Mercer County, ND database with five SO_2 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 1-1**), and hourly emissions data from 15 point sources within 50 km. 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. **Figure 1-1** shows a layout of the sources, monitors, and the meteorological station. **Tables 1-1** and **1-2** 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 sources (Antelope Valley Station and the Great Plains Synfuels Plant, operated by the Dakota Gasification Company) meant that emissions from those facilities dominated the impacts.

[7] The AECOM supplemental low wind study that addresses the adverse comments of the Sierra Club can be found at the EPA docket site: https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2014-0464-0326, Exhibit 7. Kincaid was not included because it was found to have omitted important SO_2 sources.

Figure 1-1: Map of Mercer County, ND Model Evaluation Layout

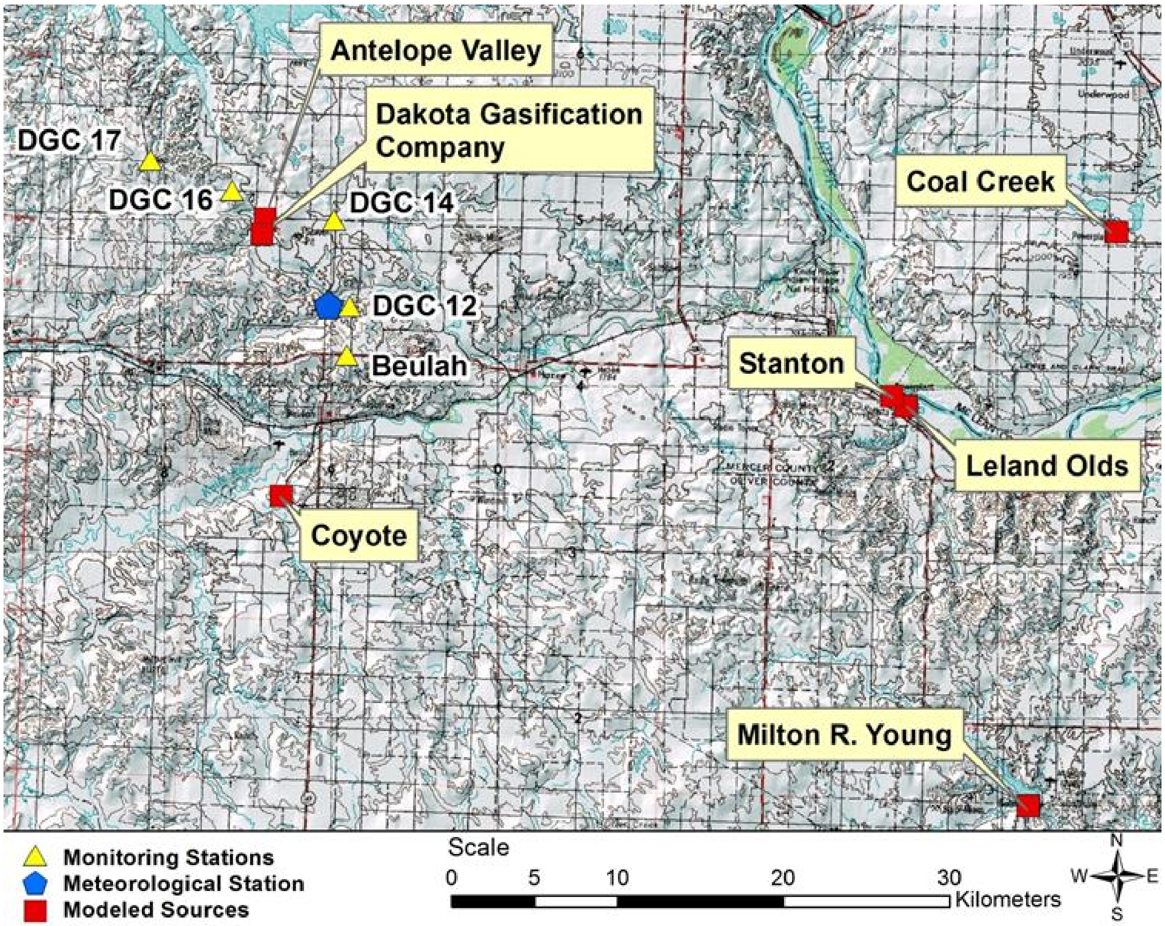


Table 1-1: Source Information for the Mercer County, ND Database

Data Base	Source ID	UTM X (m)	UTM Y (m)	Base Elev. (m)	Stack Height (m)	Stack Top Elev. (m)	Stack Diameter (m)
ND	Antelope Valley	285920	5250189	588.3	182.9	771.2	7.0
ND	Antelope Valley	285924	5250293	588.3	182.9	771.2	7.0
ND	Leland Olds	324461	5239045	518.3	106.7	625.0	5.3
ND	Leland Olds	324557	5238972	518.3	152.4	670.7	6.7
ND	Milton R Young	331870	5214952	597.4	171.9	769.3	6.2
ND	Milton R Young	331833	5214891	600.5	167.6	768.1	9.1
ND	Coyote	286875	5233589	556.9	151.8	708.7	6.4
ND	Stanton	323642	5239607	518.2	77.7	595.9	4.6
ND	Coal Creek	337120	5249480	602.0	201.2	803.2	6.7
ND	Coal Creek	337220	5249490	602.0	201.2	803.2	6.7
ND	Dakota Gasification Company	285552	5249268	588.3	119.8	708.1	7.0
ND	Dakota Gasification Company	285648	5249553	588.3	68.6	656.9	0.5
ND	Dakota Gasification Company	285850	5248600	588.3	76.2	664.5	1.0
ND	Dakota Gasification Company	285653	5249502	588.3	30.5	618.8	0.5

Notes: SO_2 emission rate and exit velocity vary on hourly basis for each modeled source. Exit temperature varies by hour for the ND sources. The UTM zone is 14.

Table 1-2: Monitor Locations for the Mercer County, ND Database

Data base	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[a]	279025	5253844	709.8
ND	Beulah	290823	5242062	627.1

[a] This monitor's elevation is above stack top for several of the ND sources.

2.0 Surrounding Terrain Features

Many similarities exist between the surrounding terrain of the PacifiCorp Dave Johnston Power Plant and the Mercer County North Dakota Evaluation Study. Dave Johnston is located in very similar climate and terrain as the facilities in Mercer County. Both facilities are in semi-arid climates, and are both located in a river valley with elevated terrain a few kilometers from the emission sources.

Dave Johnston Power Plant is situated along the bank of the North Platte River where the topography is dominated by the Wyoming Plateau (**Figure 2-1**). The surrounding area consists of rolling to hilly plains, although there are occasional terrain features that include prominent buttes and mountain ranges. A plateau area rising to near 1800 m elevation (nearly 300 m above stack base for Dave Johnston) is one of the more significant terrain features stretching east-west to the south of the plant. This significant terrain feature (the Box Elder Canyon area) that rises above stack height is the location of the maximum modeled concentrations for Dave Johnston. It is approximately 8 km to the southwest and is denoted with a blue circle symbol in **Figure 2-1**. East and West of Dave Johnston Power Plant, the terrain is relatively flat with rolling hills well below stack top height.

The facilities involved in the Mercer County, ND Evaluation Study are all located within the Missouri Plateau region of North Dakota. Complex terrain is noted to the west and northwest of the facilities with relatively flat terrain in all other directions, shown in **Figure 2-2**. One of the highest peaks, marked by a blue diamond in **Figure 2-2**, is located about 8 km to the northwest of the facilities with an elevation of 709 m above sea level. Located on this peak terrain feature is the site of one of several ambient SO_2 monitors sited in Mercer County.

The similar terrain conditions surrounding Dave Johnston Power Plant to that of the Mercer County, ND evaluation study is one element of this “apple-to-apples” comparison. Another similarity is the tall stacks for both Dave Johnston and the sources in the Mercer County, ND database. Finally and most importantly, for both applications the high terrain areas showed peak model-predicted concentrations in stable atmospheric conditions with default AERMOD settings. The Mercer County, ND evaluation results were that this prediction was too high by about a factor of 2, and that the use of the ADJ_U* and LOWWIND3 options reduced the overprediction substantially, which still resultedin a model over-prediction. Given the similarities between the two applications, we expect that the Dave Johnston predicted impacts on high terrain are also overstated, and the use of the low wind options will mitigate these peak predictions while resulting in somewhat modest over-predictions.

Figure 2-1: Topography Map Surrounding Dave Johnston Power Plant

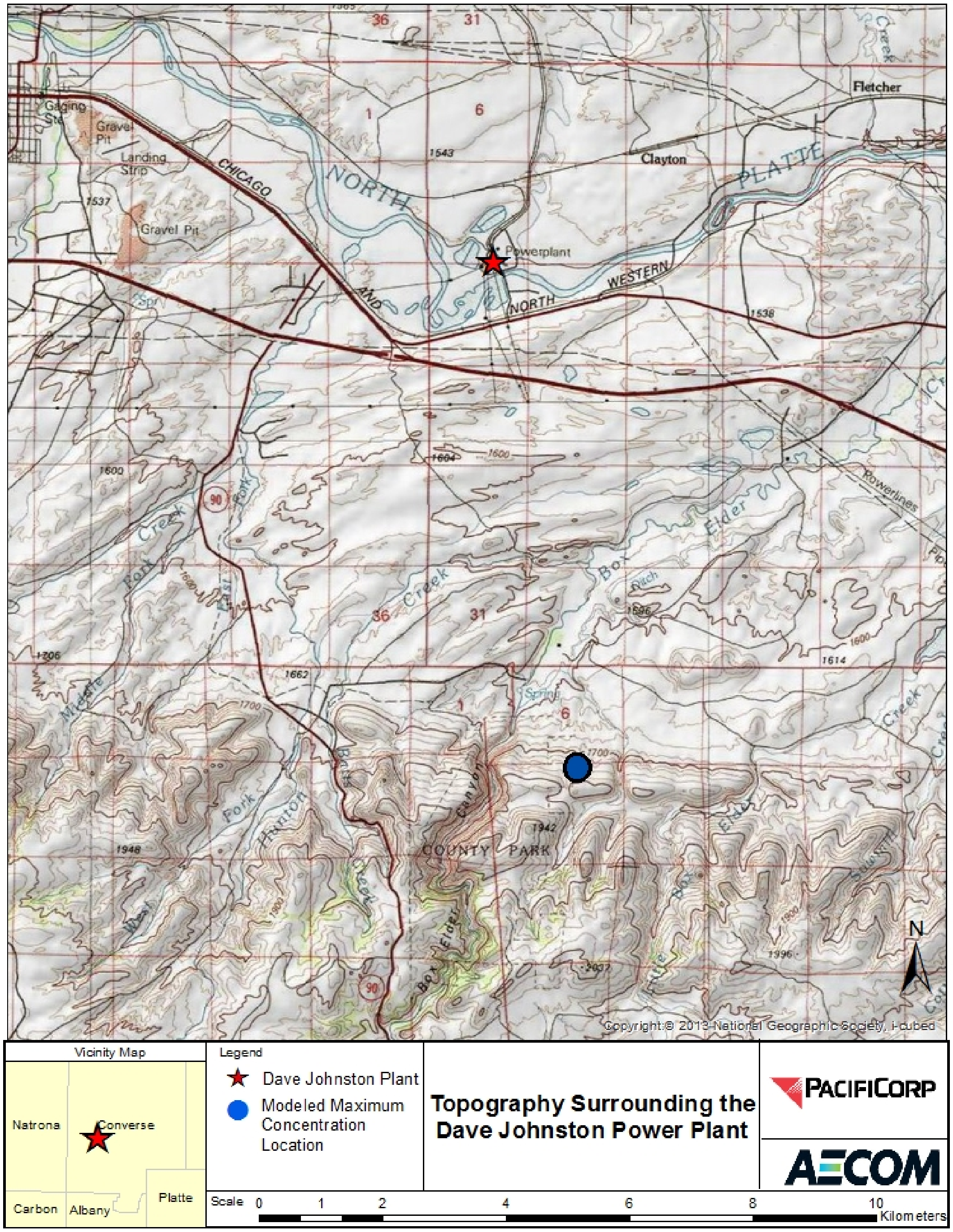
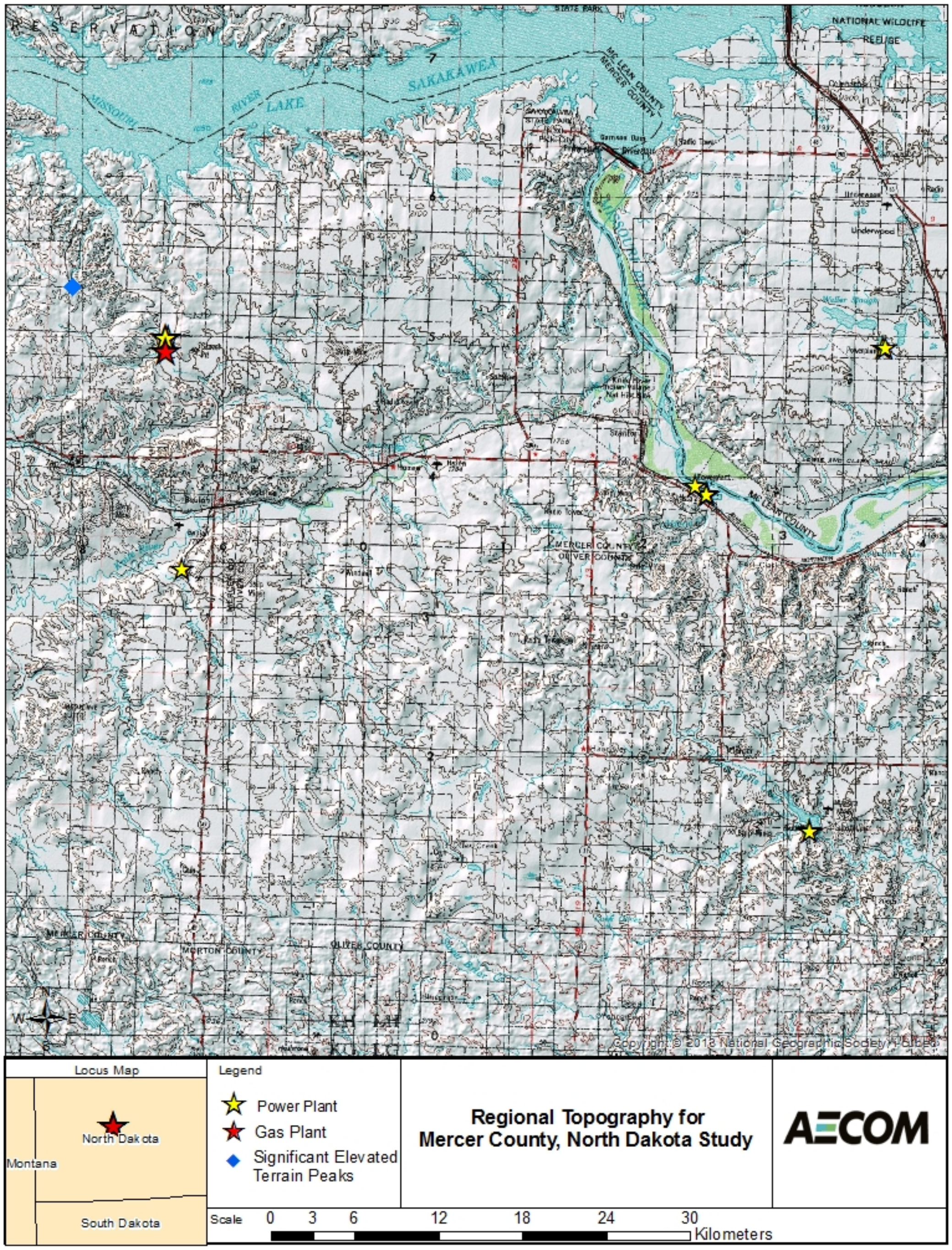


Figure 2-2: Topography Map for Mercer County, ND SO_2 Sources



3.0 Stack Parameter Similarities

As discussed in the SO_2 DRR Modeling Protocol for Dave Johnston, the station has four boiler units (Units 1 through 4). Exhaust from each of the boiler stacks are vented through separate flues, however Unit 1 and Unit 2 exit a single stack, and Unit 3 and Unit 4 also exit a single stack. Heights and effective (merged) exit diameters as reported in Table 3-1. Both stacks are considered to be tall stacks within a region with some areas of complex terrain, as discussed in the previous section. This configuration of tall stacks is similar to those modeled in the Mercer County, ND evaluation study.

Figure 3-1: Dave Johnston– Physical Stack Parameters(1)

Unit	Description	Stack Base Elevation (feet msl)	Stack Height (feet)	Flue Diameter (feet)
Unit 1	Tangential Coal Fired Boiler	4954	496	16 (effective)
Unit 2	Tangential Coal Fired Boiler			
Unit 3	Tangential Coal Fired Boiler	4956	497	25 (effective)
Unit 4	Tangential Coal Fired Boiler			

(1) Emission rates, exhaust temperature, and exhaust flow rate will be based on hourly CEMs data.

4.0 Results of Sensitivity Comparison Study

Three modeling scenarios were chosen to investigate the change in predicted concentrations with the use of non-default low wind options at Dave Johnston Power Plant. AERMET/AERMOD version 15181 was run using the following configuration options;

- AERMET Default / AERMOD default;
- AERMET ADJ_U* / AERMOD default;
- AERMET ADJ_U* / AERMOD LOWWIND3.

4.1 Results of the 99th Percentile Normalized Concentrations for Dave Johnston Power Plant

The 4th highest (99th percentile) daily 1-hour peak SO_2 concentrations from the 2013-2015 modeling period for both Dave Johnston and North Dakota Study are summarized in **Table 4-1**. For this comparative modeling, the emission rates were normalized by a constant factor, consistent with EPA's Monitor Technical Assistance Document guidance[8]. Emission rates do not include ambient background monitor concentrations.

Under AERMET/AERMOD default and AERMET ADJ_U*/AERMOD default modeling conditions, the location of the 4th highest daily 1-hour peak SO_2 normalized concentration from Dave Johnston Power Plant is at the nearby complex terrain located to the south of Dave Johnston. **Figure 4-1** shows an isopleth map of the 4th highest daily 1-hour SO_2 concentration using default AERMET/AERMOD options. There is a large concentration gradient that occurs along the complex terrain to the south. The results from AERMET ADJ-U*/AERMOD default (**Figure 4-2**) continued to show the 4th highest daily 1-hour SO_2 concentration at the complex terrain to the south, but there is a more gradual concentration gradient under the ADJ_U* scenario. **Figure 4-3** shows that 4th highest daily 1-hour SO_2 concentration using AERMET ADJ_U*/AERMOD LOWWIND3 model options occur at the same location as the other two configuration options. There are no tight gradient signatures observed.

As shown in the three figures below, the location of the maximum concentration remains remarkably similar among the three configuration options, however the concentration gradient is sharpest with the results from AERMET/AERMOD default option and the most gradual using AERMET ADJ_U*/AERMOD LOWWIND3 model options.

[8] Available at https://www3.epa.gov/airquality/sulfurdioxide/pdfs/SO2MonitoringTAD.pdf.

Table 4-1: Model-Predicted 4th Highest Daily Peak 1-hour SO_2 Concentrations for Dave Johnston and Mercer County, ND

Model Options	Dave Johnston Power Plant Predicted Daily 1-hour Highest 99th Percentile SO_2 Concentrations (µg/m³)[1]	Mercer County, ND Predicted Daily 1-hour Highest 99th Percentile SO_2 Concentrations (µg/m³)
AERMET; AERMOD Default v15181	84.8	174.5
AERMET w/ ADJ_U*; AERMOD v15181	39.5	122.3
AERMET w/ ADJ_U*; AERMOD LOWWIND3 v15181	30.8	102.1

[1] Model-predicted concentrations based on normalized emission rates.

Figure 4-1: Isopleth Map of the 99th Percentile Normalized SO_2 Concentrations Using AERMET/AERMOD Default options for Dave Johnston

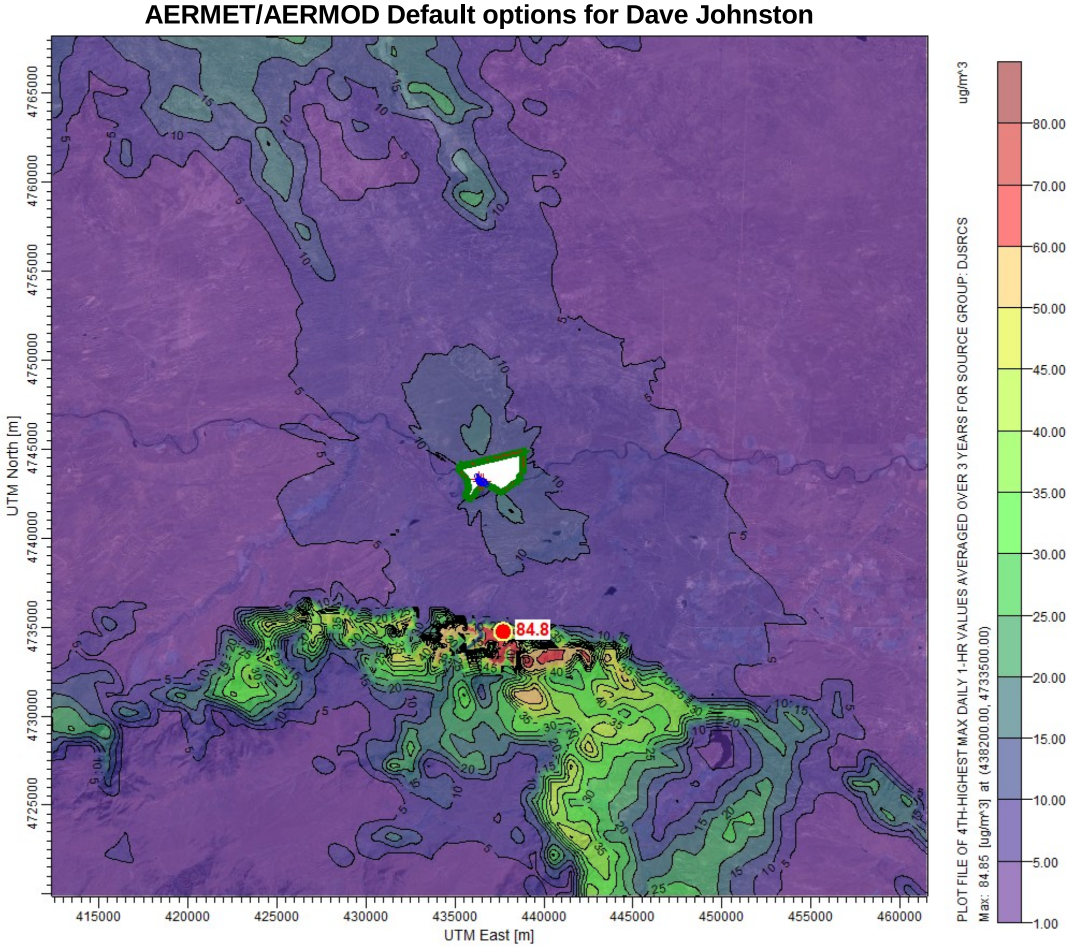


Figure 4-2: Isopleth Map of the 99th Percentile Normalized SO_2 Concentrations Using AERMET ADJ_U*/AERMOD options for Dave Johnston

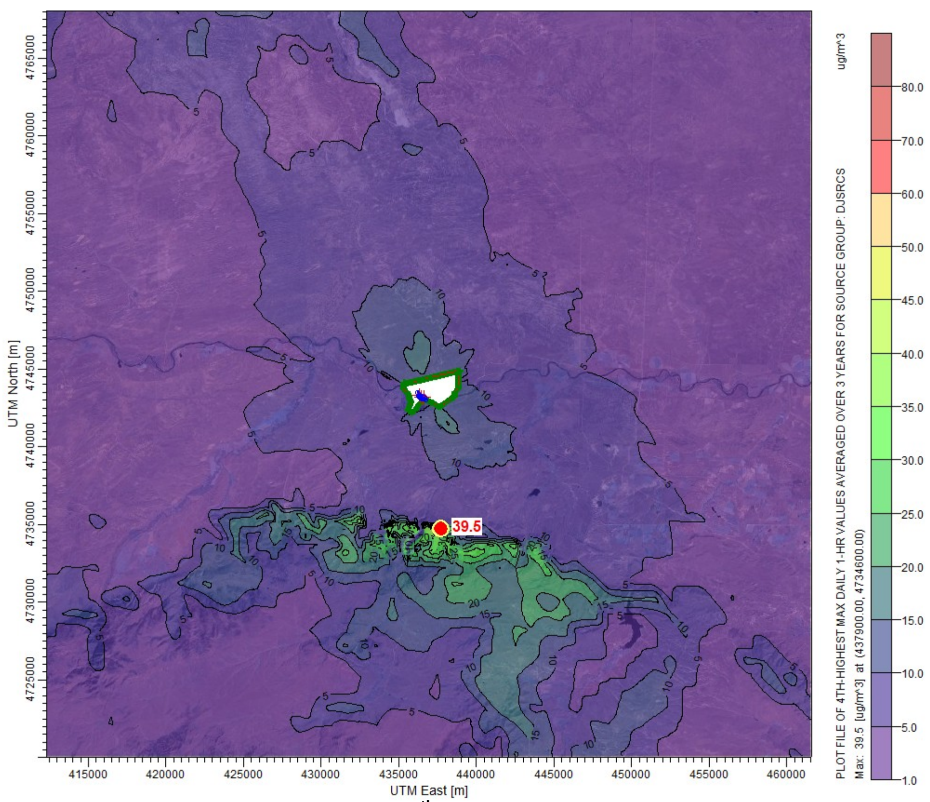
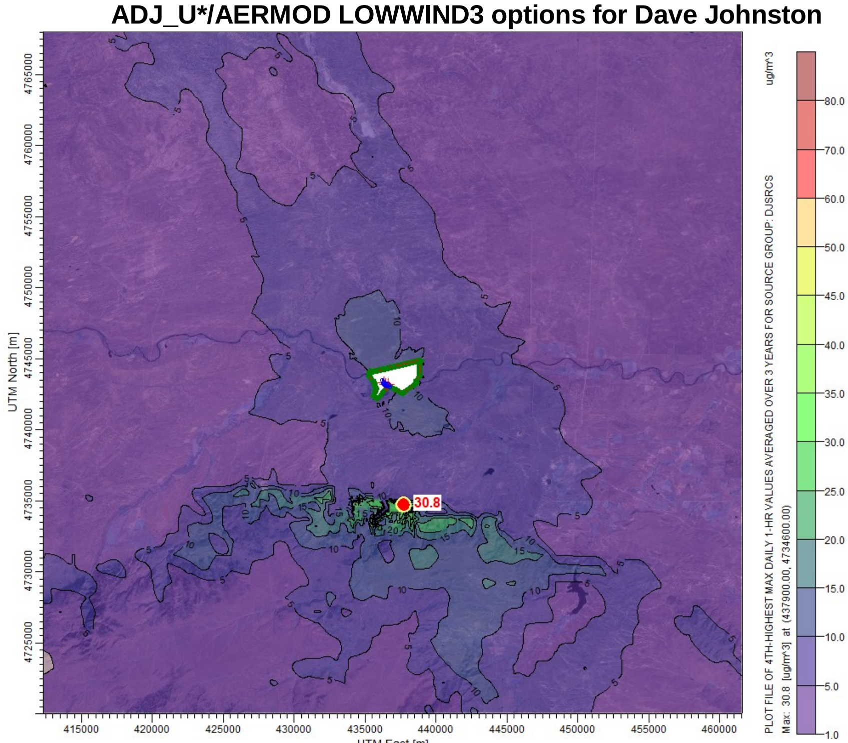


Figure 4-3: Isopleth Map of the 99th Percentile SO_2 Concentrations Using AERMET ADJ_U*/AERMOD LOWWIND3 options for Dave Johnston



4.2 Results of the 99th Percentile Concentrations for Mercer County, ND

The 4th highest daily peak 1-hour SO_2 concentrations observed at each monitor location were compared against the modeled concentrations. The 1-hour SO_2 design concentrations for the North Dakota evaluation database are summarized in **Table 4-2** and graphically plotted in **Figure 4-4**. These charts indicate that at all the sites; the model-predicted values are higher than the observed. The overall results indicate the following:

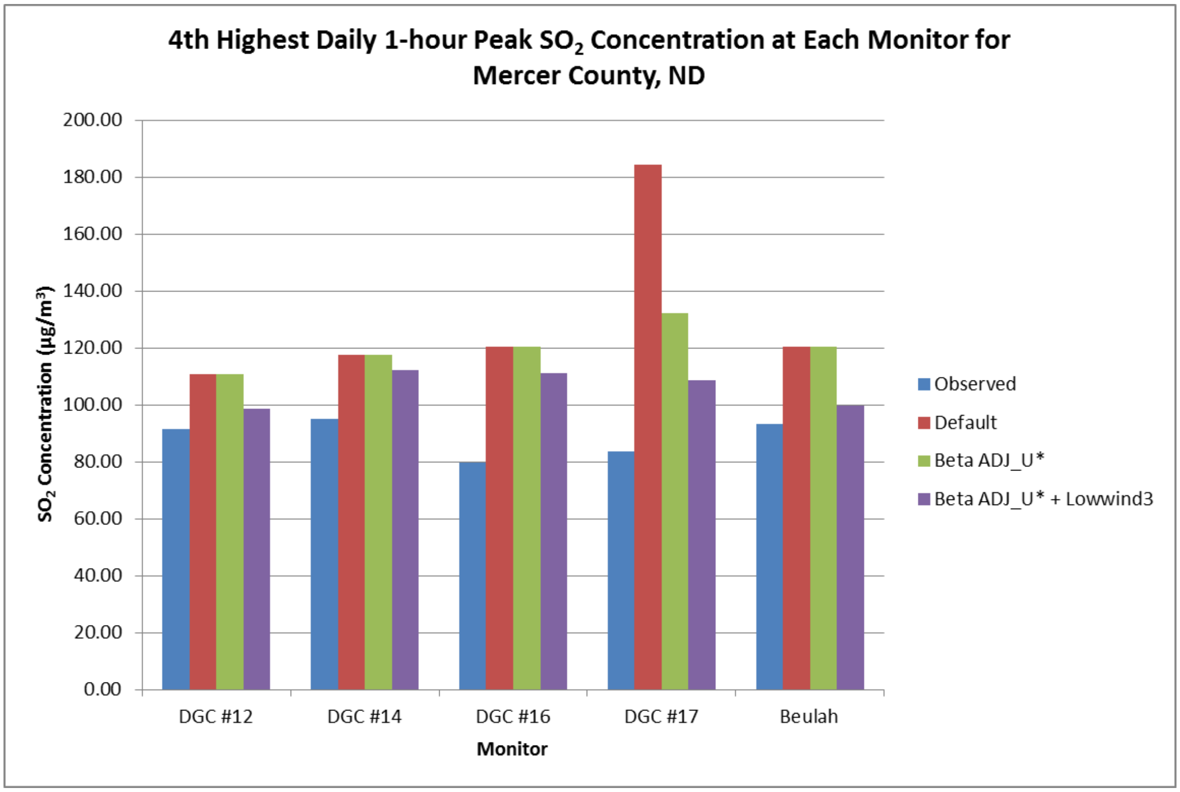
- The highest design concentration from all monitor sites for both default and low wind options are higher than observed.
- The AERMOD v15181 default highest design concentration from all monitor sites is greater than the ones using the low wind options.
- For the monitors in simple terrain (DGC#12, DGC#14, and Beulah), the evaluation results were similar for both the default and the low wind options.
- 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 low wind options (ADJ_U* and LOWWIND3), the ratio is significantly better, at less than 1.3.

Table 4-2: 4th Highest Daily Peak 1-hour SO_2 Concentrations (µg/m^3) for Mercer County, ND Evaluation Study

	DGC #12	DGC #14	DGC #16	DGC #17	Beulah	Highest Concentration
Observed	91.52	95.00	79.58	83.76	93.37	95.00
AERMET; AERMOD Default v15181	110.77	117.51	120.30	184.49	120.31	184.49
AERMET w/ ADJ_U*; AERMOD v15181	110.77	117.51	120.30	132.30	120.31	132.30
AERMET w/ ADJ_U*; AERMOD LOWWIND3 v15181	98.75	112.09	111.20	108.76	99.54	112.09

Background concentration value of 10 µg/m^3 added to model-predicted concentrations.

Figure 4-4: Histogram of the 4th Highest Daily Peak 1-hour SO_2 Concentrations from Mercer County, ND Evaluation Study



5.0 Evaluation Comparison Conclusions

The model evaluation of AERMOD's low wind options was conducted to in order to demonstrate an "apples-to-apples" comparison between Dave Johnston and Mercer County North Dakota evaluation database on the impacts of 1-hour SO_2. Modeled impacts are based on the latest version of AERMET/AERMOD (v15181) on both of these tall-stack databases. The results from Dave Johnston show very similar behavior to those identified in the Mercer County North Dakota evaluation study for the following reasons:

- The peak modeled impacts for AERMOD default options occurred in elevated terrain several km away.
- The peak impacts for AERMOD default options occurred in stable, light wind conditions, which are the conditions for which the low wind options are designed to address.
- When the low wind options are used, the change in the concentration magnitude is similar between the North Dakota and the Dave Johnston cases.
- When the low wind options are used, the concentrations are more comparable between the flat terrain and high terrain areas for Dave Johnston, which was observed in the North Dakota database.
- When the low wind options are used, the meteorological conditions associated with both predicted and observed high concentrations include a mix of stable and unstable conditions for both the North Dakota and Dave Johnston applications, consistent with the North Dakota monitored values.

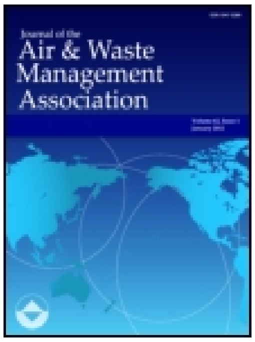
As described in the Mercer County evaluation, the predicted-to-observed ratios of 99^{th} percentile SO_2 concentration using the low wind options remained above 1.0, resulting in an over-prediction. This same result is expected with the low wind options for the Dave Johnston Power Plant.

This discussion of terrain setting and source similarities, in addition to a model sensitivity comparison approach (as requested by EPA) is provided for documentation to EPA in support of the request to use AERMOD low wind options (both ADJ_U* and LOWWIND3) for use in 1-hour SO_2 modeling.

Appendix B

Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases

(Technical Paper authored by: Robert J. Paine, Olga Samani, Mary Kaplan, Eladio Knipping, and Nuresh Kumar – published in the Journal of the Air & Waste Management Association - 03 November 2015)



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TECHNICAL PAPER

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_2 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_2 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_2 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, σ_v, which can be parameterized as being proportional to the friction velocity, u_* (Smedman, 1988; Mahrt, 1998). These investigators

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uawm.

found that there was an elevated minimum value of σ_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 σ_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 σ_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_6 releases. From analyses of hourly samples of SF_6 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 σ_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 σ_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 σ_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_2 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 σ_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 σ_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 σ_v value of 0.2 m/sec).

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

Test Case 4: Low wind beta option for AERMET and the LOWWIND2 option for AERMOD (minimum σ_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_2 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_2 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_2 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

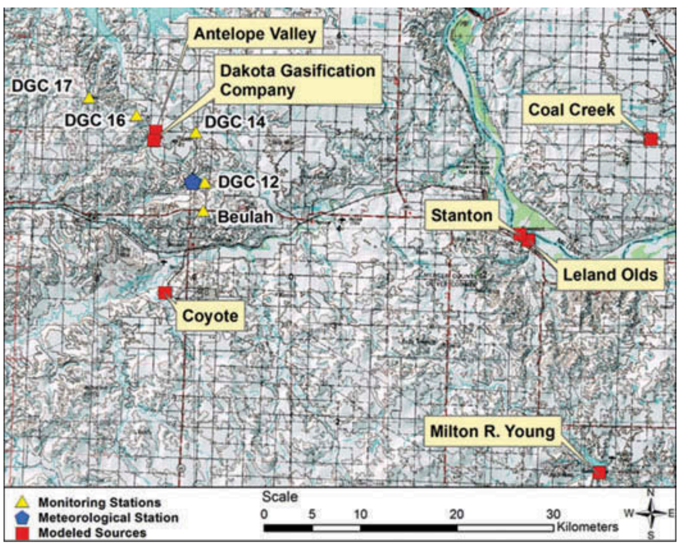

Figure 1. Map of North Dakota model evaluation layout.

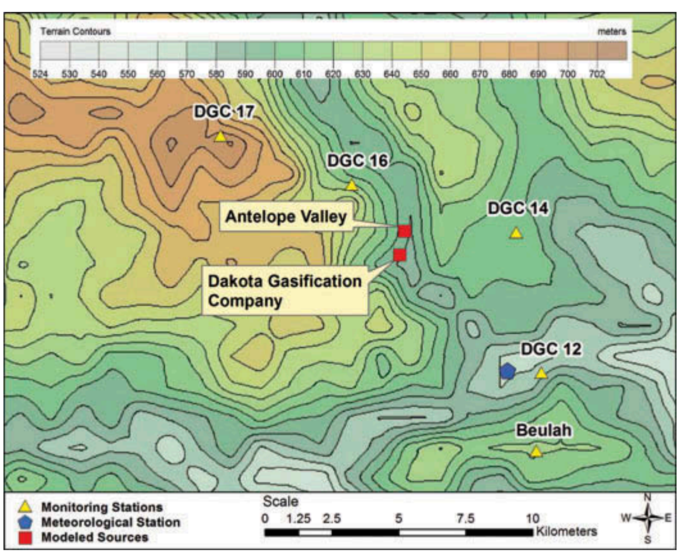

Figure 2. Terrain around the North Dakota monitors.

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_2 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_2 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_2 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_2 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[a]	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: [a]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

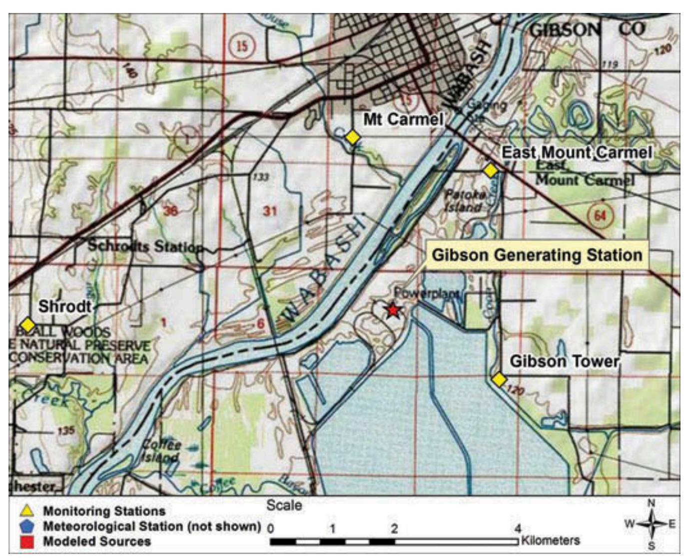

Figure 3. Map of Gibson model evaluation layout.

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_2 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_2 NAAQS design concentration

An operational metric that is tied to the form of the 1-hour SO_2 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^3 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 10μg/m^3) 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	DGC#12	91.52	109.96	1.20
(Default AERMET, Default	DGC#14	95.00	116.84	1.23
AERMOD)	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	DGC#12	91.52	109.96	1.20
(Beta AERMET, Default	DGC#14	95.00	116.84	1.23
AERMOD)	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	DGC#12	91.52	103.14	1.13
(Beta AERMET, AERMOD with	DGC#14	95.00	110.17	1.16
LOWWIND2 σ_v = 0.3 m/sec)	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	DGC#12	91.52	95.86	1.05
(Beta AERMET, AERMOD with	DGC#14	95.00	100.50	1.06
LOWWIND2 σ_v = 0.5 m/sec)	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	DGC#12	91.52	82.18	0.90
(SHARP)	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 σ_v in AERMOD is increased from 0.3 to 0.5 m/sec. For a minimum σ_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_2 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:

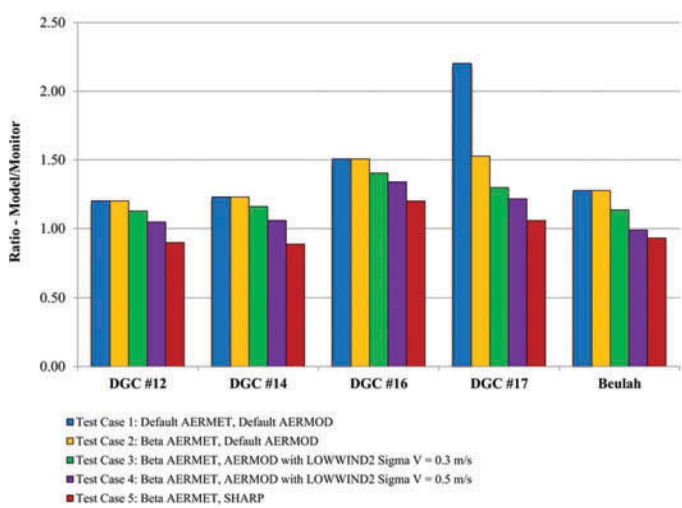

Figure 4. North Dakota ratio of monitored to modeled design concentration values at specific monitors.

- 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

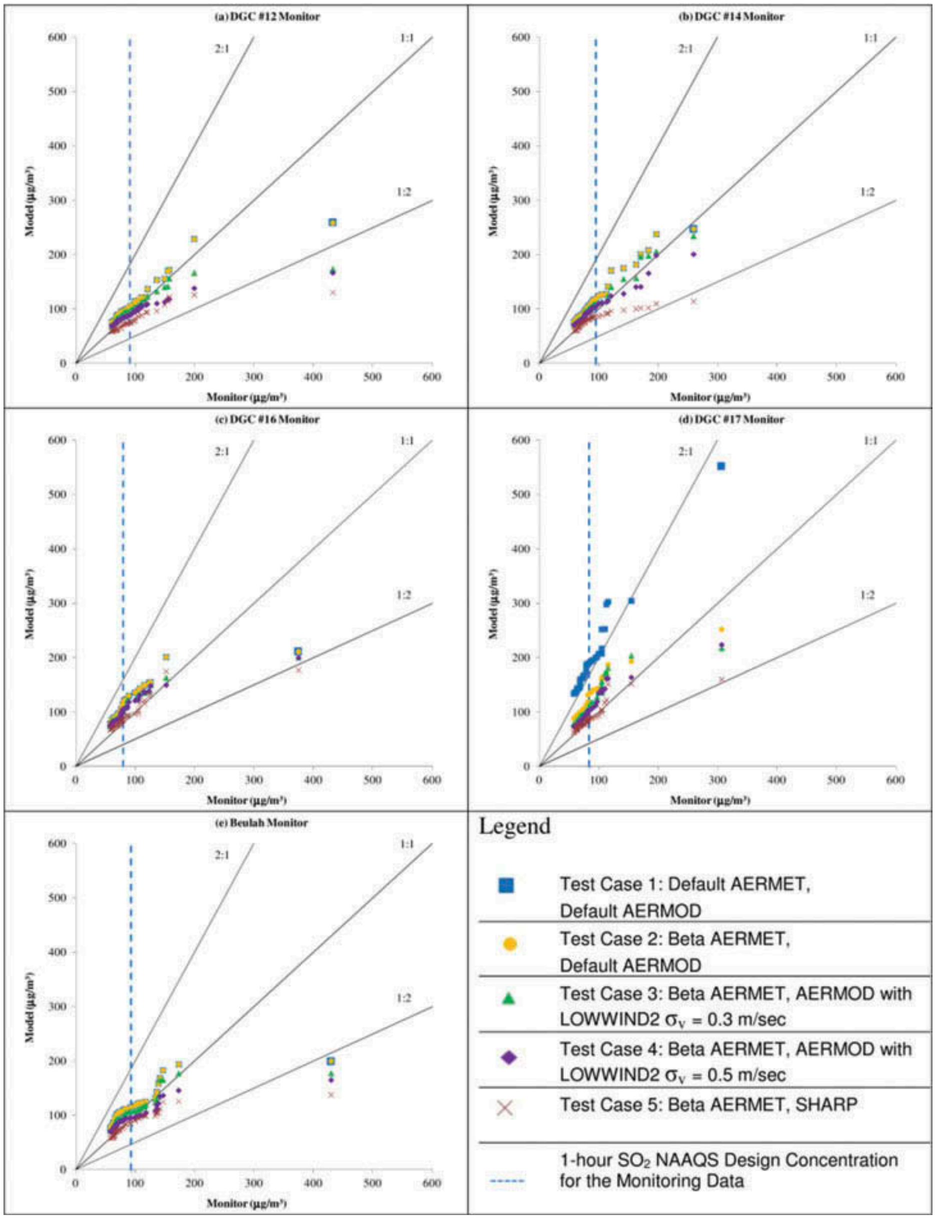

Figure 5. North Dakota Q-Q plots: top 50 daily maximum 1-hr SO_2 concentrations: (a) DGC #12 Monitor. (b) DGC#14 monitor. (c) DGC#16 monitor. (d) DGC#17 monitor. (e) Beulah monitor.

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_2, 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 μg/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 μg/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 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	Mt. Carmel	197.25	278.45	1.41
(Default AERMET, Default	East Mt. Carmel	206.89	230.74	1.12
AERMOD)	Shrodt	148.16	189.63	1.28
	Gibson Tower	127.12	193.71	1.52
Test Case 2	Mt. Carmel	197.25	287.16	1.46
(Beta AERMET, Default	East Mt. Carmel	206.89	229.22	1.11
AERMOD)	Shrodt	148.16	189.63	1.28
	Gibson Tower	127.12	193.71	1.52
Test Case 3	Mt. Carmel	197.25	280.32	1.42
(Beta AERMET, AERMOD with	East Mt. Carmel	206.89	224.65	1.09
LOWWIND2 σ_v = 0.3 m/sec)	Shrodt	148.16	184.82	1.25
	Gibson Tower	127.12	192.22	1.51
Test Case 4	Mt. Carmel	197.25	277.57	1.41
(Beta AERMET, AERMOD with	East Mt. Carmel	206.89	224.65	1.09
LOWWIND2 σ_v = 0.5 m/sec)	Shrodt	148.16	176.81	1.19
	Gibson Tower	127.12	192.22	1.51
Test Case 5	Mt. Carmel	197.25	225.05	1.14
(SHARP)	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: 99th percentile peak daily 1-hr maximum, averaged over the years modeled and monitored.

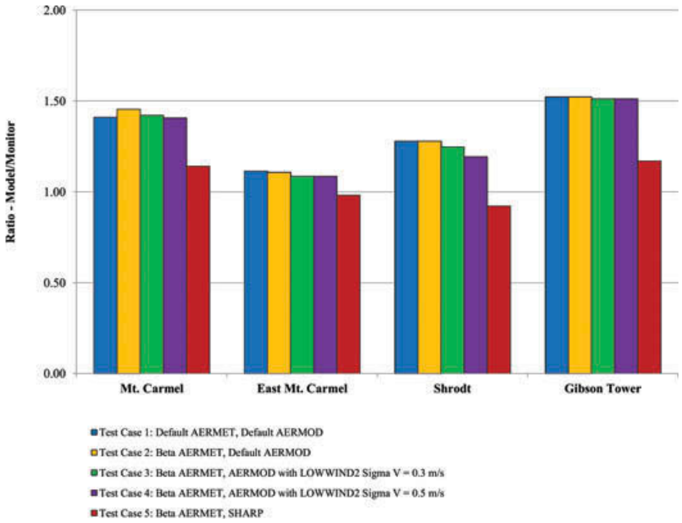

Figure 6. Gibson ratio of monitored to modeled design concentration values at specific monitors.

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.

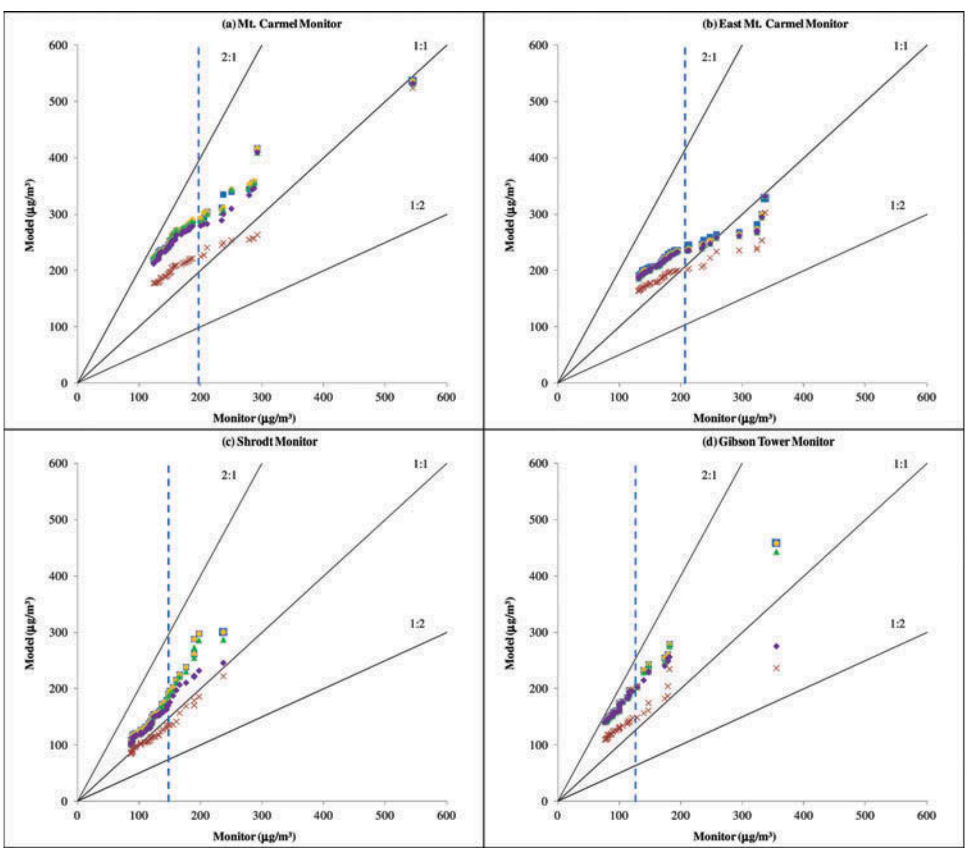

Figure 7. Gibson Q-Q plots: top 50 daily maximum 1-hour SO_2 concentrations. (a) Mt. Carmel monitor. (b) East Mt. Carmel monitor. (c) Shrodt monitor. (d) Gibson tower monitor. For the legend, see Figure 5.

- 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 σ_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 σ_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_2 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 σ_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 σ_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 σ_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 σ_v of 0.4 m/sec. This model, which was evaluated with site-specific meteorological data and four SO_2 monitors operated for 1 year, performed well in flat terrain, but overpredicted in elevated terrain, where a minimum σ_v value of 0.6 m/sec actually performed better. This would result in an average value of the minimum σ_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 σ_v" approach in AERMOD that enables the user to specify separate minimum σ_v values for stable and unstable conditions. This capability would, of course, be backward-compatible to the current minimum σ_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

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Appendix C

AERMOD Low Wind Speed Improvements: Status Report and New Evaluations

AERMOD Low Wind Speed Improvements: Status Report and New Evaluations

Paper # 935

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ABSTRACT

Some of the most restrictive dispersion conditions and the highest model predictions for AERMOD occur under low wind speed conditions, but before 2010, there had been limited model evaluation for these conditions. After a 2010 AECOM study, EPA proceeded to implement various improvements to the AERMET meteorological pre-processor (to address underpredictions of the friction velocity in low wind conditions) as well as the AERMOD dispersion model (to address under-predictions of the lateral wind meander). There have been several AERMOD releases with various options to address this issue, as well as additional model evaluations to further test the AERMOD implementation.

In July 2015, EPA proposed an updated set of options for AERMET and AERMOD for implementation as default options in the model. As part of the public comments, the Sierra Club provided new evaluations that led to questions as to whether the low wind options are sufficiently protective of air quality standards, especially the short-term SO_2 and NO_2 NAAQS. This study provides updated evaluation results to address these new concerns.

INTRODUCTION

When the United States Environmental Protection Agency (EPA) issued a proposed rulemaking to revise Appendix W to 40 CFR part 51, published in the July 29, 2015 Federal Register (80 FR 45340), it also released a revised version of AERMOD (15181), which replaced the previous version of AERMOD dated 14134. In the proposed revision to Appendix W, EPA proposed refinements to the default options in its preferred short-range model, AERMOD, involving low wind conditions. These refinements, included as beta options in version 15181 of AERMOD, involve an adjustment to the computation of the friction velocity ("ADJ_U*") in the AERMET meteorological pre-processor and a higher minimum lateral wind speed standard deviation, sigma-v (σ_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"[1]. At the public hearing for the proposed Appendix W revisions (the 11th Modeling Conference), EPA provided[2] evaluation results to support their proposal.

In comments to the docket on behalf of industrial trade organizations (the American Petroleum Institute and the American Iron & Steel Institute) to support EPA's low wind proposal, AECOM included references to a recently published peer-reviewed journal article[3] and supplementary evaluation information[4] involving tall-stack field databases to support the EPA proposal for incorporation of the low wind options noted above as default options.

Although most comments to the EPA docket supported the proposed low wind options, the Sierra Club issued comments[5] to the contrary, recommending that EPA should not adopt the proposed low wind options as defaults in the AERMOD modeling system. The Sierra Club analysis is further discussed below.

The purpose of this study has been to review the Sierra Club comments and modeling analysis and to rerun the evaluation for some of the databases for tall point sources used by the Sierra Club. The statistical metrics used in our evaluation are focused upon the design concentration for the 1-hour SO_2 National Ambient Air Quality Standard (NAAQS), which has a statistical form that is not represented in the statistical metrics used in the Sierra Club's model evaluation. The focus on the statistical 1-hour SO_2 design concentration (99th percentile daily maximum concentration over a year) is most appropriate for tall point sources such as power plants as that is commonly the criteria pollutant of interest. For low-level sources, other criteria pollutants such as carbon monoxide, which does not have statistically-based NAAQS design concentrations, can also be important.

SUMMARY OF AERMOD LOW WIND OPTIONS

In 2005, the EPA promulgated a new dispersion model, AERMOD[6], which replaced the Industrial Source Complex (ISC) model[7] as the preferred model for short-range air dispersion applications. Historically with ISC, winds below 3 knots (or 1.5 m/s) were presumed to be calm and were not modeled. As AERMOD and available wind measurements at airports have evolved since 2005, it has become quite routine for modeling applications (including those conducted for New Source Review) to include hours with wind speed observations much lower than 1.5 m/s. The instrumentation and recording methods for Automated Surface Observing System (ASOS) stations have also evolved. Some ASOS stations are now equipped with sonic anemometers with the ability to record winds less than 0.1 m/s. The inclusion of lower wind speed observations into AERMOD meteorological databases was made possible with these ASOS stations. Modeling issues under conditions of low wind speeds have become more prevalent with EPA's recommended procedures and the AERMINUTE tool for incorporating sub-hourly winds into AERMOD's meteorological databases.

One suspected area of AERMOD model bias has been for the situation of very low wind speeds (e.g., less than 1 m/s), stable conditions, and near-ground releases, as documented by Paine et al., 2010 (the "AECOM study", co-funded by the American Petroleum Institute and the Utility Air Regulatory Group[8]). With lower wind speeds more frequently being modeled, the use of these values as input to AERMOD is pushing the known bounds of a steady-state Gaussian model, which inherently assumes uni-directional wind flow. Because this is sometimes not the case during near-calm conditions, AERMOD or any other steady-state Gaussian model must be applied with caution, because the concentration approaches infinity at zero wind speed. The results of using very low wind speed input to AERMOD are the simulation of a plume that is generally too compact due to the lack of along-wind dispersion in the model formulation and under-representation of wind direction variability. As a result of the low wind issue, the AECOM study was conducted and the results were provided to EPA that specifically examined and improved AERMOD's ability to predict under low wind speed stable conditions.

The AECOM 2010 study examined two aspects of the model: (1) the meteorological inputs, as it related to u_* (friction velocity) and (2) the dispersion model itself, particularly the minimum lateral turbulence (as parameterized using sigma-v) assumed by AERMOD. As part of phase 1 of the study (involving three research-grade meteorological databases), the authors (Paine et al., 2010) concluded that their evaluation indicated that in low wind conditions, the u_* formulation in AERMOD underpredicts this important planetary boundary layer parameter. This results in an underestimation of the mechanical mixing height, as well as underestimates of the effective dilution wind speed and turbulence in stable conditions.

As part of phase 2 of the AECOM 2010 study (involving two low-level tracer release studies: Oak Ridge and Idaho Falls), the authors concluded that the AERMOD minimum sigma-v value of 0.2 m/s was too low by about a factor of 2, especially for stable, nighttime conditions.

The AECOM 2010 study found that the default AERMOD modeled concentrations were being over-predicted by nearly a factor of 10 for the Oak Ridge database and a factor of 4 for the Idaho Falls database. However, the proposed adjustments to the u_* formulation in AERMET and the incorporation of a minimum sigma-v in AERMOD substantially improved the model performance. The results of the AECOM 2010 study were provided to EPA in the spring of 2010.

EPA responded appropriately to these issues by incorporating low wind model formulation changes as beta options in AERMET and AERMOD versions 12345, 13350, 14134, and 15181. The formulation changes to AERMET were similar to those suggested by AECOM in their 2010 report, although EPA relied upon a Qian and Venkatram (2011) peer-previewed paper[9] for the AERMET formulation of the friction velocity ("ADJ_U*") adjustments. As a result of experience and comments received since the initial low wind implementation in late 2012, EPA proposed its recommended options in July 2015 for incorporation as defaults in the AERMOD modeling system.

SIERRA CLUB EVALUATION OF LOW WIND OPTIONS IN AERMOD VERSION 15181

The Sierra Club initially expressed its concerns about the AERMOD low wind options in a Camille Sears presentation[10] made at the 2013 EPA Modeling Workshop. As part of their comments on the proposed EPA changes to AERMOD presented in 2015, Camille Sears conducted additional evaluations on some of the evaluation databases that EPA has posted[6] for AERMOD studies. The specific evaluation databases selected by the Sierra Club included Baldwin, Kincaid, Lovett, Tracy, and Prairie Grass, with features noted below.

- Baldwin (1-hr SO_2): Rural, flat terrain, 3 stacks, stack height = 184.4 m, 1 full year
- Kincaid (1-hr SO_2): Rural, flat terrain, 1 stack, stack height = 187 m, about 7 months
- Lovett (1-hr SO_2): Rural, complex terrain, stack height = 145 m, 1 full year
- Tracy (1-hr SF_6): Rural, complex terrain, 1 stack, stack height = 90.95 m, several tracer release hours
- Prairie Grass (1-hr SF_6): Rural, flat terrain, 1 stack, release height = 0.46 m (no plume rise), several tracer release hours.

The evaluation techniques selected by Camille Sears for AERMOD were designed by EPA in the early 1990s, and the evaluation results were updated for various versions of AERMOD up to 2003 and 2005, when the most recent evaluation documents[11,12] were published. EPA's model evaluation procedures were developed to evaluate the ability of the model to estimate peak 1-hour average concentrations. This was appropriate for all criteria pollutants at that time which had deterministic short-term NAAQS, for which only a single excursion per year was allowed. This preceded the promulgation of statistically-based probabilistic forms of the 1-hour NAAQS for SO_2 and NO_2 (99^{th} and 98^{th} percentile of the daily 1-hour maximum values per year). For example, for SO_2, the ranked 1-hour concentration for the "design concentration" at any location (which has the same statistical form of the NAAQS) could theoretically range anywhere between the 4th highest and the 73rd highest 1-hour concentration in a full year.

EPA's recommended model evaluation statistic (developed prior to the promulgation of revisions to the SO_2 and NO_2 NAAQS in 2010) is the "robust highest concentration" (RHC), which focuses upon a fit involving the highest 26 concentrations among data from all monitor locations. EPA's 1992 model evaluation guidance[13] references the RHC statistic as the preferred approach. While this statistic was useful for the previous forms of the short-term NAAQS, including the SO_2 secondary NAAQS (2^{nd}-highest 3-hour concentration, which is the 99.93^{th} percentile value), it is clear that this statistic is inconsistent with the current short-term NAAQS for SO_2 and NO_2. As such, in evaluating model performance, especially for tall point sources for which the determination of modeled SO_2 NAAQS compliance is highly important, it is appropriate to focus upon the form of the 1-hour design concentrations.

The results of the Sierra Club evaluation are provided in Figure 1 as a screen capture from their comment document. The relevant lines of results to review in the figure are the third line (AERMOD default – no low wind options) and the fifth line (AERMOD with both ADJ_U* and LOWWIND3 options). Although we view the statistic presented as inconsistent with the 1-hour NAAQS and therefore can potentially misrepresent model performance in that regard, the following items are worth noting:

- Even with the RHC approach that was used, the Baldwin and Prairie Grass results show over-predictions or unbiased results with the low wind option; they are not reviewed here.

- The Kincaid and Lovett results show apparent under-predictions even for the default model, with slightly more under-prediction for the low wind options. However, the 100th percentile statistic addressed by the RHC misrepresents the more relevant and more stable 99th percentile (for SO_2) and 98th percentile (for NO_2) daily maximum NAAQS statistics. We also note below that the Kincaid evaluation study omitted important SO_2 sources that make this evaluation data unreliable.

- The short-term tracer studies (Tracy and Prairie Grass) are not amenable to an operational evaluation study that uses a long period (such as a full year) of data to address a wide range of meteorological conditions. Therefore, we did not use those databases in this supplemental study except for a brief look at the Tracy evaluation.

Figure 1 Summary of Sierra Club RHC Statistical Results

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A summary of Modeled RHC/Monitored RHC values for these modeled scenarios and field studies is presented in the following table:

Scenario	Baldwin (1-hr SO_2)	Kincaid (1-hr SO_2)	Lovett (1-hr SO_2)	Tracy (1-hr SF_6)	Prairie Grass (1-hr SF_6)
v. 02222	1.42	0.84	0.90	1.05	1.19
v. 12345	1.56	0.83	0.78	1.12	1.16
v. 15181	1.55	0.83	0.77	1.12	1.17
v. 15181, ADJ_U*	1.55	0.83	0.91	0.53	1.19
v. 15181, ADJ_U*, LOWWIND3 (0.3, 0.5, 0.95)	1.40	0.72	0.79	0.42	0.95

The results of the evaluation with low wind options could depend upon whether the measured turbulence data (especially the horizontal turbulence data) is withheld from the modeling. The horizontal turbulence issue is noteworthy because recent EPA guidance indicates that the hourly averages of wind direction fluctuations should use four 15-minute averages, thus neglecting wind direction meander among the 15-minute periods. In addition, EPA may consider[14] that the use of the observed sigma-theta (and possibly sigma-w data), in addition to the low wind meander adjustments, could "over-correct" for the low wind issue.

In some research-grade experiments, such as Tracy, the turbulence data is obtained from sonic anemometers, which could result in higher turbulence measurements in low winds because these instruments have a very low wind detection threshold as opposed to more commonly-used cup and vane wind systems. Sonic anemometers can have operational difficulties for routine monitoring in general due to problems in humid climates with wet probe errors and a very large power requirement[15], which makes battery backup in the event of power outages problematic. In addition, the hourly averages of the horizontal wind direction standard deviation (sigma-theta) for Tracy[16] and the other databases developed for EPA during the Complex Terrain Model Development program used true hourly averages rather than averaging four 15-minute averages. This can result in a double-counting of meander in AERMOD and can possibly overstate the vertical turbulence component as well. Therefore, the option to remove the observed turbulence input to AERMOD for the low wind runs may be dependent upon the averaging used. The instruments used in all of the databases that we ultimately selected for evaluation used hourly averages consisting of four 15-minute averages, thus not double-counting the wind meander.

DESIGN OF OUR STATISTICAL EVALUATION

To address the issues brought up by the Sierra Club in its model evaluation, we provide the results of a similar evaluation analysis with the following features:

- Alternative statistical measures (more relevant for the form of the 1-hour SO_2 NAAQS) are reported, as further discussed in bullets below.

- Three tall-stack databases were considered, two of which were modeled by the Sierra Club, plus one additional AERMOD evaluation database (Clifty Creek) to increase confidence in the overall results: Lovett, Kincaid, and Clifty Creek. Lovett represents a complex terrain setting, Kincaid a flat setting, and Clifty Creek represents an intermediate setting with the power plant in the Ohio River gorge, but with stack top still higher than the higher elevation monitors.

- For the RHC statistic, we also used the daily 1-hour maximum instead of all hourly values, to be more consistent with the form of the 1-hour NAAQS.

- For the RHC statistic, we also discarded (for the case of SO_2 for a year of data) the top 3 daily 1-hour maximum values so that the statistic estimates the correct form of the standard (this statistic can be referred to as “R4HC” because it estimates the 4^{th} highest concentration).

- We also conducted an R4HC evaluation for each monitor separately, and then took the geometric mean of the modeled-to-observed ratios over all monitors to determine the overall model performance with the monitors each given equal weight.

- In supplemental information provided separately to EPA (too lengthy to include in this paper), we provided an appendix for each database evaluated, we include quantile-quantile (Q-Q) plots for each monitor to pair the evaluation in space.

- In this paper, we show plots of the observed and predicted 99^{th} percentile peak daily 1-hour maximum concentrations in ranked pairs to focus on the form of the SO_2 NAAQS and ability of the model to prove a predicted design concentration that is at least as high as the highest observed design concentration.

- Our modeling options included all default options, use of the ADJ_U* option in AERMET (but default AERMOD – no LOWWIND3), and ADU_U* plus LOWWIND3. Due to the underlying science that justifies the correction to the friction velocity formulation (ADJ_U*), we did not consider LOWWIND3 without ADJ_U*.

LOVETT EVALUATION RESULTS

Description of Field Study Setting

The Lovett Power Plant study (Paumier et al.[17]) consisted of a buoyant, continuous release of SO_2 from a 145-m tall stack located in a complex terrain, rural area in New York State. The data spanned one year from December 1987 through December 1988. Data available for the model evaluation included 9 monitoring sites on elevated terrain; the monitors were located about 2 to 3 km from the plant. The monitors provided hourly-averaged concentrations. A map of the terrain overlaid with the monitoring sites is shown in Figure 2. The important terrain feature rises approximately 250 m to 330 m above stack base at about 2 to 3 km downwind from the stack. The plant was a base-loaded coal-fired power plant with no flue gas desulphurization controls; hourly emissions and stack flow rate and temperature data were available. Meteorological data included winds, turbulence, and ΔT from a tower instrumented at 10 m, 50 m, and 100 m. National Weather Service surface data (used for cloud cover) were available from a station 45 km away.

AERMET/AERMOD version 15181 was run for the Lovett evaluation database using the following 8 configuration options:

- AERMET Default / AERMOD Default, including all observed turbulence;
- AERMET Default/ AERMOD Default with all observed turbulence removed;
- AERMET ADJ_U* / AERMOD LOWWIND3, including all observed turbulence;
- AERMET ADJ_U* / AERMOD LOWWIND3 with all observed turbulence removed; and
- AERMET ADJ_U* / AERMOD LOWWIND3 with observed horizontal turbulence removed, but retaining the vertical turbulence data.
- AERMET ADJ_U* / AERMOD (default), including all observed turbulence;
- AERMET ADJ_U* / AERMOD (default) with all observed turbulence removed; and
- AERMET ADJ_U* / AERMOD (default) with observed horizontal turbulence removed, but retaining the vertical turbulence data.

The EPA-proposed model option parameters (0.3, 0.5, 0.95) were selected for the LOWWIND3 model runs, consistent with the Sierra Club report.

Results of the 99th Percentile Concentration Comparison

To be more consistent with the form of the 1-hour NAAQS, the 4th highest (99th percentile) daily peak 1-hour SO_2 concentrations observed at each monitor location were compared against the model-predicted concentrations of similar rank. Summarized in Figure 3 are the predicted concentrations determined using model default and low wind options as stated above. The overall results indicate that the modeling scenario using low wind options, but without turbulence, had an overall maximum 4th highest daily 1-hour concentration across all monitors greater than the overall highest observed.

Discussion of Lovett Evaluation Results

After we closely replicated the Sierra Club results, we investigated alternative evaluation approaches for the predicted and observed concentrations. We computed RHC statistics for the 1) highest 1-hour concentration, 2) the 4th highest 1-hour concentration (discarding the top 3 values, but using all hourly values, and 3) the 4th highest daily maximum 1-hour averaging periods of SO_2 concentrations for each monitoring site. For the third set of statistics, we calculated a geometric mean of these ratios to gain a better understanding of the overall model performance that accounts for all monitors; see Table 1).

Figure 2 Map of Lovett Power Plant and Monitor Locations

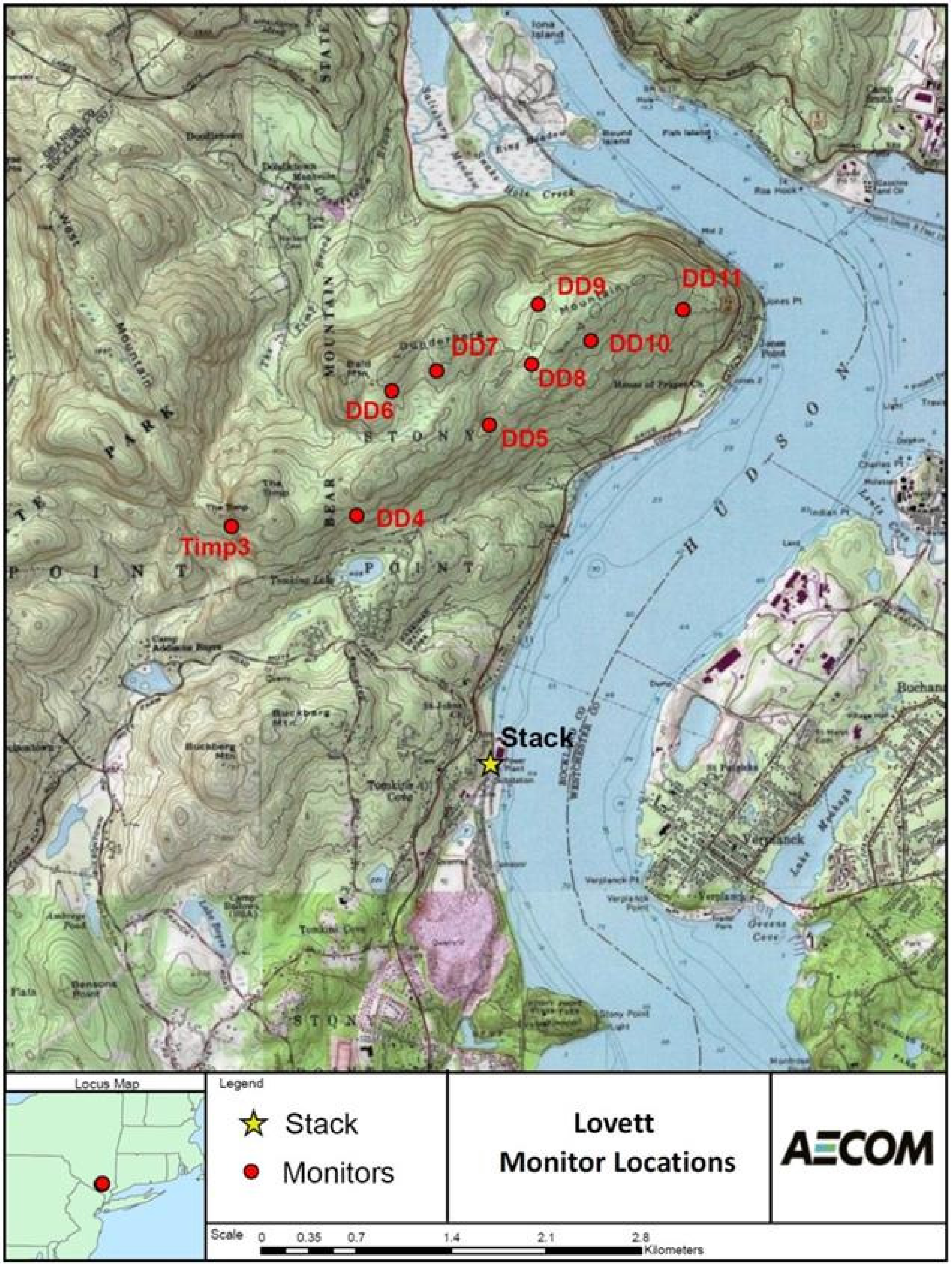


Figure 3 Histogram of the 4th Highest Daily Peak 1-hour SO_2 Concentrations

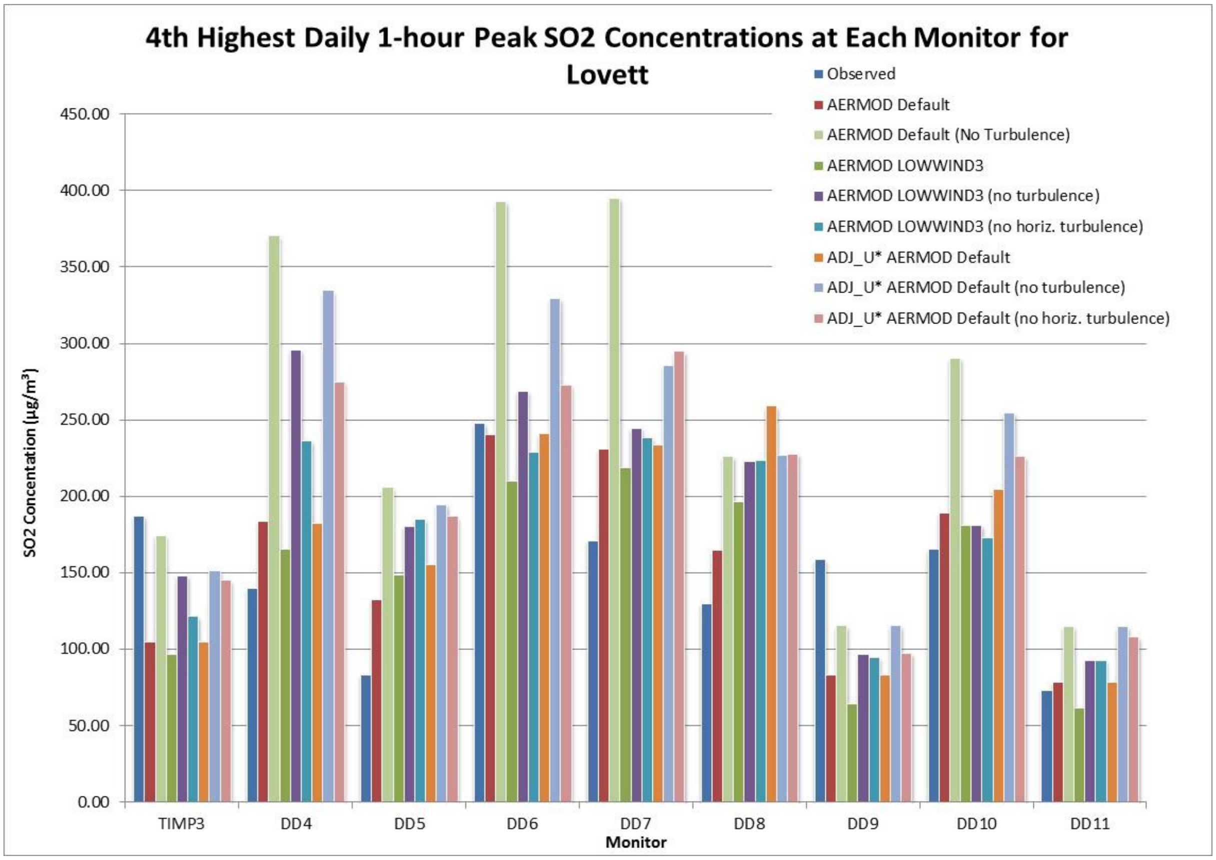


Table 1 Ratio of Predicted-to-Observed Robust 4th Highest Daily Peak Concentration (R4HC; 99th Percentile) for Each Monitor at Lovett

Monitor	AERMOD 15181, Default, all turb.	AERMOD 15181, Default, no turb.	AERMOD 15181, all low wind options, all turb.	AERMOD 15181, all low wind options, no turb.	AERMOD 15181, all low wind options, no horiz. turb.	AERMOD 15181, ADJ_U*, all turb.	AERMOD 15181, ADJ_U*, no turb.	AERMOD 15181, ADJ_U*, no horiz. turb.
TIMP3	0.53	0.62	0.40	0.58	0.52	0.47	0.51	0.53
DD4	1.49	3.19	1.26	2.49	1.83	1.40	3.08	2.16
DD5	1.55	2.85	2.13	2.18	2.06	2.26	2.74	2.40
DD6	0.81	1.46	0.63	1.00	0.79	0.69	1.25	0.92
DD7	1.29	1.86	1.29	1.42	1.18	1.33	1.65	1.61
DD8	1.03	1.47	1.63	1.19	1.27	1.84	1.23	1.28
DD9	0.38	0.60	0.32	0.52	0.57	0.38	0.60	0.63
DD10	1.23	2.22	1.33	1.26	1.18	1.41	1.72	1.57
DD11	1.24	1.95	0.94	1.64	1.70	1.19	1.96	2.02
Geometric Mean	0.97	1.57	0.94	1.21	1.11	1.06	1.41	1.30

The evaluation results indicate a slight under-prediction by the model using default and low wind model options using all turbulence data. The model over-predicts for the modeling runs that omit all turbulence or only the horizontal turbulence. We also include modeling results with the AERMOD default options, but with turbulence omitted, to reflect the modeling performance with input data similar to typical airport data. That model run shows a substantial over-prediction tendency, indicating the benefits of the use of observed turbulence data, and the need without such data to employ the low wind options for improved AERMOD model performance.

We also computed and then ranked the 99th percentile peak daily 1-hour maximum concentration – the "design concentration" - (both predicted and observed) for each of the 9 monitors. We then plotted the ranked pairs as a Q-Q plot for each model tested. The highest ranked pair was examined closely because that pair of values represents the controlling design concentration for observations and model predictions. Due to the fact that SO_2 monitored concentrations can have a 10% uncertainty due to calibration tolerances permitted by EPA[18], it is possible that predicted/observed ratios within 10% of 1.0 are unbiased.

The results indicate that the modeling options for default AERMOD with turbulence included, both low wind options with only vertical turbulence included, or just the ADJ_U* option with all turbulence included are nearly unbiased for this test. The default model with no turbulence is approaching a factor-of-2 over-prediction and it is the worst-performing model (see Figure 4). The low wind option run (both ADJ_U* and LOWWIND3) with no turbulence (Figure 5) still shows an over-prediction, and with full turbulence shows a slight under-prediction (Figure 6), but with consideration of impacts from an unmodeled nearby background source (Bowline Point), it could be within the 10% uncertainty range for an unbiased model. The model with both low wind options and no turbulence shows a modest over-prediction. If only ADJ_U* is used, then the use of full turbulence input shows a modest over-prediction, and eliminating all turbulence leads to over-predictions. Therefore, it appears that the only case in which horizontal (but not vertical) turbulence should be removed (to prevent underpredictions) from input to AERMOD is in the case for which both ADJ_U* and LOWWIND3 are employed.

Figure 4 Q-Q Plot of the Ranked 4th Highest (99th Percentile) Daily 1-hour SO_2 Concentrations for Each Monitor Using AERMOD Default (No Turbulence)

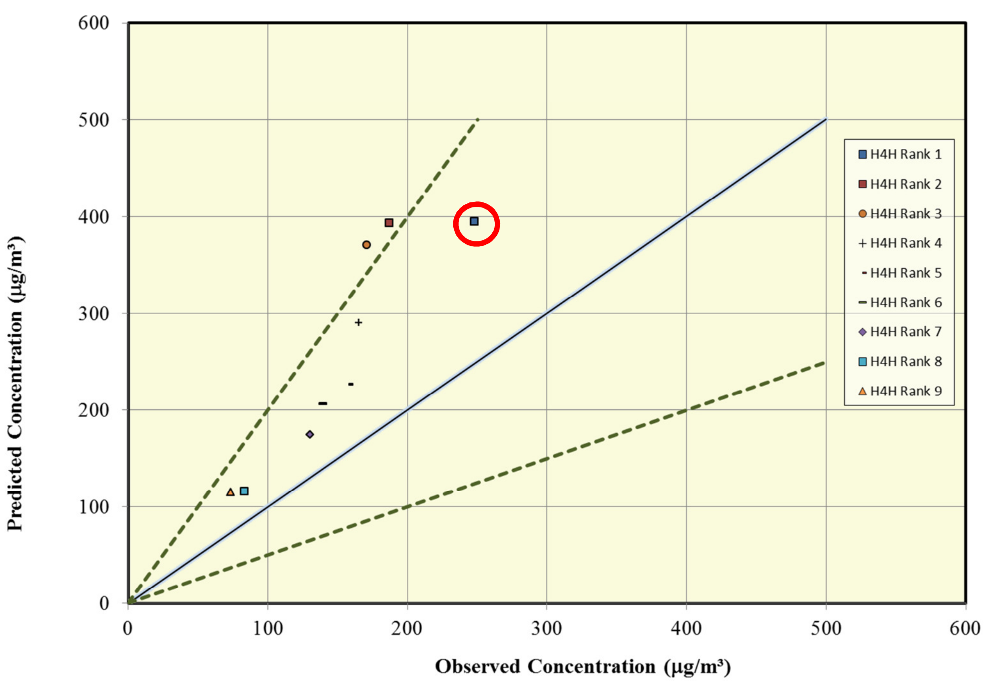


Figure 5 Q-Q Plot of the Ranked 4th Highest (99th Percentile) Daily 1-hour SO_2 Concentrations for Each Monitor Using AERMOD LOWWIND3 (No Turbulence)

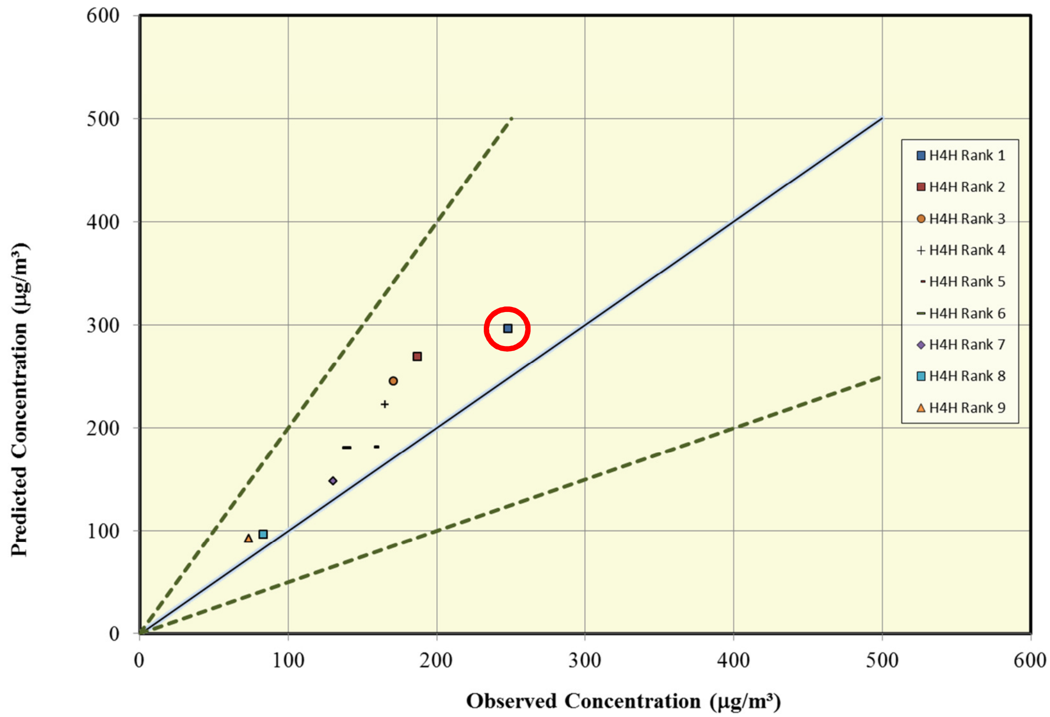
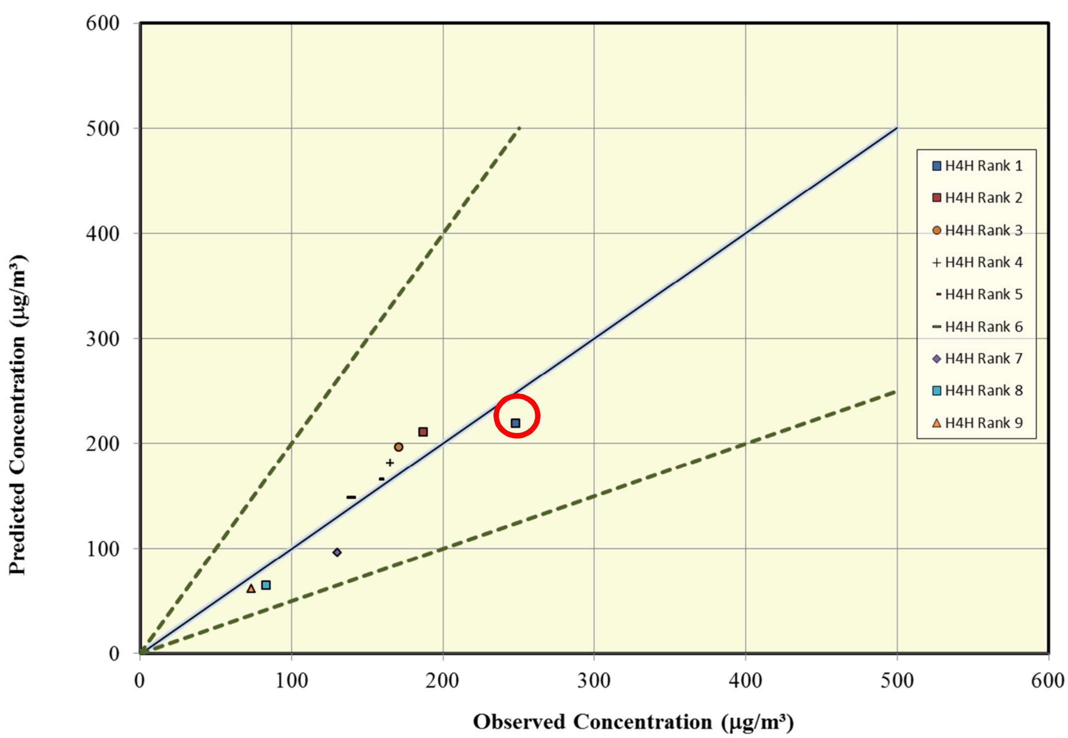


Figure 6 Q-Q Plot of the Ranked 4th Highest (99th Percentile) Daily 1-hour SO_2 Concentrations for Each Monitor Using ADJ_U* and LOWWIND3 (All Turbulence Used)



CLIFTY CREEK EVALUATION RESULTS

Description of Field Study Setting

The Clifty Creek Power Plant is located in rural southern Indiana along the Ohio River with emissions from three 208-m stacks during this study. The area immediately north of the facility is characterized by cliffs rising about 115 m above the river and intersected by creek valleys. Six nearby SO_2 monitors (out to 16 km from the stacks) provided hourly averaged concentration data. A map of the terrain overlaid with the monitoring sites is shown in Figure 7. Hourly-varying emissions (for this base-loaded with no SO_2 controls in 1975) were provided for the three stacks. Meteorological data from a nearby 60-m tower for 1975 were used in this evaluation study. The meteorological data included winds at 60 m and temperature at 10 m. The on-site meteorological tower did not include turbulence measurements. This database was also used in a major EPA-funded evaluation of rural air quality dispersion models in the 1980s[19].

AERMET/AERMOD version 15181 was run using the following two configuration options (fewer options than Lovett due to the lack of turbulence data):

- AERMET Default / AERMOD Default
- AERMET ADJ_U* / AERMOD LOWWIND3.

Results of the 99th Percentile Concentration Comparison

The 4th highest (99th percentile) daily peak 1-hour SO_2 concentrations observed at each monitor location were compared against the model-predicted concentrations. This comparison was performed for AERMOD version 15181 default and the low wind options. The 1-hour SO_2 design concentrations for the Clifty Creek evaluation database are plotted in Figure 8.

Figure 7 Map of Clifty Creek Power Plant and Monitor Locations

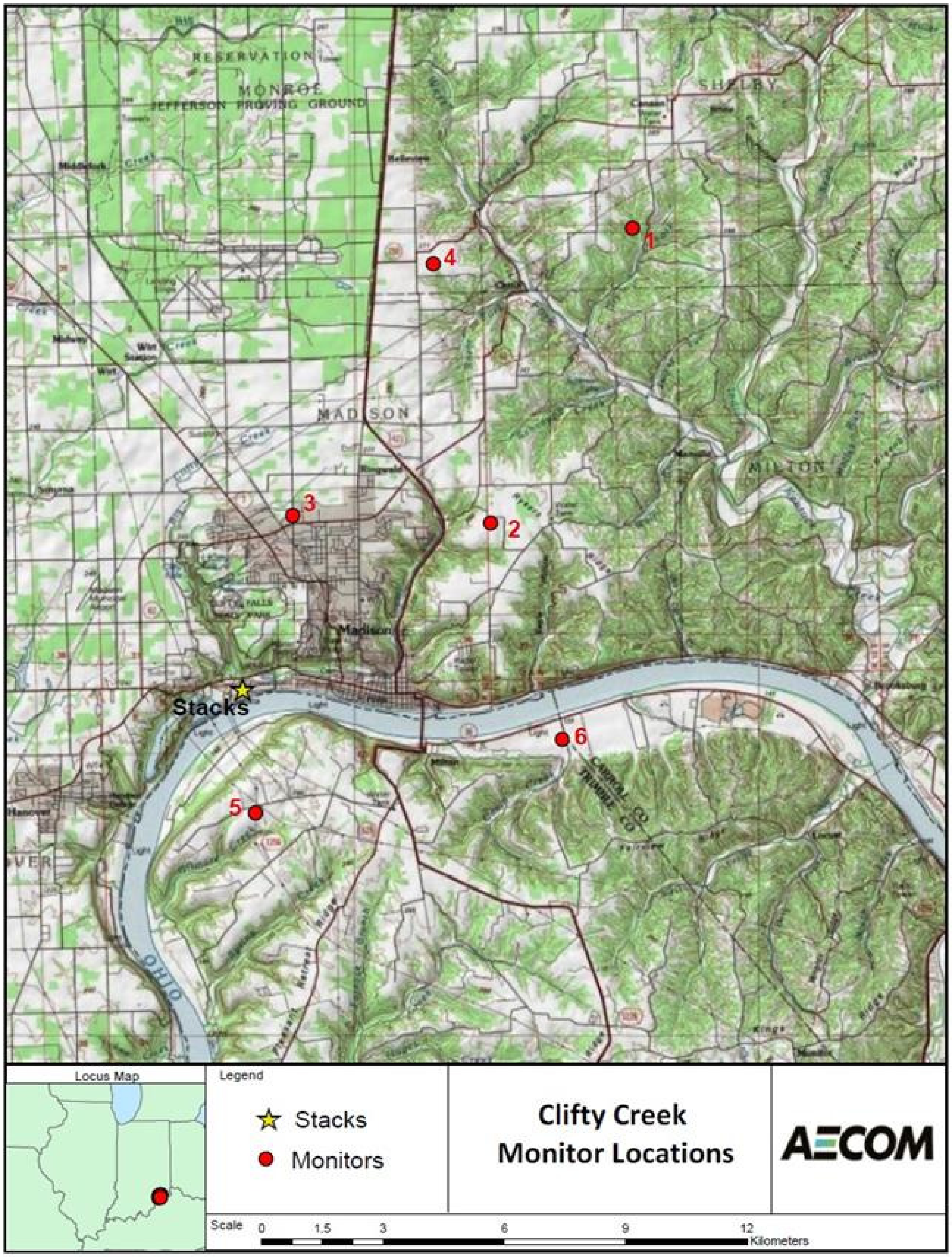
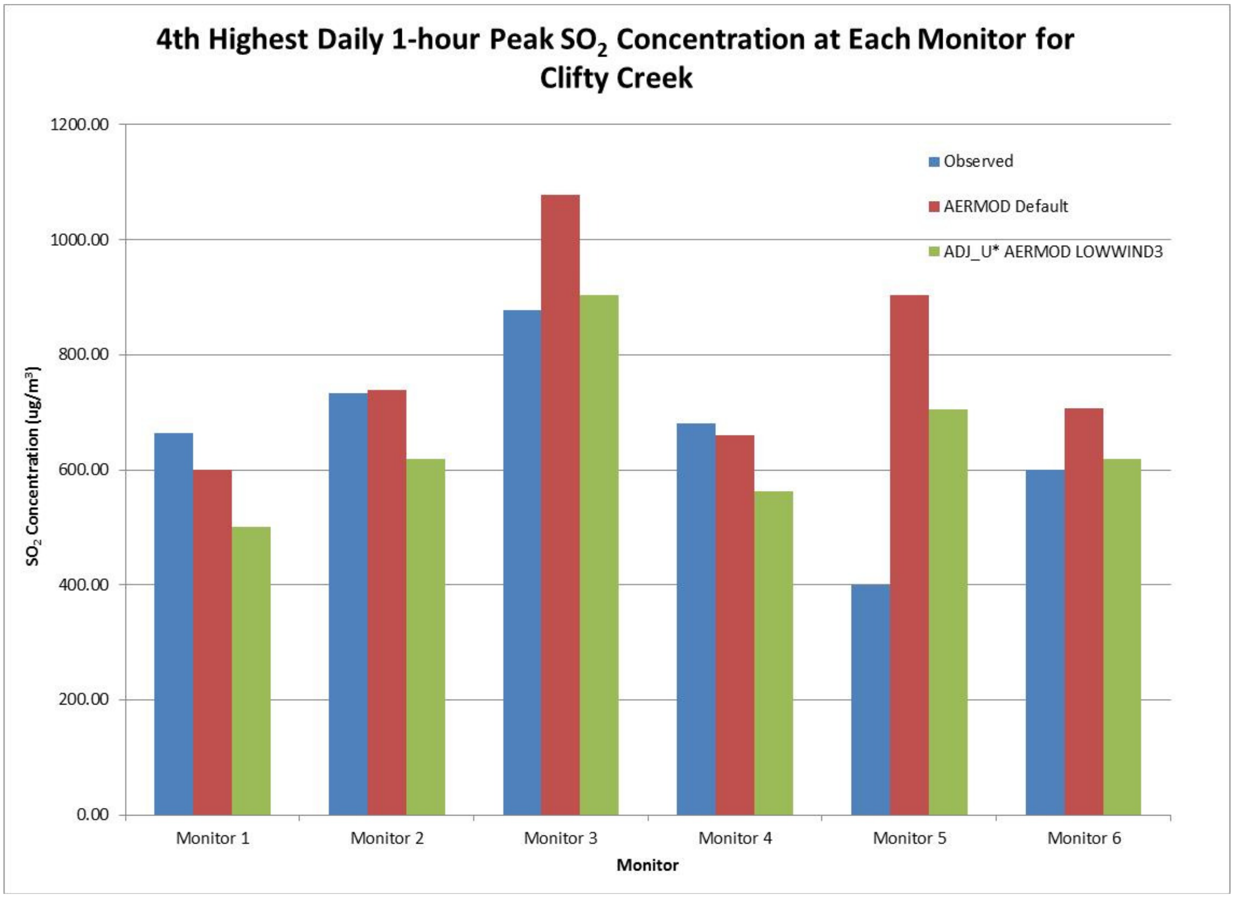


Figure 8 Histogram of the 4th Highest Daily Peak 1-hour SO_2 Concentrations



The overall results indicate the following:

- The highest design concentration over all monitor sites for both default and low wind options are higher than its observed counterpart. The over-prediction for the default option is larger.
- The AERMOD v15181 default highest design concentration from all monitor sites is greater than the low wind result.
- Model-predicted design concentrations being higher or lower than observed were relatively evenly split across the six monitors.

Discussion of Clifty Creek Evaluation Results

RHC statistics were calculated for 1) the top twenty-six 1-hour, 2) the 4th highest 1-hour (using all hours), and 3) the 4th highest daily 1-hour averaging periods of SO_2 concentrations for each monitor site. A geometric mean of these ratios were then calculated to gain a better understanding of the overall model performance. The results for the third set of statistics are summarized in Table 2. Overall, the results indicate the two modeling approaches are nearly unbiased, with the default run slightly over-predicting, while the low wind options run is slightly under-predicting. The overall result for the low wind options were within the 10% uncertainty for monitored SO_2 concentrations.

Table 2 Ratio of Predicted-to-Observed Robust 4th Highest Daily Peak Concentration (R4HC; 99th Percentile) for Each Monitor at Clifty Creek

Monitor	AERMOD 15181 Default	AERMOD 15181 LOWWIND3
1	0.81	0.79
2	0.86	0.75
3	1.30	1.06
4	0.75	0.65
5	2.47	1.62
6	1.35	1.08
Geometric Mean	1.14	0.94

To provide a graphical depiction of the performance of the model options for predicting the 1-hour SO_2 NAAQS, we computed and then ranked the 99th percentile peak daily 1-hour maximum concentration (both predicted and observed) for each of the 6 monitors. We then ranked the 6 observed and predicted values independently and plotted the ranked pairs as a Q-Q plot for each model tested:

- Figure 9 for AERMET Default / AERMOD Default, and
- Figure 10 for AERMET ADJ_U* / AERMOD LOWWIND3.

An examination of the circled point in each figure (paired predicted and observed design concentrations) indicates that both modeling approaches over-predict for the controlling design concentration, but the default model over-predicts more.

Figure 9 Q-Q Plot of the Ranked 4th Highest (99th Percentile) Daily 1-hour SO_2 Concentrations for Each Monitor Using AERMOD Default

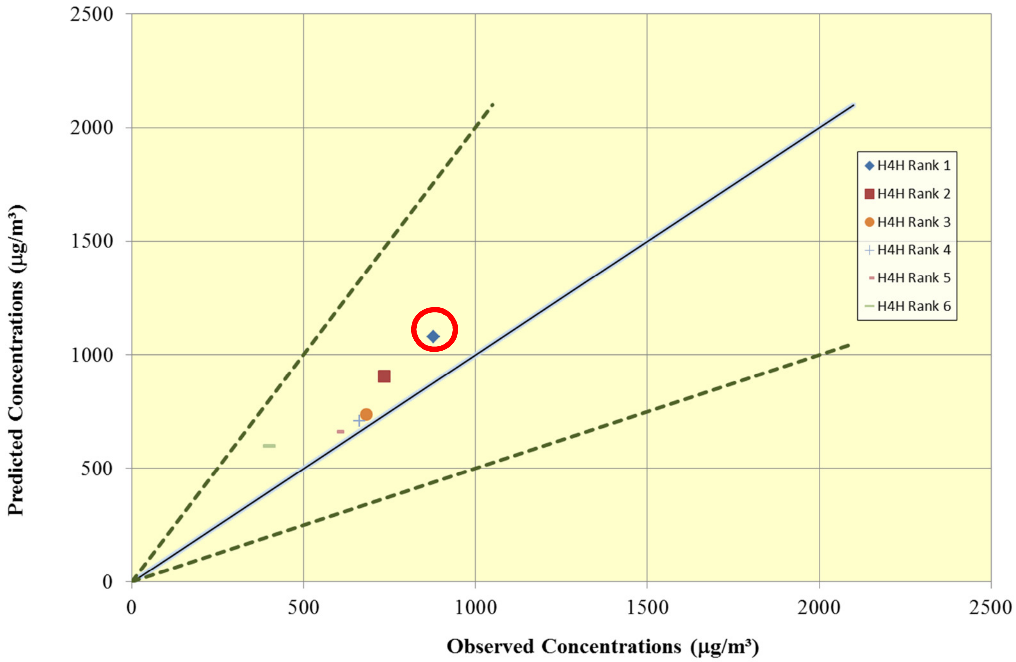
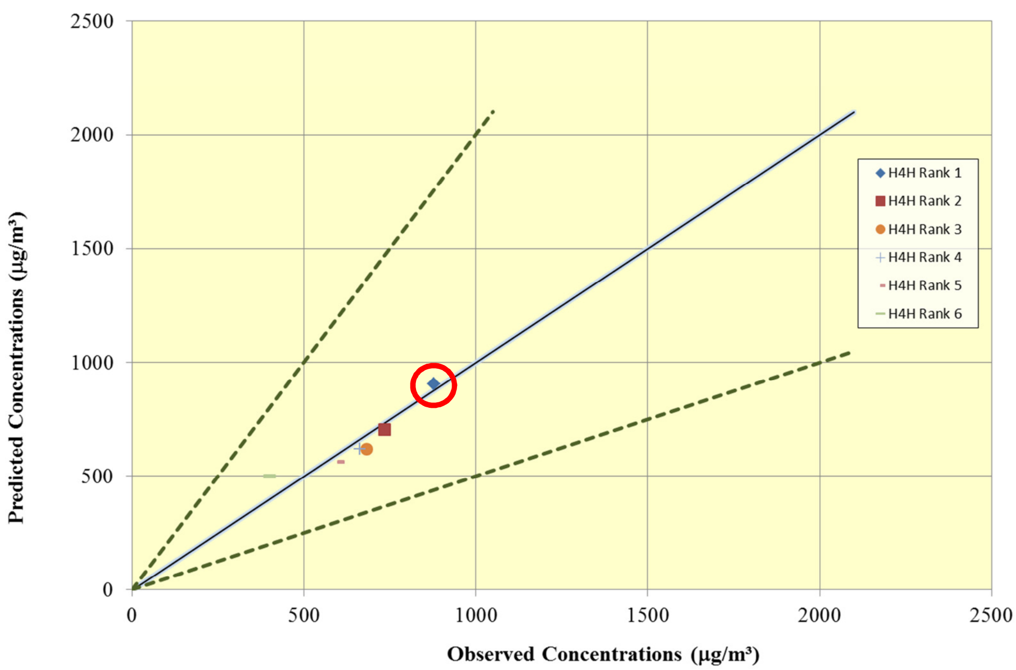


Figure 10 Q-Q Plot of the Ranked 4th Highest (99th Percentile) Daily 1-hour SO_2 Concentrations for Each Monitor Using ADJ_U* and LOWWIND3



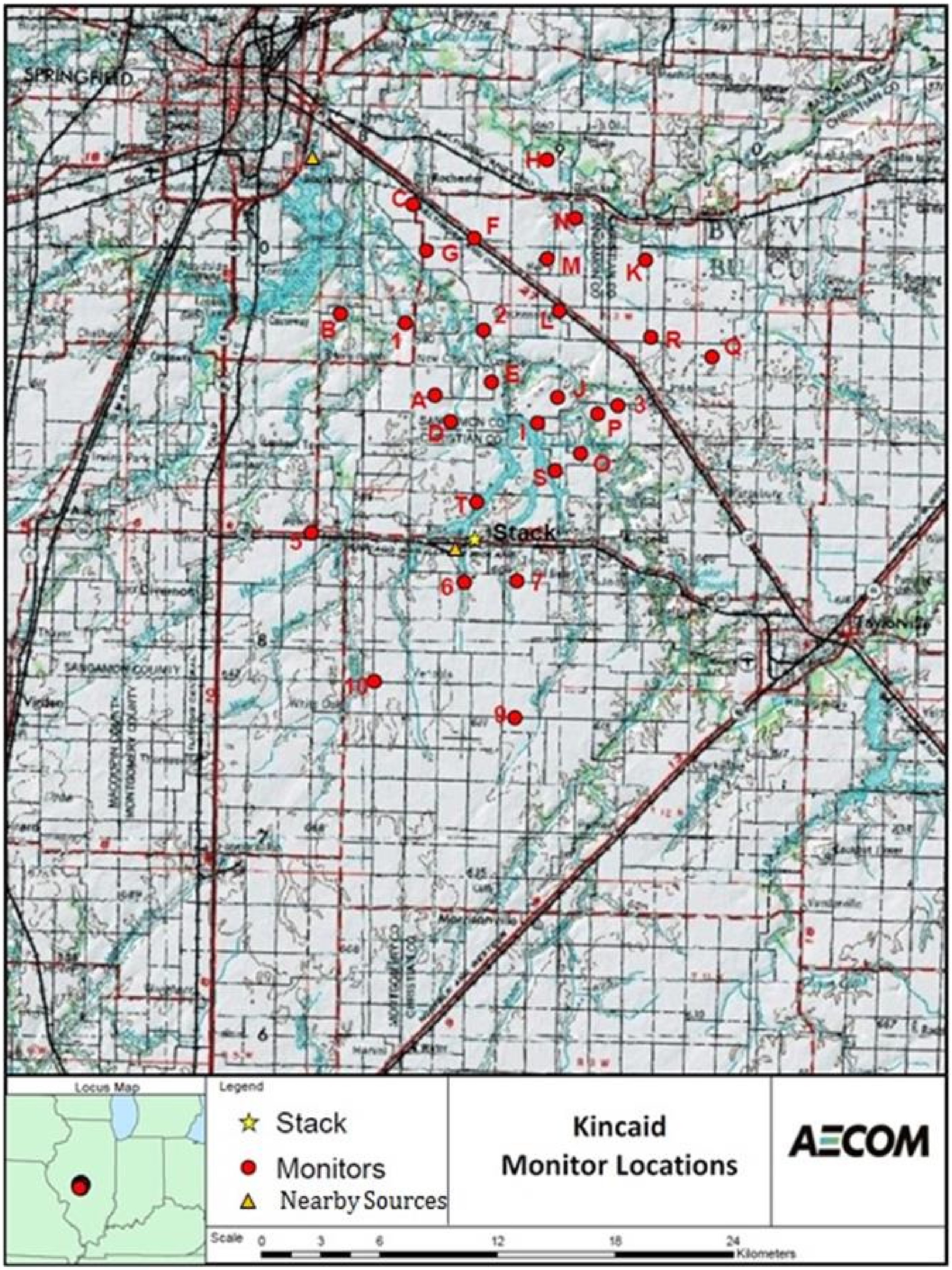
KINCAID FIELD STUDY

The Kincaid SO_2 study[20,21] was conducted at the Kincaid Generating Station in central Illinois, about 25 km southeast of Springfield, Illinois. It involved a buoyant, continuous release of SO_2 from a 187-m stack in rural flat terrain. The study included about seven months of data between April 1980 and June 1981 (a total of 4,614 hours of samples). There were 28 operational SO_2 monitoring stations providing 1-hour averaged samples from about 2 km to 20 km downwind of the stack. A map of the terrain overlaid with the monitoring sites is shown in Figure 11. Meteorological data included wind speed, direction, horizontal turbulence, and temperature from a tower instrumented at 2, 10, 50, and 100 m levels, and nearby National Weather Service (NWS) data. Vertical turbulence measurements were also included in the onsite tower data at 100-m level.

A review of the monitor-by-monitor differences between modeled and observed design concentrations indicates that monitors near unaccounted-for nearby sources of SO_2 are significantly affecting the modeling results. From Figure 11, it is clear that monitors C, G, F, 1, and B are relatively close to the Dallman plant in the northwestern part of the field study domain. It is also evident that monitors 6, 7, and 10 are relatively close to the local coal preparation plant.

Since there appear to be significant contributions from un-modeled SO_2 sources, this evaluation database, without a correction to add the unmodeled sources, is not appropriate for inclusion in this study. The analysis that is needed to determine the magnitude of the unmodeled emissions is beyond the scope of this study. Although the Kincaid SO_2 experiment may be seriously compromised without information on the unmodeled sources, it may be possible to reasonably estimate the approximate magnitude of the emission sources that were missed for future updates of this database. In contrast, the Kincaid SF_6 study is not similarly affected because of the single source of this tracer release. However, the extent of the time period covered by the intensive Kincaid tracer study is much less than that of the SO_2 study, which limits its applicability for a full-year SO_2 database evaluation.

Figure 11 Map of Kincaid and Monitor Locations, Along with Nearby Emission Sources Omitted from the Evaluation Database



OTHER TALL-STACK EVALUATION DATABASES

Evaluation of the low wind modeling approaches for North Dakota and Gibson Generating Station are described in details in a November 2015 Journal of the Air & Waste Management Association article[3]. This section presents a brief summary of the databases and the evaluation results.

An available 4-year period of 2007-2010 was used for the Mercer County, ND evaluation database with five SO_2 monitors within 10 km of two nearby emission facilities (Antelope Valley and Dakota Gasification Company), site-specific meteorological data at one of the sites (10-m level data in a low-cut grassy field), and hourly emissions data from 15 point sources (all tall stacks). The terrain in the area is rolling and features three of the monitors above or close to stack top for some of the nearby emission sources. 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.

The overall evaluation results for the North Dakota database indicated the following:

- The highest modeled design concentration at all monitor sites for both default and low wind options are higher than observed.
- The AERMOD v15181 default highest design concentration from all monitor sites is greater than the ones using the low wind options.
- For the monitors in simple terrain, the evaluation results were similar for both the default and the low wind options.
- The evaluation result for the monitor in the highest terrain shows that the ratio of modeled to monitored concentration is more than 2, but when this location is modeled with the low wind options, the ratio is significantly better, at less than 1.3.

An available 3-year period of 2008-2010 was used for the Gibson Generating Station evaluation database in southwest Indiana with four SO_2 monitors within 6 km of the plant, airport hourly meteorological data (from Evansville, Indiana 1-minute 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. Due to the fact that there are no major SO_2 sources within at least 30 km of Gibson, we modeled emissions from only that plant.

The overall evaluation results for Gibson indicated the following:

- The highest modeled design concentration from all monitor sites for both default and low wind options are higher than observed.
- The AERMOD v15181 default highest design concentration from all monitor sites is greater than that for the low wind options.

- The ratios of the modeled to monitored concentrations at each monitor are greater than 1.0. The default option over- predicts by about 41-52% at two of the monitors and by about 12-28% at the other two monitors. The low wind options reduce the over-predictions to 5-28% at the four monitors

BRIEF REVIEW OF TRACY EVALUATION

For the databases used for EPA's Complex Terrain Model Development project (documented in several "Milestone Reports"; the one for Tracy is the Fifth Milestone Report[16]), the turbulence data sigma-theta in the horizontal and sigma-w in the vertical) as archived for use in the CTDMPLUS model was processed using a full 60-minute average. Shortly after the databases were developed, EPA issued a year 1987 and later a year 2000 updated guidance document for site-specific meteorological measurements (Meteorological Monitoring Guidance for Regulatory Modeling Applications). The guidance for taking direct measurements of horizontal and vertical turbulence recommends using 15-minute averaging times and averaging the 4 values to obtain an hourly average. The reason for this is for computing stability class (for models in use before AERMOD), but this method also provides short-term turbulence data appropriate for plume dispersion in AERMOD.

The use of 15-minute averages for sigma-theta and sigma-w avoids overestimates of the plume dispersion in AERMOD with the following considerations:

- For the horizontal (crosswind, lateral) turbulence (sigma-theta), the use of 15-minute averages does not account for wind direction meandering during the course of an hour to the extent that the full 60-minute average does. It is important to include meander unless the model separately accounts for it (CTDMPLUS does not). However, since AERMOD (especially with the low wind options) accounts for plume meander separately, the use of 60-minute averages for sigma-theta would "double-count" the meander, and that would be expected to result in a model underprediction.

- For the vertical turbulence (sigma-w), the use of 15-minute averages helps to provide AERMOD with intra-hour averages that avoid the consideration of updrafts and downdrafts that do not disperse the plume, but which affect the longer-term (60-minute) average by increasing the value of sigma-w. The use of a 60-minute average leads to a modeled dilution of the plume for impacts in complex terrain.

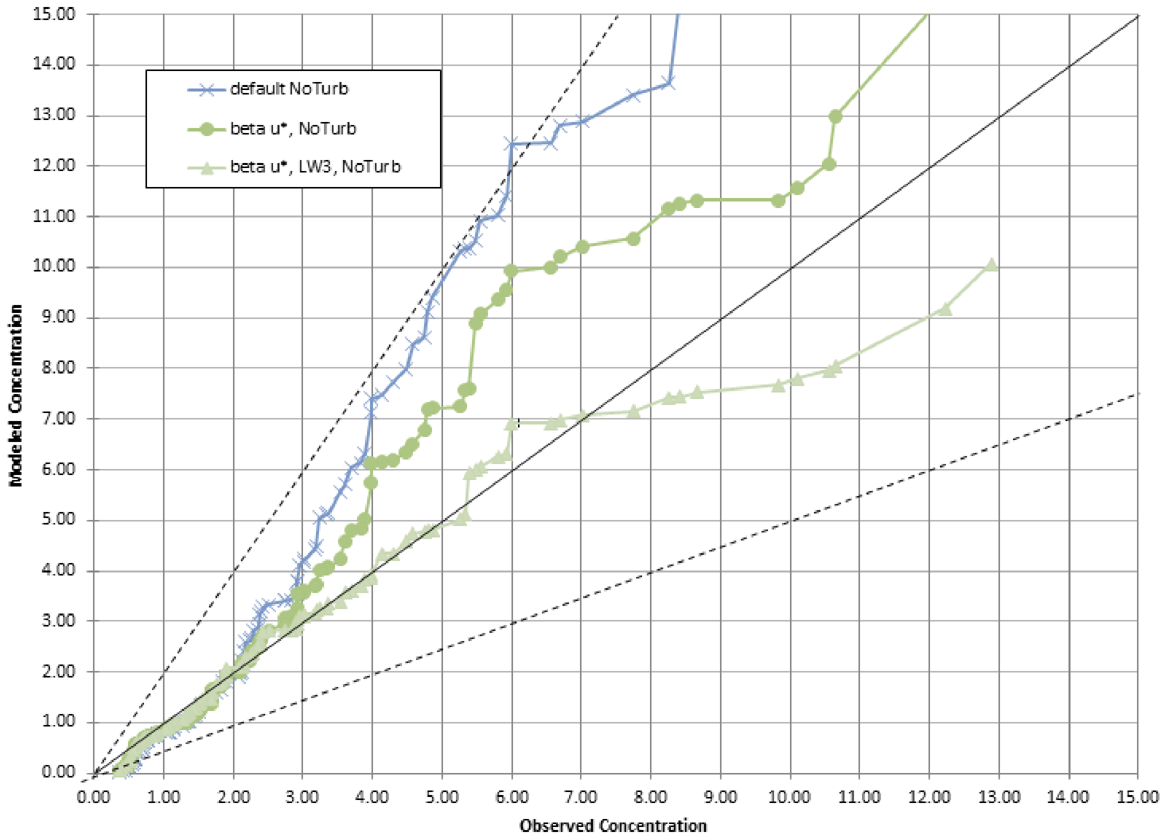
Due to the 60-minute averaging times for the Tracy turbulence data, we recommend for this database as used in AERMOD modeling that the turbulence data should not be used. We re-ran AERMOD with default and low wind options with the turbulence data removed from the model input; the results are shown in Figure 12.

The results without turbulence used show the following:

- The default AERMOD run shows an overprediction tendency of about a factor of 2.
- The use of the ADJ_U* option (but not LOWWIND3) shows an overprediction tendency of about 50%

•	The use of the ADJ_U* plus the LOWWIND3 options shows a nearly unbiased prediction over the entire range of concentrations. There are modest underpredictions for the peak concentrations and modest overpredictions for the mid-range of concentrations.

Figure 12 Tracy Evaluation Results with Meteorological Data Omitting Turbulence Data



CONCLUSIONS

The model evaluation for AERMOD's low-wind options was conducted in this study to target the 1-hour SO_2 design concentration (99th percentile daily maximum 1-hour concentration per year). This statistic is more pertinent for tall combustion sources than the RHC statistic established by EPA in the early 1990's due to the promulgation in 2010 of short-term probabilistic standards for SO_2 and NOx.

Model evaluation results are considered for the latest version of AERMOD (version 15181) on all of the tall-stack databases discussed in this report (except for Kincaid SO_2, which is set aside due to source inventory problems). The results for the four remaining databases show that the proposed low wind options (ADJ_U* and LOWWIND3) over-predict the 1-hour SO_2 design concentration, while the default model over-predicts to a greater degree. This is especially the case in complex terrain (Lovett) without site-specific turbulence data.

Of the four full-year databases considered, only one (Lovett) had turbulence data (15-minute averages), and AERMOD with only vertical turbulence data performed well (virtually unbiased) for the low wind options, while the use of both vertical and horizontal turbulence resulted in slight under-prediction if both the ADJ_U* and LOWWIND3 options were employed. If only the ADJ_U* option was employed, then the use of full turbulence data led to a slight over-prediction, and exclusion of turbulence led to higher over-predictions.

Based on these results, we conclude for the tall-stack databases reviewed in this study that the use of low wind options (ADJ_U* and LOWWIND3) will modestly predict the 1-hour SO_2 design concentration if observed horizontal turbulence data is not used. This finding indicates that the LOWWIND3 option plus inclusion of horizontal turbulence measurements may tend to over-correct for wind meander. Since the LOWWIND3 option does not affect the vertical plume spread, it is appropriate to use the observed vertical turbulence measurements in conjunction with the low wind options. Also, if only the ADJ_U* option is used, then the use of both horizontal and vertical turbulence (as shown in the case of Lovett) is acceptable.

This report augments information previously provided to EPA, which includes a peer-reviewed paper involving the North Dakota and Gibson evaluations using ADJ_U* and LOWWIND3 as well as a supplemental evaluation using LOWWIND3 after it became available.

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KEYWORDS

SO_2, AERMOD, modeling, low wind

Appendix D

30-year Listing of Monthly Precipitation Data

30-Year Precipitation Data (inches) for Converse Co AP (1986-1994, 2000-2016) & Converse 1 SE (1996-1999)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.17	0.80	0.45	2.68	1.05	3.54	1.57	0.35	1.35	1.24	1.14		14.35
1987	0.33	0.83	1.19	0.05	2.73	0.81	1.05	0.96	0.90	0.25	0.91	0.69	10.72
1988	0.15	0.47	1.41	0.27	1.26	0.23	1.15	0.46	0.93	0.00	0.60	0.38	7.31
1989	0.03	0.85	0.37	1.41	1.59	1.51	0.67	1.92	2.42	0.93	0.24	0.38	12.31
1990	0.67	0.61	1.81	1.75	2.76	0.13	2.83	0.65	0.47	0.47	1.17	0.24	13.57
1991	0.30	0.14	0.76	1.87	7.48	2.71	0.65	0.35	1.04	0.47	0.93	0.12	16.83
1992	0.15	0.31	1.04	0.38	1.87	3.16	1.39	0.95	0.21	0.07	0.74	0.93	11.21
1993	0.37	1.51	0.70	3.83	1.11	4.40	1.07	0.87	1.20	0.65	1.11	0.38	17.20
1994	0.46	0.37	0.24	0.50	1.24	0.20	1.78	1.63	0.46	0.54	0.97	0.53	8.93
1996	0.67	0.24	0.77	1.70	3.10	0.85	1.13	0.52	0.49	2.92	0.87	0.88	14.16
1997	0.72	1.06	0.48	2.06	6.94	1.52	2.98	1.74	0.48	1.18	0.15	0.72	20.03
1998	1.22	2.11	1.86	1.26	1.50	2.93	0.87	2.32	1.57	6.78	0.50	0.48	23.41
1999	0.93	0.25	0.63	5.13	2.15	2.81	0.45	0.20	2.93	0.43	0.58	0.23	16.74
2000	0.46	0.68	0.59	2.33	1.3	0.97	0.46	0.29	1.9	1.56	0.25	0.3	11.09
2001	0.3	0.31	0.43	1.58	0.81	0.66	1.99	0.31	1.06	1.15	0.37	0.05	9.02
2002	0.04	0.1	0.94	0.93	0.94	0.48	1.1	1.54	1.32	0.37	0.13	0.06	7.95
2003	0.1	0.2	1.7	2.61	1.78	3.86	0.01	2.52	1.65	0.29	0.27	0.43	15.42
2004	T	0.57	0.28	0.65	0.67	1.66	1.88	0.55	2.31	0.76	0.34	0.1	9.77
2005	0.31	0.14	0.49	1.14	2.55	0.87	0.92	0.96	0.65	1.34	0.51	0.1	9.98
2006	0.59	0.3	0.48	0.87	1.48	0.09	0.99	1.52	1.07	0.36	0.4	0.41	8.56
2007	0.24	0.12	1.21	1.03	3.41	0.63	0.59	0.86	0.68	1.35	0.07	0.45	10.64
2008	M	0.23	0.91	1.12	4.58	0.58	0.37	0.72	1.28	0.74	0.55	0.26	11.34
2009	0.65	0.46	0.76	2.9	1.03	1.98	1.06	0.59	1.18	1.12	0.02	0.23	11.98
2010	0.07	0.4	0.78	1.24	3.43	2.88	1.58	0.3	0.08	0.89	0.48	0.51	12.64
2011	0.46	0.48	0.4	1.42	4.23	1.79	0.52	1.38	0.07	1.64	0.22	0.45	13.06
2012	0.23	0.43	T	1.21	0.88	0.51	0.29	0.31	0.28	0.89	0.18	0.19	5.4
2013	0.09	0.4	0.48	1.95	1.7	0.57	0.6	0.43	1.04	2	0.22	0.6	10.08
2014	0.49	0.97	0.78	1.31	2.22	1.06	2.15	1.7	0.9	0.42	0.35	0.74	13.09
2015	0.34	0.52	0.52	3.25	3.82	2.08	0.82	0.51	0.35	1.68	0.05	0.41	14.35
2016	0.28	0.57	1	2.3	1.7	0	0.05	1	0.82	0.13	0.49		8.34

30-Year Precipitation Data (inches) for Torrington Experimental Farm (1987-1997) and Torrington Municipal Airport (1998-2016)													
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
1987	0.2	0.98	1.21	0.71	3.56	3.06	1.25	1.39	0.63	0.2	0.74	0.81	14.74
1988	0.2	0.12	0.51	1.67	3.27	1.33	3.24	0.26	0.75	0.14	0.24	0.18	11.91
1989	0	0.68	0.47	1.33	1.91	1.04	0.22	0.83	1.7	0.42	0.13	0.42	9.15
1990	0.15	0.72	2.31	1.39	2.58	1.11	2.19	2.06	2.12	0.63	1.07	0.06	16.39
1991	0.28	0.11	0.47	1.53	4.58	4.52	1.02	0.48	0.92	0.57	0.59	0.12	15.19
1992	0.25	0.42	0.96	0.15	1.36	1.33	3.8	1.56	0.22	0.7	0.25	0.81	11.81
1993	0.29	1.29	0.7	1.42	0.45	5.18	1.18	2.36	1.9	1.6	1.12	0.27	17.76
1994	0.18	0.28	0.25	0.96	0.5	1.37	2.73	0.5	0.78	1.29	0.39	0.97	10.2
1995	0.38	0.1	0.19	0.7	5.37	3.35	0.54	0.03	1.42	0.38	0.35	0.38	13.19
1996	0.5	0.02	0.27	1.3	4	1.15	0.38	0.69	1.19	0.58	0.28	0.13	10.49
1997	0.35	0.13	0.13	1.9	6.14	2.22	2.53	1.85	1.53	1.77	0.2	0.15	18.9
1998	0.13	0.23	0.95	1.12	2.49	2.33	0.96	2.24	0.42	3.21	1.02	0.28	15.38
1999	0.35	0.07	0.64	2.28	1.68	3.23		0.2	2	0.09	0.15	0.09	10.78
2000	0.5	0.57	0.93	2.23	1.43	0.43	1.2	1.07	1.77	1.24	0.1	0.2	11.67
2001	0.07	0.17	0.22	2.13	1.87	0.71	3.34	0.33	1.75	1.13	0.14	0.01	11.87
2002	0.09	0.06	0.43	0.45	0.48	0.76	0.56	1.91	1.67	0.46	0.15	0.04	7.06
2003	0.16	0.2	1.93	2.24	1.29	2.17	1	0.72	0.88	0.2	0.53	0.3	11.62
2004	0.05	0.28	0.12	0.89	1.22	0.89	2.68	0.38	4.04	0.79	0.3	0.02	11.66
2005	0.17	0.07	0.19	1.33	2.08	4.7	2.65	1.13	0.3	1.66	0.12	0.11	14.51
2006	0.14	0.17	1.25	0.54	1.53	1.5	0.92	1.1	0.67	0.34	0.01	0.22	8.39
2007	0.09	0.19	0.83	1.1	1.72	0.12	2.76	0.37	0.69	1.91	0.06	0.72	10.56
2008	0.08	0.26	0.24	1.04	2.66	1.35	1.35	3.43	1.53	0.42	0.29	0.02	12.67
2009	0.3	0.06	0.49	2.94	0.71	4.49	3.91	1.37	0.5	1.64	0.22	0.24	16.87
2010	0.01	0.64	0.83	2.47	2.77	4.74	0.57	0.88	0.24	1.04	0.43	0.47	15.09
2011	0.22	0.36	0.85	2.57	5.46	2.29	1.83	0.41	0.13	1.73	0.18	0.24	16.27
2012	0.22	0.35	0	0.79	0.61	2.19	1.17	0	0.57	0.88	0.09	0.07	6.94
2013	0.05	0.2	0.15	1.91	1.31	1.66	0.51	0.88	2.37	3.94	0.32	0.38	13.68
2014	0.2	0.56	0.67	1.14	5.24	2.13	1.35	2.7	2.59	0.11	0.74	0.12	17.55
2015	0.24	0.1	0.08	3.19	6.87	2.54	1.92	0.29	0.08	0.76	0.87	0.56	17.5
2016	0.14	0.63	1.64	2.90	2.63	0.06	0.69	1.14	0.89	0.20	0.21		11.13