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JUN 29 2016

MEMORANDUM

SUBJECT: Request for Approval of Alternative Model: Use of Surface Friction Velocity (ADJ_U*) Non-Regulatory Default Option in AERMET/AERMOD version 15181

FROM: Dr. Rebecca Matichuk, Environmental Scientist
Office of Partnerships and Regulatory Assistance, Air Program, Indoor Air, Transportation and Toxics Unit
Region 8

TO: George Bridgers, Director of Model Clearinghouse
Air Quality Modeling Group, Office of Air Quality Planning and Standards

THRU: Scott Jackson, Unit Chief
Office of Partnerships and Regulatory Assistance, Air Program, Indoor Air, Transportation and Toxics Unit
Region 8

This memorandum is in response to a request to use an alternative formulation of surface friction velocity (ADJ_U*) in the American Meteorological Society/Environmental Protection Agency (EPA) Meteorological Model (AERMET). In May 2016, EPA Region 8 received a request from the North Dakota Department of Health (NDDH) and operators from the Montana-Dakota Utilities Company (MDU) to utilize the adjusted u* (ADJ_U*) non-regulatory default option in AERMET (version 15181) to characterize Sulfur Dioxide (SO_2) emissions from the R.M. Heskett station located near Bismarck, North Dakota for the SO_2 Data Requirements Rule (SO_2 DRR – 40 CFR Part 51, Subpart BB). The request and supplemental information were provided in a modeling protocol submitted by MDU for the R.M. Heskett station, and attached to this memorandum (see Attachment 1).

EPA Region 8 is recommending approval of this request and is seeking concurrence from the Office of Air Quality Planning Standards - Air Quality Modeling Group Model Clearinghouse. Based on the information provided in the request, EPA Region 8 has concluded that the second condition of Section 3.2.2(b) of Appendix W has been satisfied by the submittal from MDU, and would like to approve the use of the ADJ_U* option in AERMET version 15181 as the meteorological preprocessor for AERMOD version 15181 for this modeling analysis.

The remainder of this memorandum includes a Technical Report that discusses the specific attributes of the facility proposing to use the ADJ_U* non-regulatory default option in AERMET, version 15181, and information that supports our request for approval.

Thank you for your careful attention to this matter and we look forward to your response. Please contact me at 303-312-6867 with any questions about this request or the attachment.

Attachment 1 – Montana-Dakota Utilities Co.: SO_2 Characterization for the R.M. Heskett Station Modeling Protocol

Technical Report

Dr. Rebecca Matichuk
EPA Region 8 Air Quality Modeling Contact
June 20, 2016

Request Background

In August 2015,[1] the U.S. Environmental Protection Agency (EPA) issued the SO_2 Data Requirements Rule (DRR), which directs state and tribal air agencies to identify maximum ambient air 1-hour SO_2 concentrations in areas with sources of SO_2 emissions with annual emissions greater than 2,000 tons for the most recent year for which emissions data are available as necessary to characterize SO_2 concentrations in the vicinity of these sources. The affected sources are those that were not previously captured as part of EPA's initial non-attainment area designations for the 1-hour SO_2 National Ambient Air Quality Standard (NAAQS) in August 2013 and those that were not identified in the March 2015 Consent Decree.[2] 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. Alternatively, instead of a source characterization, each identified source can modify its air operating permit prior to January 13, 2017.

The North Dakota Department of Health (NDDH) has been consulting with the owners and operators of stationary sources in the State of North Dakota subject to the SO_2 DRR. One of the SO_2 sources subject to this rule includes the Montana-Dakota Utilities Company (MDU) R.M. Heskett Station (R.M. Heskett), located northwest of Bismarck, North Dakota. Currently, MDU is pursuing the air quality modeling study option to characterize the SO_2 emissions. This option involves developing an air quality modeling protocol and coordinating the air quality modeling efforts with NDDH and EPA Region 8. The coordination efforts among the MDU operators, NDDH, and EPA Region 8 regarding the air quality modeling analysis as part of the SO_2 DRR began in March 2016.

In the latest version of the modeling protocol developed by MDU for the R.M. Heskett station, MDU requested the approval to use the adjusted u* (ADJ_U*) option in AERMET version 15181 without the use of turbulence data (which is not measured at the Bismarck airport ASOS measurement site). The version of the modeling protocol referenced here is dated May 2016, and included as Attachment 1. The modeling protocol also notes that the LOWWIND3 option in AERMOD version 15181 will not be requested for approval to utilize in the modeling protocol and air quality analysis at this time. However, MDU provided information in the modeling protocol pertaining to the LOWWIND3 option and requested the opportunity to apply for approval of the application of LOWWIND3 in the future. While this information was provided to EPA Region 8, EPA will not be reviewing the information associated with the LOWWIND3

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

[2] Entered in Sierra Club, et al. v. McCarthy, Case # 13-cv-03953-DI (N.D. Cal. March 2, 2015).

option at this time and the request for approval at this time is strictly to support the utilization of ADJ_U* in AERMET version 15181 for the R.M. Heskett Station.

Source Information

The R.M. Heskett Station is located about 10 kilometers northwest of Bismarck, North Dakota in Morton County. This Station has two existing coal-fired boilers (Unit 1 & Unit 2), each of which exhaust through their own, separate 298.8-foot stacks. The total annual emissions in 2014 for the R.M. Heskett Station is 3369 tons. Table 1 shows the physical stack parameters for the R.M. Heskett Station units.

Table 1. R.M. Heskett – Source Characteristics

Unit	Description	Stack Elevation (m msl)	Stack Height (m)	Flue Diameter (m)	Rates (Btu/hr)
Unit 1	Spreader Stoker	505.2	91.08	2.21	387×10^6
Unit 2	Atm. Fluid Bed	505.2	91.08	3.66	916×10^6

The location of the plant is shown in Figure 1, and a topographic map of the area surrounding the R.M. Heskett Station is provided in Figure 2. As shown in Figure 2, there is complex terrain (with elevations above stack top) within four kilometers of the plant. As shown in Figure 1 and Figure 2, the area in the immediate vicinity (i.e., within 3 km) of the R.M. Heskett Station can be characterized as having a rural land use type.

Figure 1: Location of the R.M. Heskett Station.

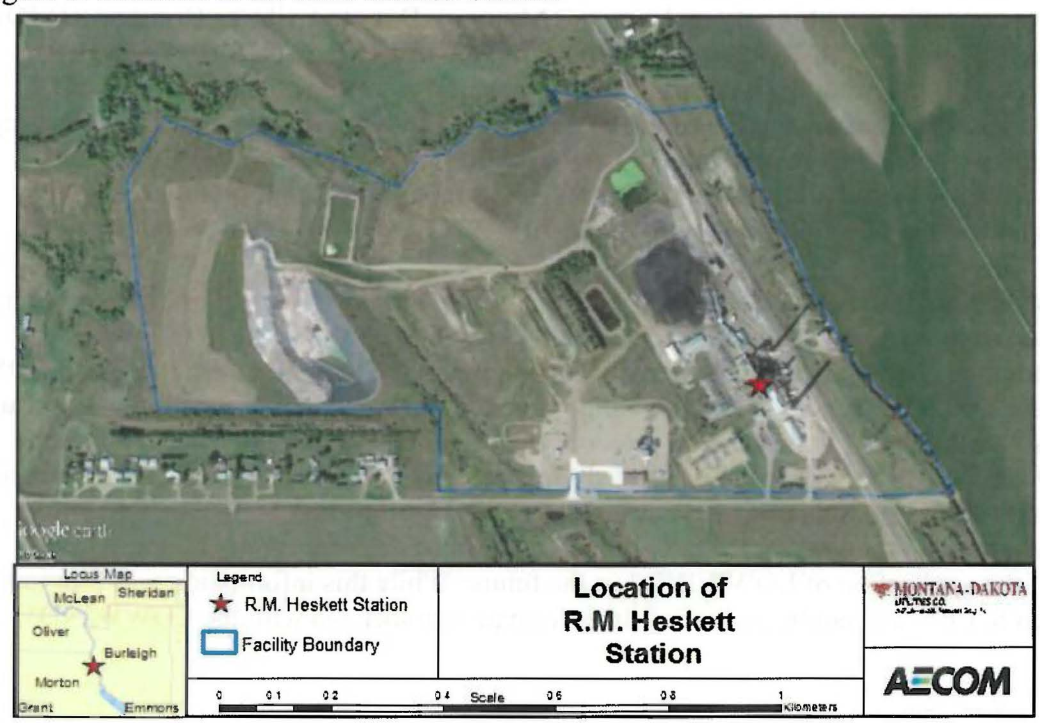
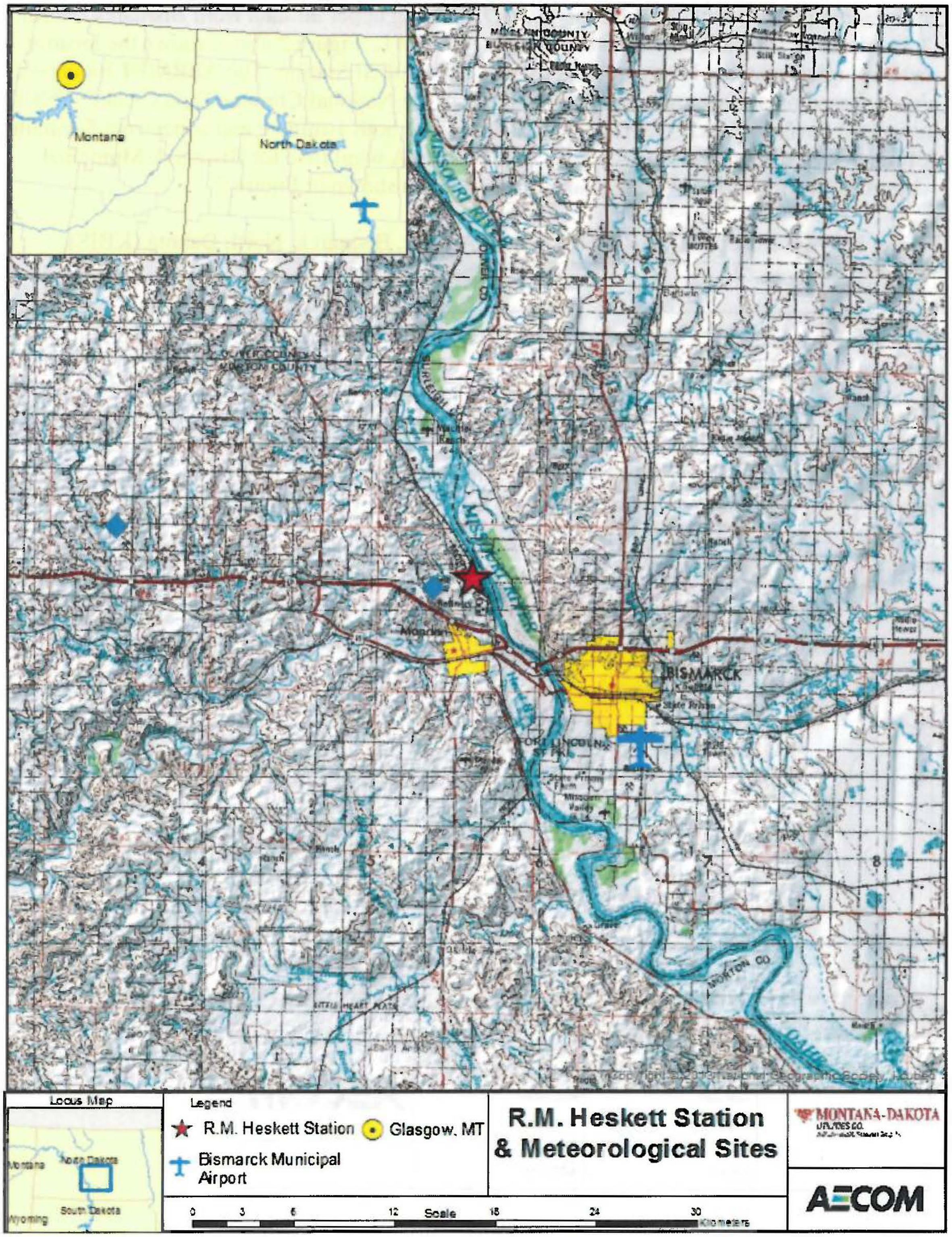
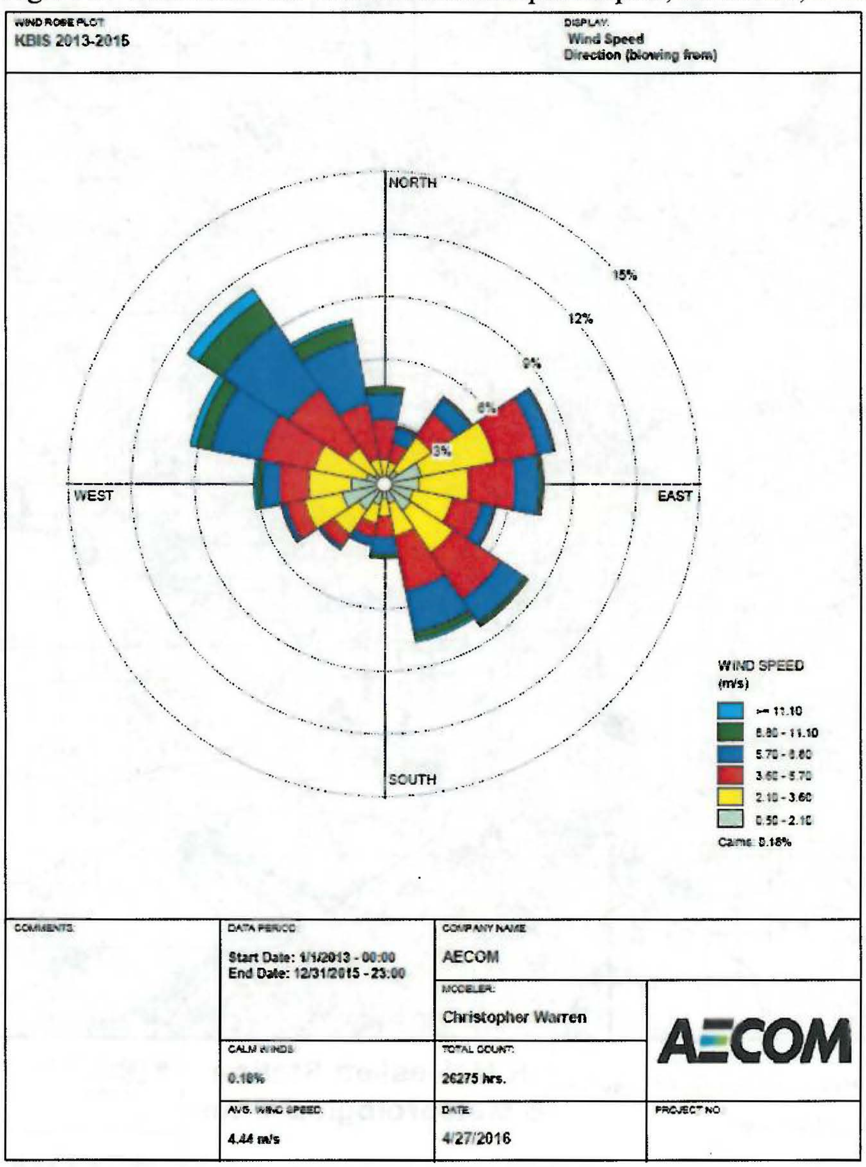


Figure 2: Topography in the Vicinity of R.M. Heskett Station and Location of Meteorological Stations Relative to R.M. Heskett Station.



The hourly meteorological data for the R.M. Heskett Station will be represented by surface observations from the Bismarck Municipal Airport in Bismarck, North Dakota along with concurrent upper air data from Bismarck, ND. Missing upper air data from Bismarck, North Dakota will be substituted with data from Glasgow, MT. Figure 2 above shows the location of meteorological stations in relationship to the R.M. Heskett Station. The AERMET inputs will also be 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. A wind rose for Bismarck Municipal Airport for the most recent three years (2013-2015) is shown in Figure 3.

Figure 3: Wind Rose for Bismarck Municipal Airport, Bismarck, North Dakota (KBIS).



Background on Default Surface Friction Velocity and ADJ_U* Option in AERMOD/AERMET Version 15181

Region 8 is evaluating the ADJ_U* non-regulatory default option in AERMET/AERMOD version 15181 request from the R.M. Heskett Station based primarily on the work performed by OAQPS and documented in Appendix F of the Addendum to the User's Guide for the AMS/EPA Regulatory Model – AERMOD, September 2004, Updated June 2015.[3] Additional information on the impact of the ADJ_U* option was also gathered from an EPA Region 10 approval for use with a gold mining source located in Alaska.[4] OAQPS concurred with the request to approve the use of ADJ_U* in a Clearinghouse Memorandum approved on February 10, 2016.[5] EPA Region 1 also requested an approval to use ADJ_U* for an energy generating facility located in Portsmouth, New Hampshire.[6] Similar to the EPA Region 10 request, OAQPS concurred with the request to approve the use of ADJ_U* in a Clearinghouse Memorandum approved on April 29, 2016.[7]

The ADJ_U* option was first integrated as a beta option in Stage 3 of the AERMET meteorological processor version 12345. The option was developed based on peer-reviewed journal articles by Qian and Venkatram[8] and Luhar and Rayner.[9] That initial AERMET model change, along with additional modifications impacting the ADJ_U* option, are described below:

1. Version 12345: Initial incorporation of a new non-regulatory default surface friction velocity adjustment option (ADJ_U*) for low-wind/stable conditions based on Qian, W., and A. Venkatram, 2011: "Performance of Steady-State Dispersion Models Under Low Wind-Speed Conditions", Boundary Layer Meteorology, 138, 475-491.[10]
2. Version 13350: Subroutine UCALST was modified based on AECOM's recommended corrections to the vertical temperature gradient parameter (theta-star). Also, modified subroutine BULKRI to incorporate a modified Bulk Richardson Number approach under the ADJ_U* non-regulatory default option.[11]
3. Version 14134: Subroutine BULKRI was modified to include the THSTAR (theta-star) adjustment for low solar elevation angles and for the ADU_U* non-regulatory default option associated with BULKRN.[12]

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[3] EPA. 2015 "Addendum: User's Guide for the AERMOD Meteorological Preprocessor (AERMET) OAQPS, AQAD, June 2015.

[4] EPA Region 10 Memorandum from Herman Wong (R10) to Alan Schuler (ADEC), October 20, 2015.

[5] EPA Clearinghouse Memo from George Bridgers (OAQPS) to Janis Hastings, Acting Director, Office of Air, Waste, and Toxics, Region 10; February 10, 2016.

[6] EPA Region 1 Memorandum from Leiran Biton to George Bridgers, April 7, 2016.

[7] EPA Clearinghouse Memo from George Bridgers to David Conroy, April 29, 2016.

[8] Qian W. and Venkatram A. 2011 "Performance of Steady-state Dispersion Models under Low Wind-Speed Conditions" Boundary-Layer Meteorology 138:475-491.

[9] Luhar AK and Rayner KN 2009. "Methods to Estimate Surface Fluxes of Momentum and heat from Routine Weather Observations for Dispersion Applications under Stable Stratification." Boundary-Layer Meteorology. 132:437-454.

[10] AERMET Model Change Bulletin (Version 12345) dated December 10, 2012. Office of Air Quality Planning and Standards, RTP, NC.

[11] AERMET Model Change Bulletin (Version 13350) dated December 16, 2013. Office of Air Quality Planning and Standards, RTP, NC.

[12] AERMET Model Change Bulletin (Version 14134). Office of Air Quality Planning and Standards, RTP, NC.

4. Version 15181: Subroutines UCALST and MPPBL were modified to incorporate a constant value of theta-star of 0.08, full inclusion of the displacement height, and a modified formulation for Monin-Obukhov length for the AJD_U* option. Subroutine UCALST was also modified to adjust USTAR for winds speeds below the "critical" wind speed. BULKRI was modified to use BETAM = 0.5 instead of 0.47 for ADJ_U*. Lastly, BULKRI incorporated additional refinements to ADJ_U* in conjunction with the Bulk Richardson Number option, including a more refined method for calculating theta star and extending its applicability to very stable/low wind conditions.

With the release of AERMOD and AERMET Version 15181, updated evaluations of the low-wind ADJ_U* non-regulatory default option, along with LOWWIND1, LOWWIND2, and LOWWIND3, were included as Appendix F to the AERMOD User's Guide Addendum. The evaluation results provided the basis for EPA proposing to include the non-regulatory default options ADJ_U* and LOWWIND3 as part of the regulatory default mode for AERMOD in the July 29, 2015 Federal Register notice proposing changes to the Guideline on Air Quality Models (Guideline).[13] It is important to note, however, these changes to the Guideline are only proposed. The final version of the Guideline could contain revisions based on comments received.

The evaluations in Appendix F of the AERMOD User's Guide Addendum (EPA 2015a) include two field studies conducted in 1974 by the Air Resources Laboratory of the National Oceanic and Atmospheric Administration to investigate diffusion under low wind speed conditions at Idaho Falls and Oak Ridge. It also includes an analysis using the Lovett database. A detailed description of the databases and the evaluations are included in Appendix F. The results of the analyses showed over-predictions of observed concentrations when using the regulatory default options in AERMET and AERMOD for both the Oak Ridge and Idaho Falls. Both evaluations showed improved model performance with the ADJ_U* option in AERMET.

Both the Oak Ridge and Idaho Falls field studies measured concentrations from low-level, non-buoyant type releases. The Lovett field study measured concentrations from a tall stack (145 m) in a rural area in complex terrain. Past evaluations of the Lovett data with AERMOD have shown good model performance. Inclusion of ADJ_U* showed slight improvement in model performance without other LOWWIND options and little difference when LOWWIND options were used. When the meteorological data was degraded, ADJ_U* noticeably reduced the model over-prediction.

Another evaluation of the low wind non-regulatory default options was conducted by OAQPS and presented in a webinar presented August 12, 2014.[14] That evaluation examined field study data collected at the Cordero Rojo Mine in Eastern Wyoming. The emission source was primarily roadway re-entrained particulate matter due to vehicular traffic. The results of that evaluation indicate statistically significant model performance improvement when using the ADJ_U* option.

Information provided in the EPA Region 10 approval of the use of ADJ_U* for a mining source in Alaska shows the impact of the ADJ_U* option versus the default u* for four meteorological

[13] Federal Register, Vol. 80, No. 145, Page 45340. July 29, 2015.
[14] http://www3.epa.gov/ttn/scram/webinar/AERMOD_14134-NO2_Memo/20140812-Webinar_Slides.pdf

parameters; calculated surface friction velocity, calculated heat flux, calculated mechanical mixing height, and calculated Monin-Obukhov (M-O) length (EPA Region 10). This was done for a variety of facility emission sources, including stacks at power plants. When looking at all source groups, the ADJ_U* option increased the values of all four parameters throughout the day. The one exception is the calculated Monin-Obukhov length for power plant sources. Just less than half the hours throughout the day had a larger M-O length with the default u*.[15] Increases in the model estimated values of u*, M-O length, mechanical mixing height, and heat flux are to be expected given the changes in the ADJ_U* option compared to the default u*.

Lastly, a recent request for the use of the ADJ_U* option was approved and concurred upon for an energy generating facility located in Portsmouth, New Hampshire. In this situation, the source was located near complex terrain with high modeled concentrations expected to occur under low wind, stable conditions. The application of the ADJ_U* option was deemed to be appropriate based upon many of the studies noted above. In addition, the approval notes a site-specific evaluation of the impact of the ADJ_U* option for the source in question at modeled receptors located in complex terrain. The assessment determined that the ADJ_U* option only had a significant effect on receptors located at or above the release height.

Process for Approving an Alternative Model

According to Section 3.2.2(a) of Appendix W, the EPA Regional Office is responsible for determining the acceptability of a model. Specifically,

> Where the Regional Administrator finds that an alternative model is more appropriate than a preferred model, that model may be used subject to the recommendations of this subsection. This finding will normally result from a determination that (1) a preferred air quality model is not appropriate for the particular application; or (2) a more appropriate model or analytical procedure is available and applicable.

Section 3.2.2(b) of Appendix W goes on to describe the approval process for an alternative model:

> There are three separate conditions under which such a model may normally be approved for use: (1) If a demonstration can be made that the model produces concentration estimates equivalent to the estimates obtained using the preferred model; (2) if a statistical performance evaluation has been conducted using measured air quality data and the results of that evaluation indicate the alternative model performs better for the given application than [the preferred model]; or (3) if the preferred model is less appropriate for the specific application, or there is no preferred model.

In December 2015, EPA issued a memorandum that clarified the approval process for non-regulatory beta options in AERMOD that have been proposed as regulatory options in the proposed revision to Appendix W.[16] This memorandum confirmed that the use of all non-regulatory default options, including the ADJ_U* option, in regulatory modeling must receive EPA Regional Office approval.

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[15] EPA Region 10 Memorandum from Herman Wong (R10) to Alan Schuler (ADEC), October 20, 2015.

[16] Clarification on the Approval Process for Regulatory Application of the AERMOD Modeling System Beta Options, Office of Air Quality Planning and Standards, December 10, 2015.

The R.M. Heskett Station request intends to use the second condition as its justification, subject to the procedures for determining the acceptability of the alternative model using "established procedures and techniques" as described in Section 3.2.2(d) of Appendix W. This subsection also states that preparation and implementation of the evaluation protocol should be acceptable to the state regulatory agency and EPA, as well as the regulated entity. EPA Region 8 held a conference call on April 14, 2016 with representatives from the EPA, NDDH, and representatives of the R.M. Heskett Station to discuss the process for demonstrating appropriateness of an alternative model. This discussion satisfied the requirements for state, EPA, and industry participation in the development of an evaluation protocol described in Section 3.2.2(d) of Appendix W.

R.M. Heskett Station Approval Package: Statistical Performance Evaluation and Site-Specific Evidence

Available Datasets for Evaluation

The R.M. Heskett Station submittal cites a field study conducted in Mercer County, North Dakota. The Mercer County North Dakota evaluation is highly relevant to the R.M. Heskett Station scenario. The Mercer County database consists of approximately four years of SO_2 monitoring data (2007-2010), hourly emissions data from 15 point sources in a region with complex terrain, and includes five monitors at elevations near or above some stack release heights at distances of nearly 10 kilometers. Although this study includes sources as far away as 50 kilometers, the study focused on two emission sources (Antelope Valley Station and the Great Plains Synfuels Plant, operated by the Dakota Gasification Company) that were in close proximity to the monitors, meaning that emissions from those facilities dominated the impacts. Table 2 provides details about the monitors. For one of these monitoring locations (DGC#17), modeled concentrations were significantly closer to monitored values, though still somewhat over-predicting with the use of the ADJ_U* option as compared to the regulatory default options, while predictions at other monitoring locations did change with use of the ADJ_U* option for this study.

Table 2: Monitor Locations for the Mercer County North Dakota Study.

Description	UTM X (m)	UTM Y (m)	Monitor Elevation (m)
DGC#12	291011	5244991	593.2
DGC#14	290063	5250217	604.0
DGC#16	283924	5252004	629.1
DGC#17[a]	279025	5253844	709.8
Beulah	290823	5242062	627.1

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

The Lovett evaluation database, which is not mentioned in the R.M. Heskett Station submittal, but is presented in the most recent AERMOD model evaluation document,[17] provides another comparable scenario to that of the R.M. Heskett Station. The Lovett database consists of 2,595 hours of ambient SO_2 monitoring data from 12 monitors near the Lovett Power Plant, located in a rural area with mountainous terrain along the Hudson River in New York. Some of the monitors had elevations above the release height of Lovett's 145 meter stack, and at distances from the source of 2 to 3 kilometers. For the Lovett evaluation database, correlation is better with the ADJ_U* option than the regulatory default option at relevant concentrations.[18] In fact, the relevant modeled concentrations at Lovett are actually higher using the ADJ_U* option compared with those using the regulatory default. This suggests greater modeled impacts using the ADJ_U* option at near-source locations (i.e., within several kilometers) than at more remote locations. This suggests that it is likely that impacts at nearer source impacts could be higher using the ADJ_U* option.

At the R.M. Heskett Station, the relevant distances for impacts in complex terrain are about 15 kilometers or greater away from the source. Though there is no evaluation database analysis for impacts in complex terrain at this distance that match the precise characteristics of the R.M. Heskett Station scenario, the Mercer County North Dakota study will provide a sufficient basis for making an assessment regarding the adequacy of the statistical performance evaluation. This approval submittal will focus on the Mercer County North Dakota study given the significant similarities among the conditions in the Mercer County North Dakota study and R.M. Heskett Station. The details of the Mercer County evaluation and its applicability to the R.M. Heskett Station are discussed below.

Better model performance in the near-field may translate into better model performance at longer distances. However, no conclusive model performance evaluation was available at the time of this review to confirm this notion, and this represents a data gap in evidence provided for this alternative model justification.

Applicability of Mercer County North Dakota Study: Similarities in Terrain Features

Many similarities exist between the surrounding terrain of Montana-Dakota Utilities R.M. Heskett Station and the Mercer County North Dakota evaluation study. R.M. Heskett Station is less than 90 kilometers south-southeast from the facilities in Mercer County, resulting in very similar climate and terrain. Both facilities are in a river valley with elevated terrain located a few kilometers from the emission sources.

R.M. Heskett Station is situated along the west bank of the Missouri River where the topography is dominated by the Missouri Plateau (Figure 2). The Missouri Plateau consists of rolling to hilly

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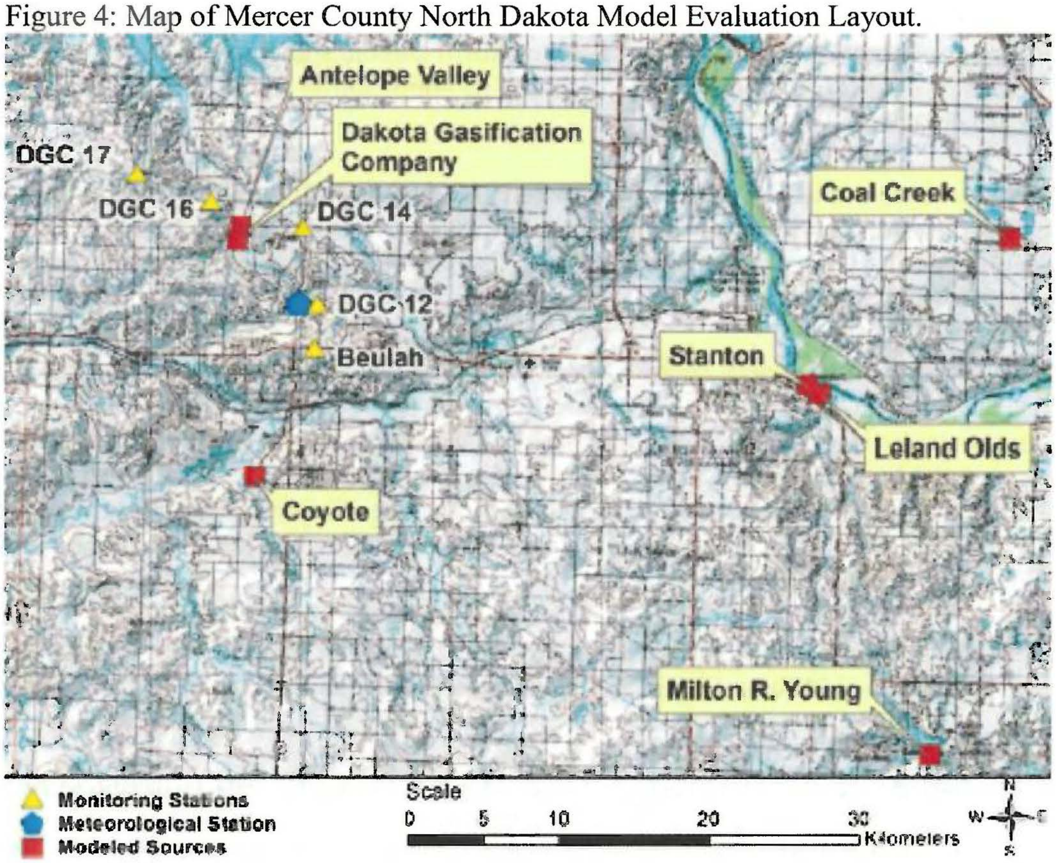
[17] Addendum: User's Guide for the AMS/EPA Regulatory Model–AERMOD. September 2004, up dated June 2015. EPA-454/B-03-001. Appendix F. Evaluation of Low Wind Beta Options.

[18] Because the form of the NAAQS is based on the three-year average of 99th percentile of daily maximum SO_2 concentrations, the 5-year average 4th highest modeled SO_2 concentration is the relevant comparison against the NAAQS. This process is described in detail in an EPA memorandum on the subject (Memorandum: Applicability of Appendix W Modeling Guidance for the 1-hour SO2 National Ambient Air Quality Standard. From Tyler Fox, EPA Air Quality Modeling Group to EPA Regional Air Division Directors. August 23, 2010).

plains, although there are occasional exceptions that include prominent buttes. An expansive area of rolling hills, at times rising to near 600 meter in elevation (nearly 100 meters above stack base for R.M. Heskett), is one of the more significant terrain features stretching north-south just west of the R.M. Heskett Station. One of the notable terrain features is a prominent bluff approximately 15 kilometers west-northwest of R.M. Heskett Station. The bluff, known as Crown Butte, peaks at approximately 707 meters above sea level. Crown Butte is marked with a blue diamond symbol in Figure 2. The other terrain feature (unnamed) that rises above stack height is closer to the R.M. Heskett Station, approximately 2.5 kilometers to the southwest and is also denoted with a blue diamond symbol in Figure 2. East of the R.M. Heskett Station, the terrain is relatively flat with rolling hills well below stack top height.

The facilities involved in the Mercer County North Dakota study are all located within the Missouri Plateau region of North Dakota. Figure 4 shows a layout of the sources, monitors, and the meteorological station. Complex terrain is noted to the west and northwest of the facilities with relatively flat terrain in all other directions, shown in Figure 4. One of the highest peaks, is located 7.6 kilometers to the northwest of the facilities with an elevation of 709 meters above sea level. Located on this peak terrain feature is the site of one of several ambient SO_2 monitors sited in Mercer County.

Figure 4: Map of Mercer County North Dakota Model Evaluation Layout.



Applicability of Mercer County, North Dakota Study: Similarities in Sources Characteristics

The tall stacks and base elevations of the sources are also similar for both the R.M. Heskett Station and the Mercer County North Dakota study. As discussed above, the R.M. Heskett Station has two boiler units (Table 1). Exhaust from both boiler stacks are vented through separate stacks with height and internal exit diameters as reported in Table 1. Both stacks are considered to be tall stacks within a region that includes 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 North Dakota study. Table 3 provides details about the emission sources from the Mercer County North Dakota study. In particular, the stack height of the R.M. Heskett Station sources is about 91 meters, and the stack heights of the Mercer County sources range from about 30 meters to 200 meters. The stack elevation of the R.M. Heskett Station sources are at about 505 meters above mean sea level, and the Mercer County sources are between about 518 and 602 meters above mean sea level.

Table 3: Source Information for the Mercer County North Dakota Study.

Description	Stack Elevation (m)	Stack Height (m)	Stack Diameter (m)
Antelope Valley	588.3	182.9	7.0
Antelope Valley	588.3	182.9	7.0
Leland Olds	518.3	106.7	5.3
Leland Olds	518.3	152.4	6.7
Milton R Young	597.4	171.9	6.2
Milton R Young	600.5	167.6	9.1
Coyote	556.9	151.8	6.4
Stanton	518.2	77.7	4.6
Coal Creek	602.0	201.2	6.7
Coal Creek	602.0	201.2	6.7
Dakota Gasification Company	588.3	119.8	7.0
Dakota Gasification Company	588.3	68.6	0.5
Dakota Gasification Company	588.3	76.2	1.0
Dakota Gasification Company	588.3	30.5	0.5

Results of Sensitivity Tests and Comparisons to Mercer County, North Dakota Study

Model Scenarios and Configuration

The R.M. Heskett Station submittal included two model scenarios to investigate the change in predicted concentrations, including a scenario with the AERMOD regulatory default options (default scenario) and a scenario with the AERMOD ADJ_U* non-regulatory default option (ADJ_U* scenario). For this comparative modeling, AERMOD/AERMET version 15181 was utilized with the following configurations:

- Modeling using 3-years (2013-2015) for emissions and meteorological data;
- Bismarck Municipal Airport in Bismarck, ND used for surface and upper-air meteorological data (missing upper-air data substituted with Glasgow, MT);
- Wind rose from Bismarck from 2013-2015 is shown in Figure 3.

- The ADJ_U* scenario will not utilize turbulence data (which is not present for the Bismarck airport meteorological data), as noted in the February 2016[19] and April 2016[20] EPA Model Clearinghouse memorandums.
- A Cartesian receptor grid:
  - 25-m receptor spacing along the R.M. Heskett Station and Tesoro Mandan Refinery boundaries for the SO2 characterization.
  - 100-m receptor spacing extending out 5 kilometers from the grid center (located near the Heskett stacks).
  - 250-m receptor spacing between 5.0 and 10 kilometers from the grid center.
  - 500-m receptor spacing will be used beyond 10 kilometers (out to 20 km).

The emission rates for the R.M. Heskett Station were normalized by a constant factor, consistent with EPA's Monitor Technical Assistance Document guidance.[21] Ambient background SO_2 concentrations were not included in the modeling comparison for either the R.M. Heskett Station or the Mercer County, North Dakota database. Additional details of the model input assumptions and configuration options are included in the R.M. Heskett Station draft modeling protocol for the 1-hour SO_2 DRR modeling activities (see Attachment 1).

Model Results: Maximum 99th Percentile Normalized Concentrations for R.M. Heskett Station

The 4th highest (99th percentile) daily 1-hour peak SO_2 concentrations for both the R.M. Heskett Station and the Mercer County North Dakota study are summarized in Table 4. The location of the 4th highest daily 1-hour peak SO_2 normalized concentration from R.M. Heskett Station is at the aforementioned Crown Butte for both model scenarios (i.e., default and ADJ_U*). Figure 5 shows an isopleth map of the 4th highest daily 1-hour SO_2 concentration using default options. There is a large concentration gradient that occurs at the location of the more distant Crown Butte, with a secondary area of high concentrations to the southwest of the R.M. Heskett Station along the nearby complex terrain. As illustrated in Figure 6, the results from the ADJ_U* scenario continues to show the 4th highest daily 1-hour SO_2 concentration at Crown Butte, but there is a more gradual concentration gradient near this bluff. Furthermore, the magnitudes of the normalized concentrations at Crown Butte are comparable to those depicted near and to the northwest of the R.M. Heskett Station.

Table 4: Model-Predicted 4th highest (99th percentile) daily 1-hour peak SO_2 concentrations [$\mu g/m^3$] for both the R.M. Heskett Station and the Mercer County North Dakota study.

Model Scenarios	R.M. Heskett Station	Mercer County, North Dakota Study					
		Design Value	DGC #12	DGC #14	DGC #16	DGC #17	Beulah
Default Options	100.2	174.49	100.77	107.51	110.30	174.49	110.31
ADJ_U*	44.09	`122.30	100.77	107.51	110.30	122.30	110.31
Observed	NA	85.00	81.52	85.00	69.58	73.76	83.37

NA = Not Applicable

[19] Region 10 MCH Memorandum [February 2016]: https://cfpub.epa.gov/oarweb/MCHISRS/index.cfm?fuseaction=main.resultdetails&recnum=16-X-01
[20] Region 1 MCH Memorandum [April 2016]: https://cfpub.epa.gov/oarweb/MCHISRS/index.cfm?fuseaction=main.resultdetails&recnum=16-I-01
[21] Available at https://www3.epa.gov/airquality/sulfurdioxide/pdfs/SO2MonitoringTAD.pdf

Figure 5: Isopleth Map of the 99th Percentile Normalized SO_2 Concentrations Using Default Options for R.M. Heskett Station.

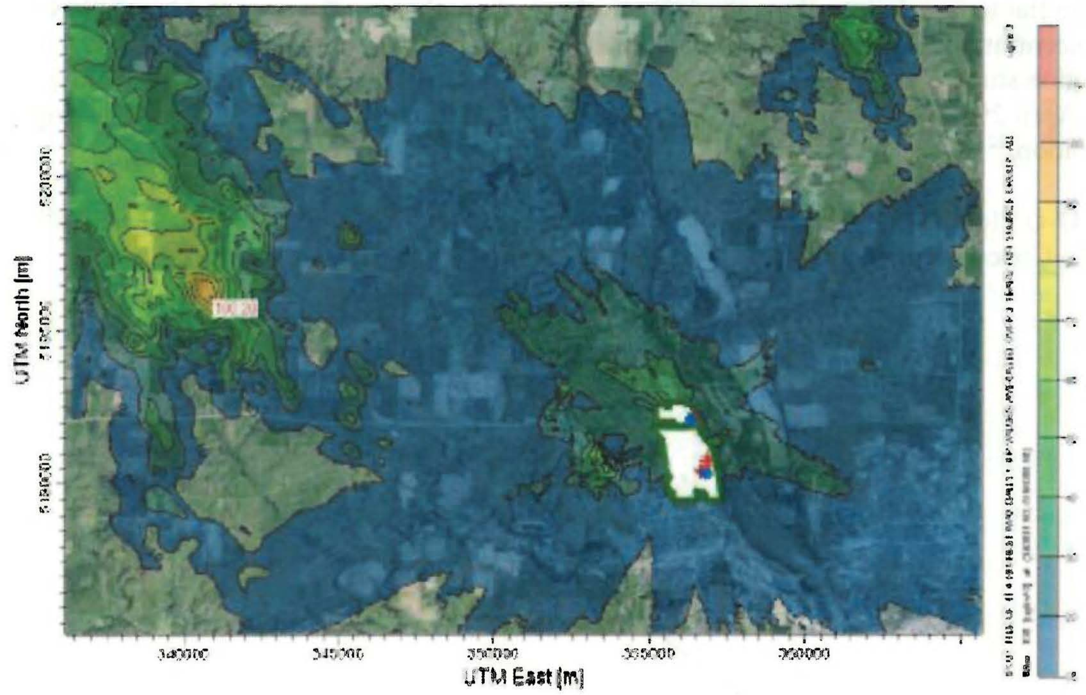


Figure 6: Isopleth Map of the 99th Percentile Normalized SO_2 Concentrations Using ADJ_U* Option for R.M. Heskett Station

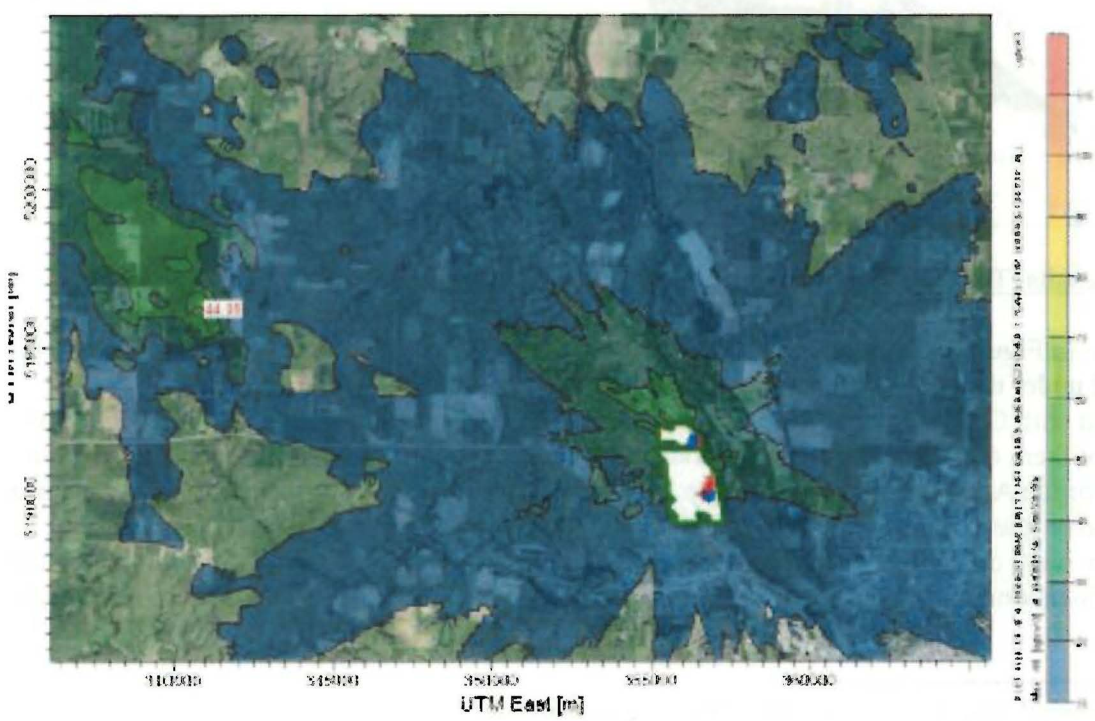
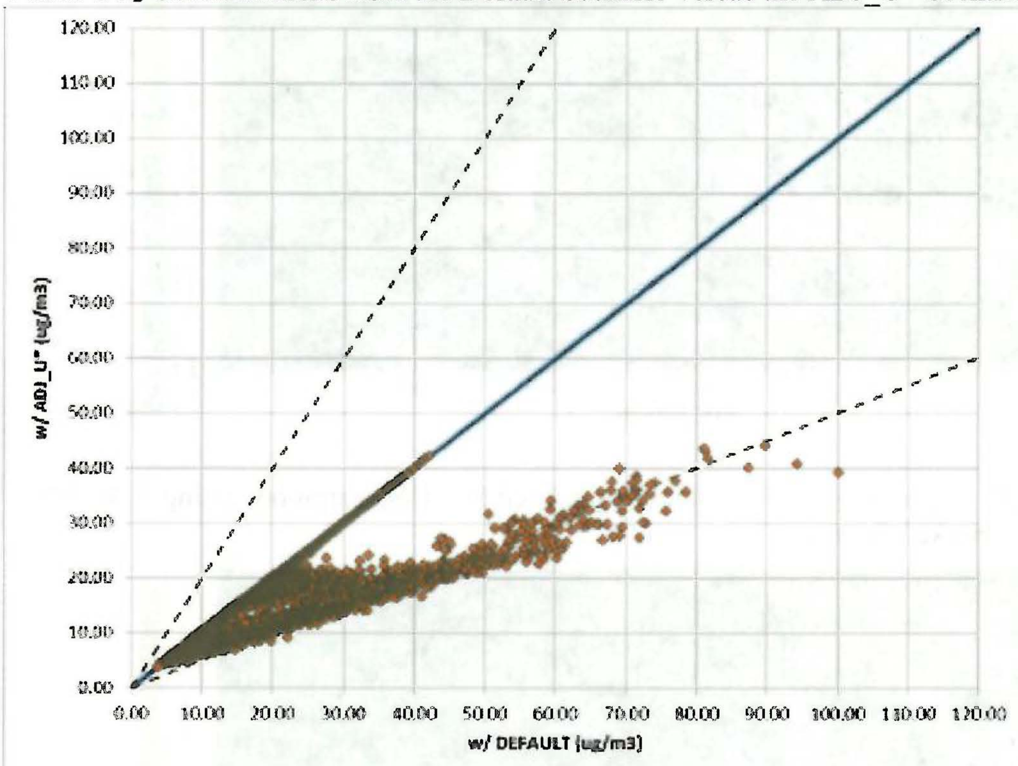


Figure 7 presents Q-Q plots paired by receptor are provided for the predicted 3-year averaged 4th highest maximum daily 1-hour SO_2 concentrations. Concentrations that correspond with receptors in flat terrain follow along the 1:1 ratio line, where those in the complex terrain have higher concentrations from the default scenario. This pattern is very similar to that observed in the evaluation study presented in EPA's Model Clearinghouse Memorandums [Dated April 7, 2016 and April 29, 2016] regarding the approval of ADJ_U* for the Schiller Station Modeling Demonstration.[22]

Figure 7: Q-Q Plot paired by Receptor of Predicted 3-year Averaged 99th Percentile Peak Daily 1-hour SO_2 Concentrations from the Default Scenario versus the ADJ_U* Scenario.



<u>Model Results: Top Ten 99th Percentile Normalized Concentrations for R.M. Heskett Station</u>

As shown in Figure 8, the top ten 3-year average 4th highest maximum daily 1-hour impacts predicted under the default scenario were predicted to all coincide with elevated terrain associated with Crown Butte. Table 5 presents the hours corresponding to these top ten impacts, with all of them occurring during low wind speed, stable conditions. This process is repeated in Table 6 for the ADJ_U* scenario. The top ten impacts from the ADJ_U* Scenario indicate a mix between daytime and nighttime hours. The top three 4th highest impacts were still occurring under low wind conditions with receptor locations near Crown Butte. The majority of the top ten receptor locations for the ADJ_U* scenario reside near R.M. Heskett Station, as shown in Figure 9.

[22] MCH Approval Memos for Schiller Station Modeling Demonstration:
https://cfpub.epa.gov/oarweb/MCHISRS/index.cfm?fuseaction=main.resultdetails&recnum=16-I-01

Figure 8: Locations of Receptors for the Top Ten 99th Percentile 3-year Averaged Daily Peak 1-hour SO_2 Concentrations Using Default Options.

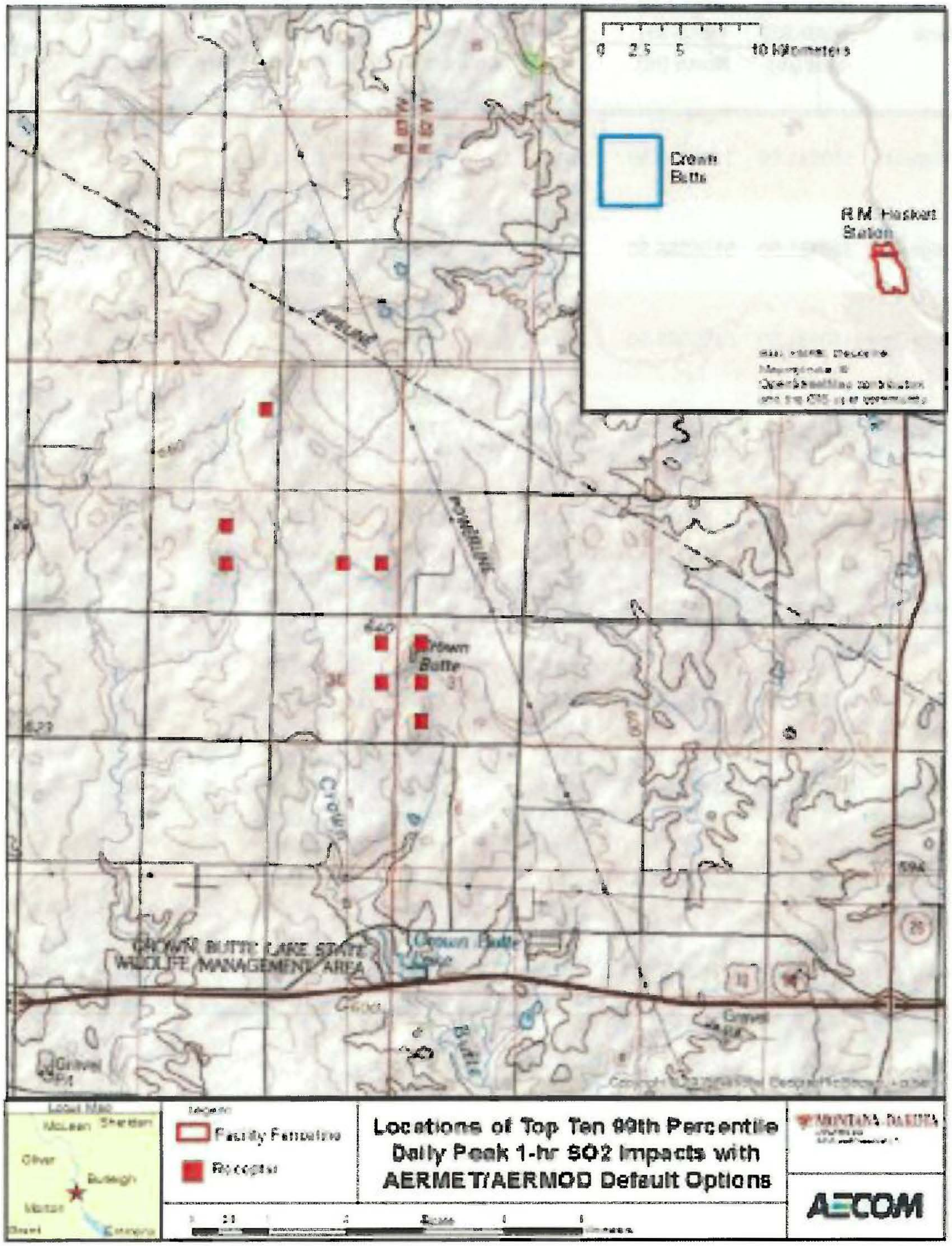


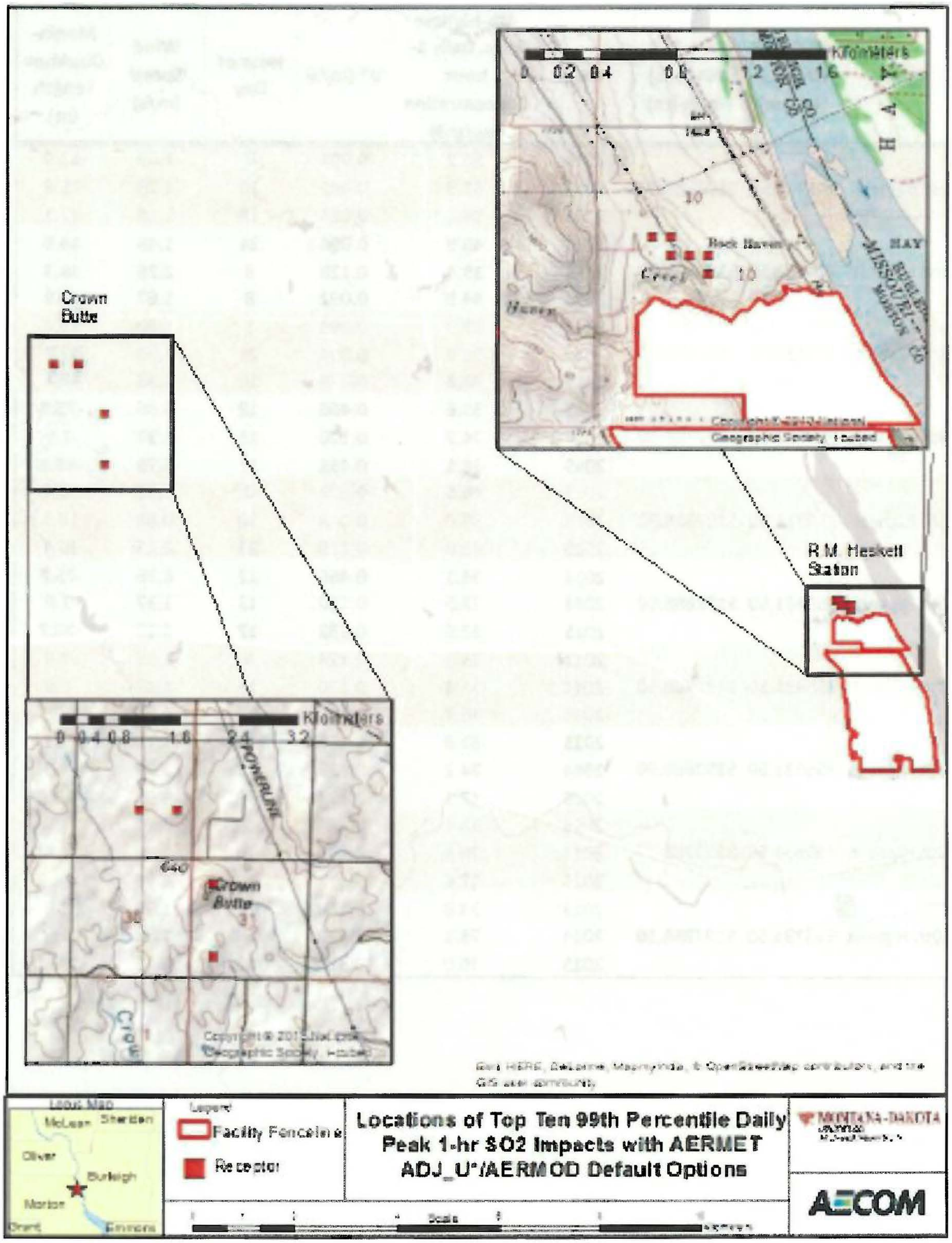
Table 5: 4th Highest Daily Peak 1-hour SO_2 Concentrations ($\mu g/m^3$) of the Top Ten 3-Year Averages for the Default Scenario.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Year	4th-highest Max. Daily 1-hour Concentration (ug/m3)	U* (m/s)	Hour of Day	Wind Speed (m/s)	Monin-Obukhov Length (m)
1st Highest	340931.50	5196088.50	2013	120.4	0.038	8	1.23	2.8
			2014	100.7	0.061	22	2.21	4.3
			2015	79.5	0.026	3	0.96	1.9
2nd Highest	340431.50	5196588.50	2013	118.9	0.038	8	1.23	2.8
			2014	88.3	0.039	20	1.28	3.0
			2015	75.6	0.050	23	1.64	3.9
3rd Highest	340931.50	5196588.50	2013	100.1	0.028	24	1.01	2.0
			2014	96.0	0.035	1	1.06	2.8
			2015	73.2	0.029	5	0.94	2.2
4th Highest	340431.50	5196088.50	2013	108.1	0.039	1	1.28	3.1
			2014	77.5	0.044	9	1.59	3.1
			2015	76.7	0.065	7	2.38	4.6
5th Highest	339931.50	5197588.50	2013	76.8	0.045	23	1.48	3.5
			2014	73.4	0.033	7	1.20	2.4
			2015	94.6	0.066	23	2.15	4.9
6th Highest	340931.50	5195588.50	2013	72.1	0.049	1	1.60	3.7
			2014	96.9	0.067	7	2.17	5.1
			2015	75.0	0.026	3	0.96	1.9
7th Highest	340431.50	5197588.50	2013	86.9	0.037	24	1.21	3.9
			2014	75.8	0.020	3	0.65	1.5
			2015	80.5	0.029	5	0.94	2.2
8th Highest	338431.50	5197588.50	2013	83.2	0.055	2	2.01	5.4
			2014	79.1	0.032	23	1.03	2.4
			2015	73.4	0.063	18	2.28	4.7
9th Highest	338431.50	5198088.50	2013	73.4	0.045	23	1.48	3.5
			2014	68.7	0.039	20	1.28	3.0
			2015	89.1	0.066	23	2.15	4.9
10th Highest	338931.50	5199588.50	2013	87.2	0.048	20	1.76	3.5
			2014	63.5	0.040	5	1.30	3.0
			2015	77.1	0.041	23	1.48	4.1

Table 6: 4th Highest Daily Peak 1-hour SO_2 Concentrations (μg/m^3) of the Top Ten 3-Year Averages for the ADJ_U* Scenario.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Year	4th-highest Max. Daily 1-hour Concentration (ug/m3)	U* (m/s)	Hour of Day	Wind Speed (m/s)	Monin-Obukhov Length (m)
1st Highest	340931.50	5196588.50	2013	56.9	0.093	6	1.69	12.9
			2014	42.3	0.092	20	1.28	16.8
			2015	33.1	0.085	18	1.16	17.1
2nd Highest	340431.50	5197588.50	2013	46.9	0.094	24	1.48	14.9
			2014	39.4	0.128	8	2.28	18.3
			2015	44.9	0.092	8	1.67	12.9
3rd Highest	340931.50	5195588.50	2013	35.3	0.093	1	1.60	13.6
			2014	50.8	0.094	21	1.59	13.7
			2015	42.8	0.078	10	1.33	13.8
4th Highest	355531.50	5192788.50	2013	33.6	0.466	12	6.36	-75.8
			2014	74.7	0.120	13	1.37	-1.9
			2015	18.1	0.433	17	5.79	-48.8
5th Highest	339931.50	5197588.50	2013	46.5	0.099	2	2.01	12.7
			2014	35.0	0.046	10	0.84	14.3
			2015	43.9	0.119	23	2.15	16.4
6th Highest	355431.50	5192888.50	2013	34.1	0.466	12	6.36	-75.8
			2014	73.5	0.120	13	1.37	-1.9
			2015	17.5	0.332	17	4.19	-20.7
7th Highest	355431.50	5192788.50	2013	33.1	0.124	9	1.11	-1.9
			2014	74.4	0.120	13	1.37	-1.9
			2015	16.7	0.332	17	4.19	-20.7
8th Highest	355631.50	5192688.50	2013	32.9	0.150	12	1.76	-2.3
			2014	74.2	0.120	13	1.37	-1.9
			2015	17.1	0.474	16	5.95	-34.6
9th Highest	355631.50	5192788.50	2013	35.1	0.124	9	1.11	-1.9
			2014	70.8	0.129	10	1.48	-1.9
			2015	17.6	0.372	10	4.75	-24.2
10th Highest	355331.50	5192888.50	2013	33.8	0.150	12	1.76	-2.3
			2014	73.1	0.120	13	1.37	-1.9
			2015	16.0	0.383	11	6.16	-140.0

Figure 9: Locations of Receptors for the Top Ten 99th Percentile 3-year Averaged Daily Peak 1-hour SO_2 Concentrations from the ADJ_U* Scenario.



Model Results: Comparison of the Results of the Top Ten 99th Percentile Normalized Concentrations for R.M. Heskett Station between Default and ADJ_U* Scenarios

The top ten 3-year averaged 4th highest maximum daily 1-hour SO_2 impacts predicted by the ADJ_U* scenario is compared against the default scenario. Table 7 compares the 3-year averaged 4th highest maximum daily 1-hour concentrations from default to ADJ_U* for the receptors that correspond to the top ten impacts from the default scenario. The surface roughness (u*) values from the default scenario ranges between 0.03 m/s to 0.05 m/s. When the ADJ_U* option is used, the corresponding u* values increase with values ranging from 0.07 m/s to 0.10 m/s. As a result, the predicted 3-year averaged 4th highest concentrations at the ten receptors around Crown Butte are reduced by 46 percent to 61 percent.

Table 7: Comparison of Predicted Concentrations from the Default Scenario versus with the ADJ_U* Scenario at receptors with the Top Ten 3-Year Averages 4th Highest Maximum Daily 1-Hour Concentrations for Default Scenario.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Elevation (m)	3-Year Average Concentration AERMET w/ Default (ug/m3)	3-Year Average Concentration AERMET w/ ADJ_U* (ug/m3)	Percent Change (%)	AERMET w/ Default Avg. u* (m/s)	AERMET w/ ADJ_U* Avg. u* (m/s)
1st Highest	340931.50	5196088.50	656.35	100.2	39.2	-61%	0.042	0.092
2nd Highest	340431.50	5196588.50	657.88	94.3	40.8	-57%	0.042	0.097
3rd Highest	340931.50	5196588.50	678.73	89.7	44.1	-51%	0.031	0.090
4th Highest	340431.50	5196088.50	659.19	87.4	40.1	-54%	0.049	0.103
5th Highest	339931.50	5197588.50	664.56	81.6	41.8	-49%	0.048	0.088
6th Highest	340931.50	5195588.50	653.28	81.3	43.0	-47%	0.047	0.088
7th Highest	340431.50	5197588.50	674.69	81.1	43.7	-46%	0.029	0.105
8th Highest	338431.50	5197588.50	659.98	78.5	35.6	-55%	0.050	0.093
9th Highest	338431.50	5198088.50	663.59	77.1	37.7	-51%	0.050	0.088
10th Highest	338931.50	5199588.50	675.00	75.9	35.6	-53%	0.043	0.074

As previously mentioned, the location of the receptors corresponding to the top ten 3-year averaged 4th highest maximum daily 1-hour SO_2 concentrations are split between those at Crown Butte and less than 1 km of R.M. Heskett Station (Figure 9). The predicted 4th highest concentrations for the default and ADJ_U* scenarios are provided in Table 8 based on the top ten receptors from the ADJ_U* scenario. For the receptors that are located at Crown Butte, the change in predicted concentrations is similar to those compared in the previous default scenario. However, those receptors that are close to R.M. Heskett Station, in the flat terrain, show that the use of the ADJ_U* option in AERMET has no effect on the predicted concentrations.

Table 8: Comparison of Predicted Concentrations from the Default Scenario versus the ADJ_U* Scenario at receptors with the Top Ten 3-Year Averages 4th Highest Maximum Daily 1-Hour Concentrations for the ADJ_U* Scenario.

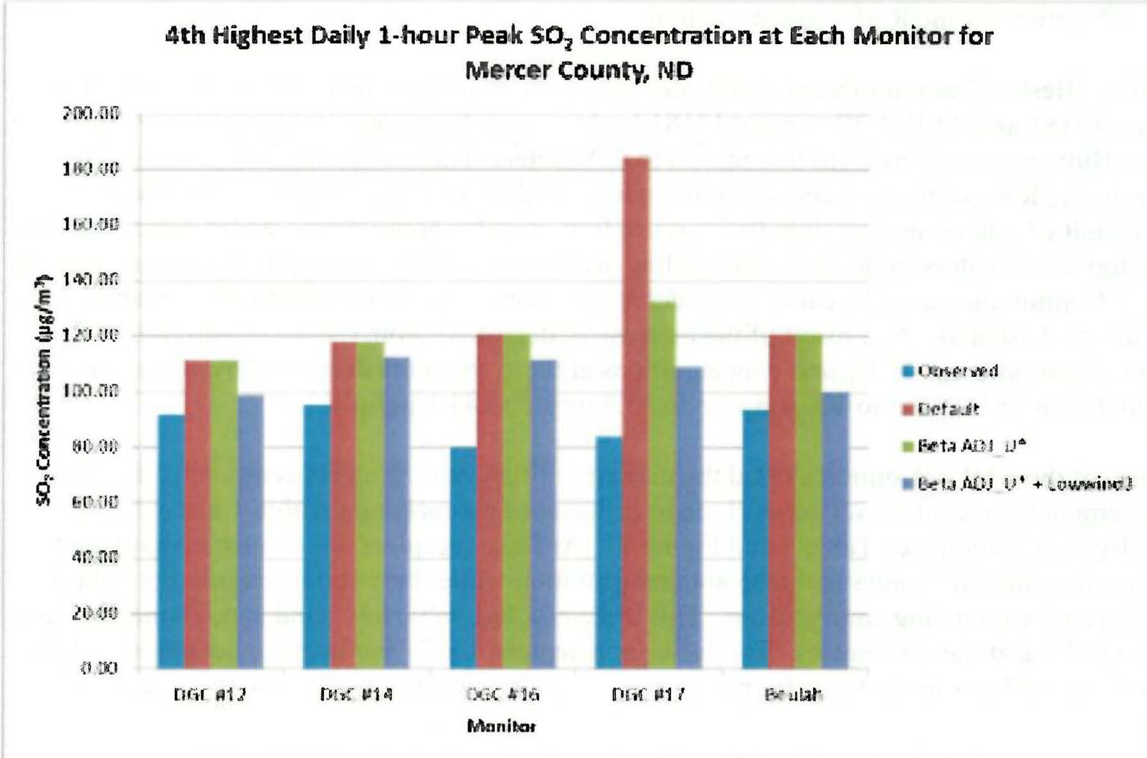
Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Elevation (m)	3-Year Average Concentration AERMET w/ Default (ug/m3)	3-Year Average Concentration AERMET w/ ADJ_U* (ug/m3)	Percent Change (%)	AERMET w/ Default Avg. u* (m/s)	AERMET w/ ADJ_U* Avg. u* (m/s)
1st Highest	340931.50	5196588.50	678.73	89.7	44.1	-51%	0.031	0.090
2nd Highest	340431.50	5197588.50	674.69	81.1	43.7	-46%	0.029	0.105
3rd Highest	340931.50	5195588.50	653.28	81.3	43.0	-47%	0.047	0.088
4th Highest	355531.50	5192788.50	514.43	42.1	42.1	0%	0.340	0.340
5th Highest	339931.50	5197588.50	664.56	81.6	41.8	-49%	0.048	0.088
6th Highest	355431.50	5192888.50	516.09	41.7	41.7	0%	0.306	0.306
7th Highest	355431.50	5192788.50	518.90	41.4	41.4	0%	0.192	0.192
8th Highest	355631.50	5192688.50	512.31	41.4	41.4	0%	0.248	0.248
9th Highest	355631.50	5192788.50	509.28	41.2	41.2	0%	0.208	0.208
10th Highest	355331.50	5192888.50	519.27	41.0	41.0	0%	0.218	0.218

<u>Mercer County, North Dakota Study: Results of the 99th Percentile Concentrations</u>

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 Mercer County North Dakota study are summarized in Table 4 and graphically plotted in Figure 10. These charts indicate that the model-predicted values are higher than the observed at all the sites. The overall results indicate the following:

- The highest design concentration from all monitor sites for both default and ADJ_U* scenarios are higher than observed.
- The highest design concentration from all monitor sites predicted from the default scenario is greater than the ADJ_U* scenario.
- For the monitors in simple terrain (DGC#12, DGC#14, and Beulah), the evaluation results were similar for both the default and ADJ_U* scenarios.
- 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 ADJ_U* option, the ratio is significantly better, at less than 1.3.

Figure 10: Histogram of the 4th Highest Daily Peak 1-hour SO_2 Concentrations from the Mercer County, North Dakota Study.



Model Results: Conclusions

The model sensitivity results from the R.M. Heskett Station show very similar dispersion and transport patterns to those identified in the Mercer County North Dakota study for the following reasons:

- The peak modeled impacts for AERMOD default options occurred in elevated terrain several kilometers away from the source.
- The peak impacts for AERMOD default options occurred in stable, light wind conditions, which are the conditions that the low wind options are designed to address.
- When the ADJ_U* option is used, the change in the concentration magnitude is similar between the Mercer County North Dakota study and the R.M. Heskett model simulations.
- When the ADJ_U* option is used, the concentrations are more homogeneous between the flat terrain and high terrain areas for R.M. Heskett, as was observed in the Mercer County North Dakota study.

Receptors in the flat terrain showed that the use of the ADJ_U* option in AERMET in conjunction with AERMOD default options had no effect on the predicted concentrations for the R.M. Heskett evaluation study. This is similar to the Mercer County North Dakota study and EPA's April 2016 Model Clearinghouse Memorandums regarding the ADJ_U* request for the Schiller station in New Hampshire. As described in the Mercer County North Dakota study, the predicted-to-observed ratios of 99th percentile SO_2 concentration using the ADJ_U* option remained above 1.0, resulting in an over-prediction. This same result is expected with the ADJ_U* option for the R.M. Heskett Station.

The R.M. Heskett Station submittal indicates that the regulatory default options in AERMET version 15181 and AERMOD version 15181 lead to controlling concentrations at receptors on Crown Butte at elevations from 656 meters to 678 meters. These concentrations consistently occur during low-wind speed and stable boundary conditions. Figure 7 of the submittal indicates that default u* values are very low (0.03 m/s to 0.05 m/s) for hours during which concentrations at the top ten receptors in the default modeling are highest. At those receptor locations, using the ADJ_U* option increases 3-year average default u* values by 100 percent to 133 percent (to 0.07 m/s to 0.10 m/s). As a result of the increase in default u* from the use of the ADJ_U* option, 3-year average 4th highest concentrations at these receptors decreased by 46 percent to 61 percent (from 75.9 $\mu g/m^3$ to 100.2 $\mu g/m^3$ to 35.6 $\mu g/m^3$ to 44.1 $\mu g/m^3$).

The use of the ADJ_U* option shifted the majority of the controlling concentrations from the more remote ten receptors at Crown Butte to a cluster of six receptors within 1 kilometer of the R.M. Heskett Station (see Table 8 and Figure 9). At these receptors, there were insignificant changes in default u* values and relevant concentration values between the regulatory default and alternative modeling configuration. This indicates that stable low wind speed conditions are not controlling at these receptors. For these six receptors, the 3-year average default u* values range from 0.03 m/s to 0.34 m/s for peak concentrations, which range from 41.0 $\mu g/m^3$ to 42.1 $\mu g/m^3$.

The analysis in the R.M. Heskett submittal indicates that the ADJ_U* option only has significant effects in the modeling domain at receptors with elevations at or above the height of release. Specifically, the analysis of the top ten 4th highest 3-year averaged predicted concentrations showed that stable conditions with low wind speeds are the controlling meteorological conditions for receptors with elevations above 656 meters, and that concentrations at these receptors are often lower by more than 46 percent under the ADJ_U* formulation than under the regulatory default formulation. For the top ten 4th highest 3-year average receptors below 656 meters, in the analysis, there is little to no change in concentration, indicating that stable conditions with low wind speeds are not controlling at elevations below the release height.

Recommendation

EPA Region 8 has reviewed the available information relevant to the R.M. Heskett Station request for approval to use the ADJ_U* option in AERMET (without turbulence data) for the air quality modeling to support the 1-hour SO_2 Data Requirements Rule. While site-specific model/monitor data are not available for this application, the accumulation of the (1) model sensitivity analysis provided through the R.M. Heskett Station modeling protocol, and the model performance information available through journal articles, field studies, and the previous EPA Model Clearinghouse approvals noted above provide a significant basis to judge the appropriateness of the ADJ_U* option in this case. Based on that review, we believe that the conditions set forth in Section 3.2.2.d of Appendix W in 40 CFR Part 51 (i.e., a statistical performance evaluation showing improved model performance) have been adequately addressed, and therefore we recommend approval of the use of the ADJ_U* option as an acceptable alternative model. We request OAQPS concurrence with this recommendation.

Note that this is a case-specific approval recommendation and is not directly applicable to any other sources or other non-regulatory default options. Also, as noted in 40 CFR, Part 52.21(l)(2), the information on the use of alternative models must be included in the appropriate public notice and comment materials.

Attachment 1 – Montana-Dakota Utilities Co.: SO_2 Characterization for the R.M. Heskett Station Modeling Protocol

NORTH DAKOTA
DEPARTMENT of HEALTH

ENVIRONMENTAL HEALTH SECTION
Gold Seal Center, 918 E. Divide Ave.
Bismarck, ND 58501-1947
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June 22, 2016

Ms. Monica Morales
Acting Director, Air Program
EPA Region 8
1595 Wynkoop Street
Denver, CO 80202

Re: MDU Heskett use of ADJ_U* option

Dear Ms. Morales:

The North Dakota Department of Health (Department) is requesting concurrence from EPA Region 8 and the EPA Model Clearinghouse (MCH) for use of the nonregulatory default beta ADJ_U* option in the AERMOD modeling system. This option is being proposed for use in modeling that will be used to characterize 1-hour SO_2 concentrations in the vicinity of Montana-Dakota Utilities Co. (MDU) R.M. Heskett Station in Mandan, North Dakota, to fulfill the Department's obligations under the Data Requirements Rule (DRR) for the 1-hour SO_2 NAAQS.

The current beta ADJ_U* option in AERMET, the meteorological preprocessor for AERMOD, is proposed to be incorporated as a preferred, regulatory default technique when the proposed revision of EPA's Guideline on Air Quality Models (Appendix W) is finalized later this year. We understand that, until the proposed Guideline is formally approved, the regulatory use of this beta option requires EPA approval as an alternative modeling technique following requirements in Section 3.2 of the current Guideline. The need for following this process was clarified in EPA's memo "Clarification on the Approval Process for Regulatory Application of the AERMOD Modeling System Beta Options," dated December 10, 2015.

MDU has submitted a formal justification for the use of the ADJ_U* option, which is included with additional documentation from EPA's Region 8 office. MDU's submittal has been thoroughly reviewed by the Department and we agree with its conclusions. As discussed in the MDU submittal, the ADJ_U* beta option was coded into AERMET to address the underestimation of the surface friction velocity u* under stable, light-wind conditions and the subsequent overprediction of modeled concentrations during such conditions. In its submittal, MDU has demonstrated that the underestimation of u* under these conditions adversely affects the predicted 99th percentile 1-hour SO_2 concentrations near Heskett Station when the AERMOD system is executed using regulatory default options. Their submittal demonstrates that the use of the ADJ_U* option reduces predicted concentrations at complex terrain receptors during stable, light-wind conditions and reduces the number of very low predicted u* values.

In its submittal, MDU used data from a previous study for a nearby, similar plant with similar complex terrain near the plant. This study demonstrated that modeled 1-hour concentrations from that plant at receptors on complex terrain were over predicted compared to monitored values under stable, light-wind conditions when the model was run using regulatory default options. The study showed that running the model using the ADJ_U* option reduced the over predictions, but did not result in under predictions compared to monitored values. The study also showed that using the ADJ_U* option in the model did not adversely affect predicted concentrations at nearby simple terrain receptors. Predicted concentrations in nearby simple terrain showed little to no change using the ADJ_U* option.

MDU's submittal also includes additional studies including published, peer-reviewed articles that demonstrate that the AERMOD modeling system run using the beta ADJ_U* option performs better than the AERMOD system using default options in situations involving stable, light-wind conditions and complex terrain. As stated above, MDU's submittal has demonstrated that such conditions are applicable to the modeling for Heskett Station.

In addition, recently EPA has cautioned potential applicants requesting approval of such beta options in AERMOD not to use wind data that includes turbulence data, such as sigma-theta or sigma-w data, as use of these data has been shown to under predict modeled concentrations in some cases. MDU's submittal states that their studies did not use such turbulence data and so are not adversely affected by their use.

The Department concurs with MDU's conclusion that use of the beta ADJ_U* option satisfies condition 2 of Appendix W, Section 3.2.2.b, i.e. that "the alternative model performs better for the given application than a comparable model in Appendix A." Thus, the Department is requesting EPA's concurrence that the use of the ADJ_U* option is justified and approvable in the modeling analysis for Heskett Station. The Department appreciates EPA's review of MDU's submittal to advance MDU's modeling analysis for 1-hour SO_2 concentrations near Heskett Station.

If you have any questions, feel free to contact us at 701-328-5188. Thank you.

Sincerely,

Terry L. O'Clair, P.E.
Director
Division of Air Quality

TLO/RJW:csc

AECOM Environment

Prepared for:
Montana-Dakota Utilities Co.
Bismarck, ND

Prepared by:
AECOM
Chelmsford, MA
60438035
June 17, 2016

Modeling Protocol for Montana-Dakota Utilities Co.: SO_2 Characterization for the R.M. Heskett Station

AECOM Environment

Prepared for:
Montana-Dakota Utilities Co.
Bismarck, ND

Prepared by:
AECOM
Chelmsford, MA
60438035
June 17, 2016

Modeling Protocol for Montana-Dakota Utilities Co.: SO_2 Characterization for the R.M. Heskett Station

Prepared By: Christopher J. Warren

Reviewed By: Robert J. Paine

Project Quality Representative Review By: Melissa McLaughlin

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1.0 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 sources of SO_2 emissions with annual emissions greater than 2,000 tons for the most recent year for which emissions data are available as necessary to characterize SO_2 concentrations in the vicinity of these sources. The affected sources are those that were not previously captured as part of EPA's initial non-attainment area designations for the 1-hour SO_2 National Ambient Air Quality Standard (NAAQS) in August 2013 and those that were not identified in the March 2015 Consent Decree entered in Sierra Club, et al. v. McCarthy, Case # 13-cv-03953-DI (N.D. Cal. March 2, 2015).

The North Dakota Department of Health (NDDH) is consulting with the owners or operators of the DRR-identified sources in North Dakota 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. According to the DRR, the method of characterizing the SO_2 concentrations around each source can be done by either:

- installing and operating an ambient air monitoring network; or
- 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:

- limits annual SO_2 emissions to less than 2,000 tons, or
- 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.

This proposed modeling protocol is provided for Montana-Dakota Utilities Co.'s R.M. Heskett Station to characterize SO_2 concentrations from current emissions using modeling. The proposed modeling procedures are consistent with applicable guidance, including the February 2016 Draft "SO_2 NAAQS Designations Modeling Technical Assistance Document" (TAD)[2] issued by the United States Environmental Protection Agency (EPA).

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

[2] Available at http://www3.epa.gov/airquality/sulfurdioxide/pdfs/SO2ModelingTAD.pdf.

1.2 North Dakota Montana-Dakota Utilities Co. R.M. Heskett Station Affected by the DRR

This protocol addresses the Montana-Dakota Utilities Co. R.M. Heskett Station, located northwest of Bismarck, North Dakota, that the NDDH has identified for consideration under the DRR. SO_2 emission sources for this plant are discussed in this protocol, and proposed modeling procedures are specified.

1.3 Report Organization

Section 2 provides a description of R.M. Heskett Station. 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 to be used. Section 4 presents specific information about the modeling approach used for the R.M. Heskett Station, the modeling of background contributions, which includes a review of nearby sources to be included in the modeling, as well as the choice of a regional background monitor. Section 5 covers the manner in which the SO_2 characterization modeling results will be presented.

2.0 Description of Montana-Dakota Utilities R.M. Heskett Station

R.M. Heskett Station is located about 10 kilometers northwest of Bismarck, North Dakota in Morton County. R.M. Heskett Station has two existing coal-fired boilers (Unit 1 & Unit 2), each of which exhaust through their own, separate 298.8-foot stacks.

The location of the plant is shown in **Figure 2-1**. A topographic map of the area surrounding R.M. Heskett is provided in **Figure 2-2**. As shown in **Figure 2-2**, there is "complex" terrain (with elevations above stack top) within 4 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 R.M. Heskett Station can be characterized as having a rural land use type.

The modeling will be performed with the actual stack heights in accordance with recommendations in the DRR and the TAD. **Table 2-1** shows the physical stack parameters that will be used in the modeling. The hourly exhaust flow rates, temperatures, and emission rates will be based on the actual data available from the continuous emission monitor (CEM) systems. The emissions for modeling will consist of actual hourly data for the most recent three calendar years (2013-2015).

The two coal-fired boilers are the major SO_2 emission sources at the R.M. Heskett Station. While there are other small insignificant sources of SO_2 at R.M. Heskett Station, they are emergency in nature and thus do not operate routinely and/or have very low actual SO_2 emissions since they combust natural gas. It should be further noted that Unit 3 is a simple-cycle combustion turbine added to the site in 2014. This unit only combusts natural gas and is also considered an insignificant contributor of hourly SO_2 emissions at R.M. Heskett Station. These small sources of SO_2 are not expected to have an impact on the results of the 1-hour SO_2 modeling and will not be included in the modeling, which is consistent with guidance provided in EPA's March 1, 2011 Clarification Memo[3]. As such, the two coal-fired boilers are the only emission sources at the R.M. Heskett Station that will be included in the 1-hour SO_2 modeling.

Table 2-1: R.M. Heskett – Physical Stack Parameters(1)

Unit	Description	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Stack Base Elevation (meters msl)	Stack Height (m)	Flue Diameter (m)
Unit 1	Spreader Stoker	356414.5	5192141.5	505.206	91.084	2.21
Unit 2	Atm. Fluid Bed	356448.5	5192035.2	505.206	91.084	3.66

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

[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 R.M. Heskett Station

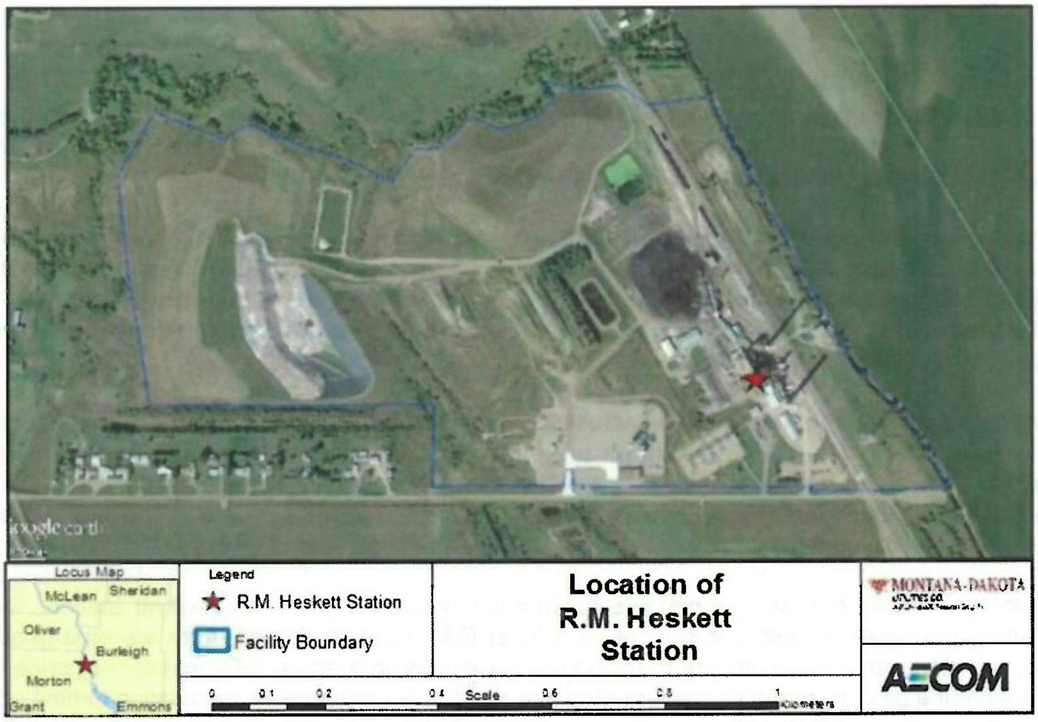
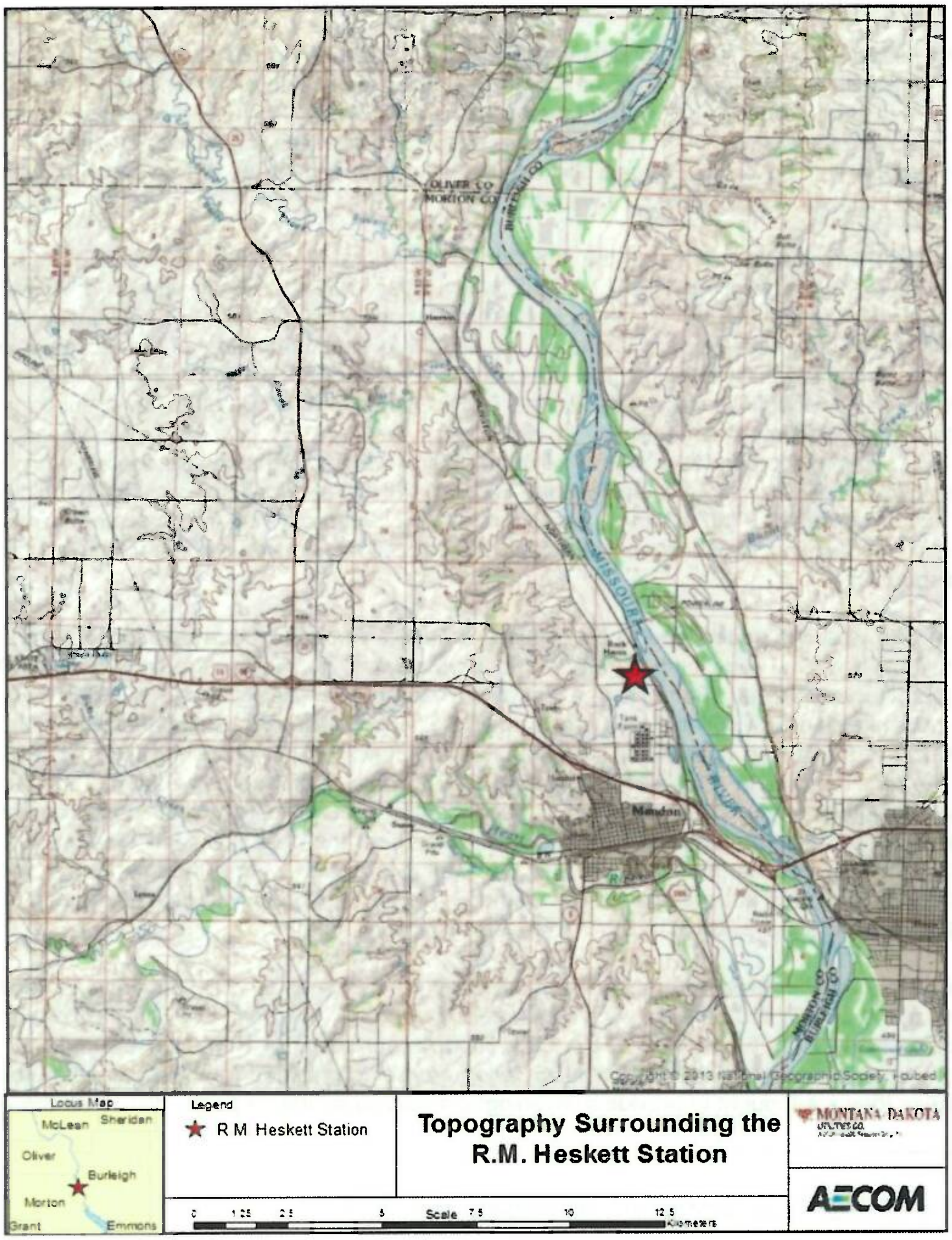


Figure 2-2: Topography in the Vicinity of R.M. Heskett Station



3.0 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 of AERMOD (15181) is proposed for use in the DRR modeling for R.M. Heskett Station. In the event EPA releases a new model version later in 2016, we reserve the option to evaluate the use of the model version update in place of Version 15181 and conduct additional modeling if warranted.

In a proposed rulemaking published in the July 29, 2015 Federal Register (80 FR 45340), the EPA released a revised version of AERMOD (15181), which replaces the previous version of AERMOD dated 14134. EPA proposed refinements to its preferred short-range model, AERMOD, involving low wind conditions. These refinements involve an adjustment to the computation of the friction velocity ("ADJ_U*") in the AERMET meteorological pre-processor. EPA's February 10, 2016 and April 29, 2016 release of the Model Clearinghouse Review of the Use of ADJ_U* Beta Option[5, 6] supports the use of this non-guideline beta option. In addition to the ADJ_U* low wind refinements, the "LOWWIND3" option incorporates a higher minimum lateral wind speed standard deviation, sigma-v (σ_v). The July 2015 EPA 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".

Consistent with what we understand to be EPA's and OMB's Appendix W review schedule, we are aware that the beta low wind options will not be promulgated in time for the July 1, 2016 DRR modeling protocol deadline. Because the low wind refinements (ADJ_U* and LOWWIND3) are currently non-guideline beta options, we provide additional technical support in Appendices A, B, C, E, and F for the use of these options for the R.M. Heskett Station DRR modeling. The Appendices address the requirements in Appendix W, Section 3.2.2 for use of an alternative refined model and include, among other things, a peer-reviewed paper and other communications that support use of the of the refinements which, as proposed by EPA, will outperform the default model. That stated, the proposed approach for the modeling at R.M. Heskett Station is to use ADJ_U* only, without turbulence data (which is not present for the Bismarck airport meteorological data), as noted in the February 10, 2016 and April 30, 2016 EPA Model Clearinghouse memos.

Although we expect the above-referenced appendices to provide substantially supportive justification for the use of the LOWWIND3 option, we are not seeking approval to use the LOWWIND3 beta option in addition to ADJ_U* as a condition of this DRR modeling protocol for R.M. Heskett Station. The discussions supporting use of the LOWWIND3 option are being provided for informational purposes only because they are thought to provide a meaningful modeling reference point. While we therefore

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[4] Available at http://www3.epa.gov/ttn/scram/guidance/guide/appw_05.pdf.

[5] Available at http://www3.epa.gov/ttn/scram/guidance/mch/new_mch/16-X-01_MCResponse_Region10_Donlin-02102016.pdf

[6] Available at https://www3.epa.gov/ttn/scram/guidance/mch/new_mch/16-I-01_MCResponse_Region1_Schiller-04292016.pdf

plan to conduct the modeling both with and without the use of LOWWIND3 to provide additional information for agency reviewers, this protocol seeks formal approval of just the ADJ_U* refinement for the required DRR modeling demonstration for R.M. Heskett Station.

Based on EPA guidance in the TAD, all stacks will be 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 will be used to incorporate downwash effects in the model for all modeled point sources. The building dimensions of nearby building structures will be input to the BPIPPRM program to determine direction-specific building data for input to AERMOD.

Consistent with the 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 the most recent three years that are available (2013-2015) will be used. Consistent with the TAD guidance and later confirmed in a January 26, 2016 e-mail from James Thurman of EPA to Robert Paine of AECOM (Appendix D), receptors used in the modeling may be excluded from the following areas that are not considered ambient air, or where a monitor could not be placed:

- over water (rivers, lakes, ponds, and swamps),
- on the secured property of Montana-Dakota Utilities Co. or any other industrial source (e.g., secured property of Tesoro Mandan Refinery),
- on roadways, railroad tracks, or other routes or areas where obstacles to traffic flow would not be allowed,
- steep terrain, especially in generally inaccessible areas with no nearby power, and
- on active landfills or dredge spoils areas.

Receptor spacing will be consistent with NDDH guidelines[7] and will feature the most closely spaced receptors close to the R.M. Heskett Station. In the unlikely case that the peak concentration might occur beyond 20 km, then additional receptors beyond the 20-km distance will be added as appropriate. The results from this receptor grid will be included in the model assessment report to the agency reviewers.

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[7] Available at http://www.ndhealth.gov/AQ/Policy/ND%20Air%20Dispersion%20Modeling%20Guide.pdf.

4.0 Modeling Configuration

4.1 Modeling Domain

R.M. Heskett Station is located near the Tesoro Mandan Refinery. The modeling domain will be established based on the area necessary to include all modeled sources (primary plus background) and all modeled receptor points. Initially, the modeling domain will be set to 20 km, as this is the furthest distance we anticipate needing receptor points. If necessary, the modeling domain will be adjusted to accommodate additional sources and/or receptors.

4.2 Receptor Grid

The proposed modeling analyses will be conducted using the following Cartesian receptor grid design.

- 25-m receptor spacing along the R.M. Heskett Station and Tesoro Mandan Refinery boundaries for the SO_2 characterization.
- 100-m receptor spacing extending out 5 kilometers from the grid center (located near the Heskett stacks).
- 250-m receptor spacing between 5.0 and 10 kilometers from the grid center.
- 500-m receptor spacing will be used beyond 10 kilometers (out to 20 km), and
- 100-m receptor spacing may be extended to certain more distant terrain areas, as appropriate.

The receptor grid used in the modeling analysis will be based on Universal Transverse Mercator (UTM) coordinates referenced to NAD 83 datum and in zone 14. Receptors are excluded only for the secured areas of the explicitly modeled sources from R.M. Heskett Station and Tesoro Mandan Refinery. **Figures 4-1** and **4-2** show the proposed receptor grids for near-field and far-field views respectfully.

The extent of this grid is expected to be sufficient to capture the maximum modeled impacts. However (as stated above), if the highest impacts are predicted at the edge of the receptor grid, additional receptors will be added to ensure that the maximum modeled impacts are captured. Furthermore, to ensure the maximum impacts are resolved to a refined receptor grid spacing, additional receptors spaced at 100-meter intervals will be placed around the area(s) of the highest modeled impacts if these impacts occur in the area with receptor spacing of more than 100 m.

The latest version of AERMAP (version 11103), the AERMOD terrain preprocessor program, will be 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 will be downloaded from the USGS website (http://viewer.nationalmap.gov/viewer/) and will consist of 1/3 arc second (~10 m resolution) NED. As per the AERMAP User's Guide, the domain will be sufficient to ensure all significant nodes are included such that all terrain features exceeding a 10% elevation slope from any given receptor, are considered.

Additionally, Section 4.2 of the TAD states that receptors do not need to be located in areas where it is not feasible to place a monitor (water bodies, etc.). The selection of any additional receptors to be excluded beyond the proposed receptor grid, as shown in **Figure 4-1**, will be conducted in consultation with the reviewing agencies.

Figure 4-1: Near-Field View of Receptor Grid for R.M. Heskett Station

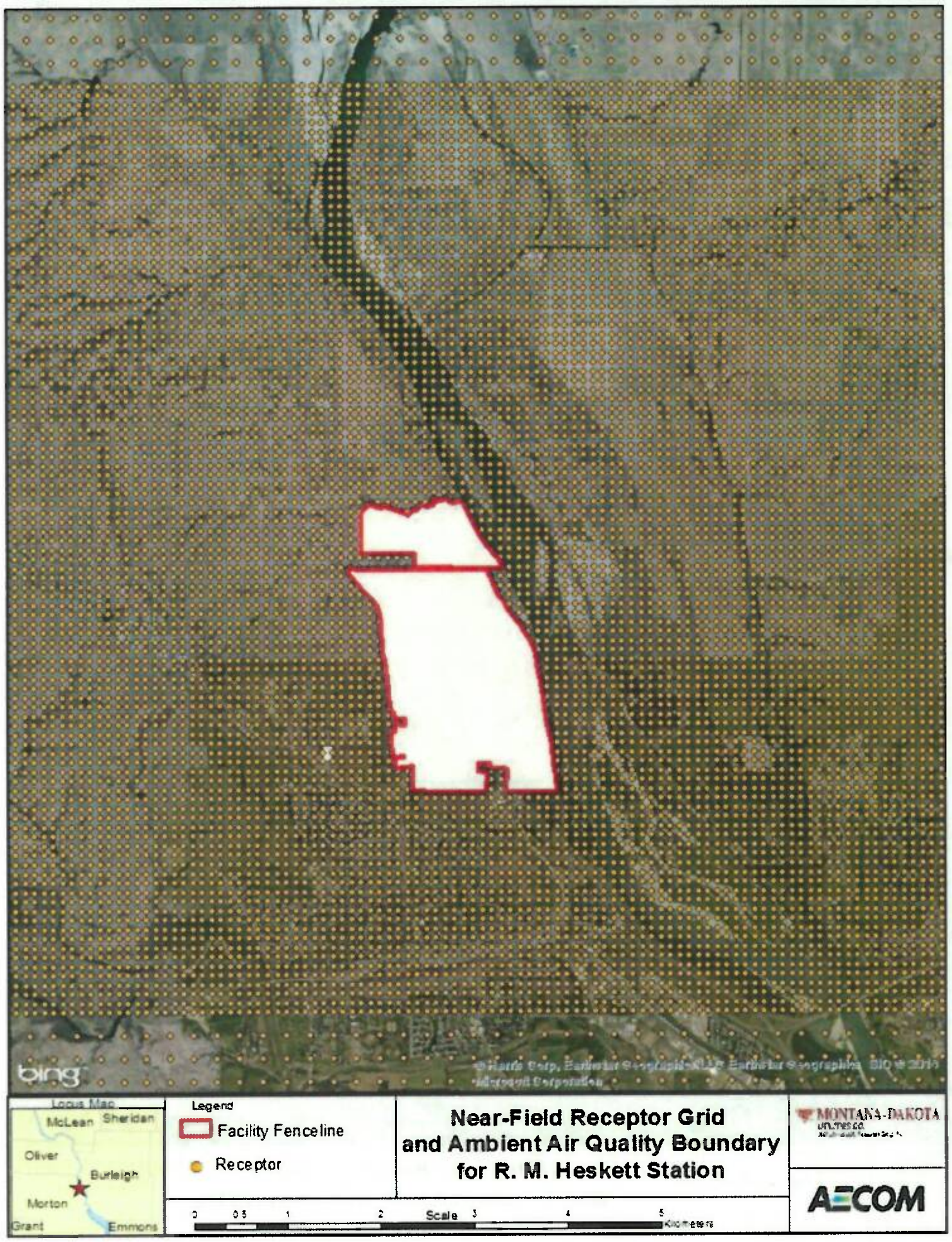
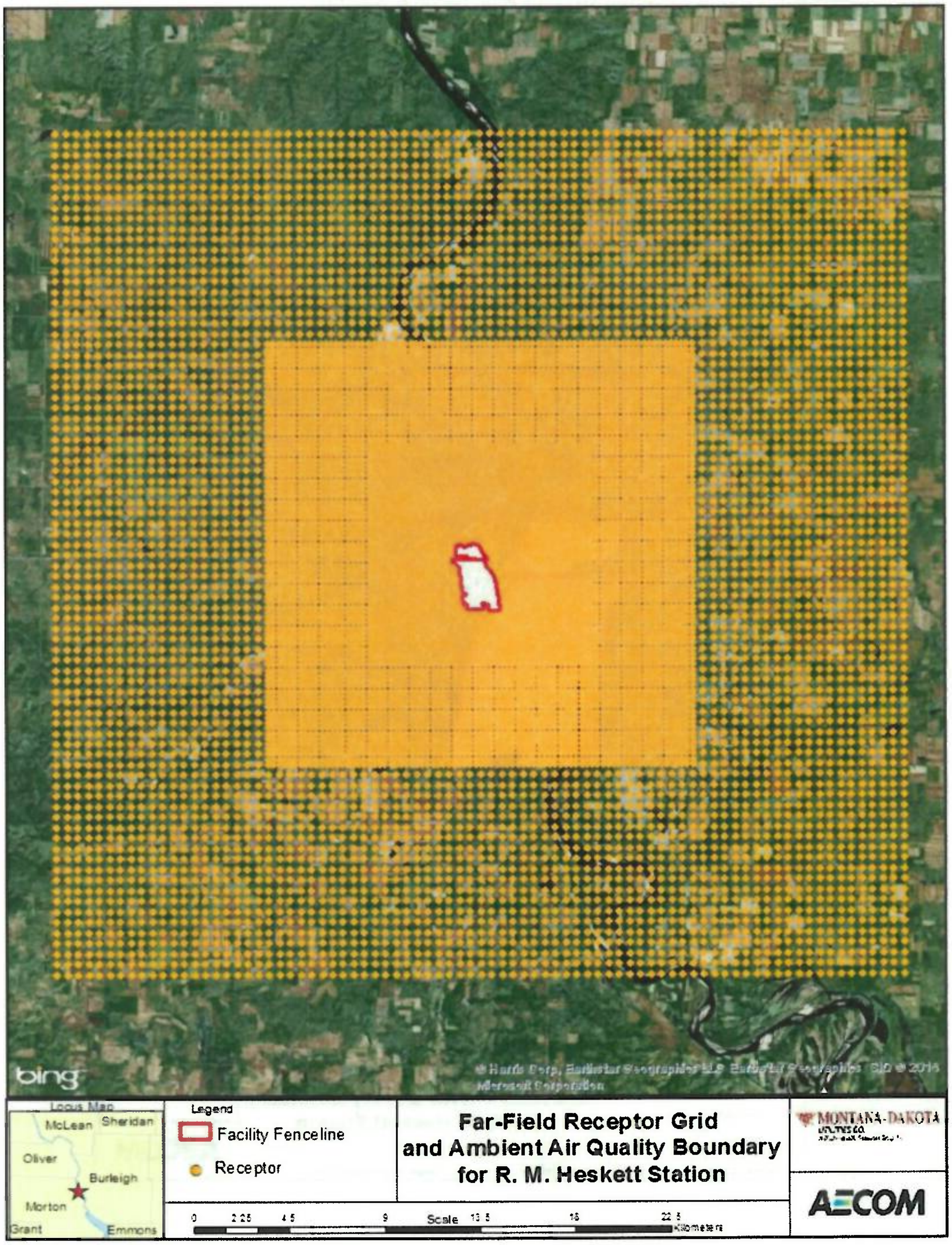


Figure 4-2: Far-Field View of Receptor Grid for R.M. Heskett Station



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) will be processed from Bismarck Municipal Airport (Bismarck, ND). Concurrent upper-air data will be obtained from the closest or most representative National Weather Service site, which is determined to be Bismarck, ND. Additional details are provided in the following sections.

4.3.1 Available Offsite Meteorological Data and NWS Upper-Air Data

The hourly meteorological data for R.M. Heskett Station will be processed with the latest version of AERMET (Version 15181). AERMET will be run utilizing three concurrent years (2013-2015) of hourly surface observations from the Bismarck Municipal Airport in Bismarck, ND along with concurrent upper air data from Bismarck, ND. The hourly surface observations at Bismarck Municipal Airport routinely have at least 90% data capture. Missing upper air data from Bismarck, ND will be substituted with data from Glasgow, MT[8]. **Figure 4-3** shows the location of meteorological stations in relationship to the R.M. Heskett Station.

The AERMET inputs will be 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) will be used to process this data. The upper air data input to AERMET will be downloaded from the NOAA/ESRL/GSD - RAOB database (http://esrl.noaa.gov/raobs/). A wind rose for Bismarck Municipal Airport for the years 2013-2015 is shown in **Figure 4-4**.

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 4-1: Meteorological Data Used in AERMET for R.M. Heskett Station

Met Site	Latitude	Longitude	Base Elevation (m)	Data Source	Data Format
Bismarck Airport – Bismarck, ND	46.774	-100.748	506	NCDC	ISHD, 1-min, 5-min ASOS
Bismarck, ND	46.774	-100.748	506	FSL	FSL
Glasgow, MT	48.200	-106.620	693	FSL	FSL

[8] A total of 19 days over the 3 years to be modeled will be substituted.

Figure 4-3: Location of Meteorological Stations Relative to R.M. Heskett Station

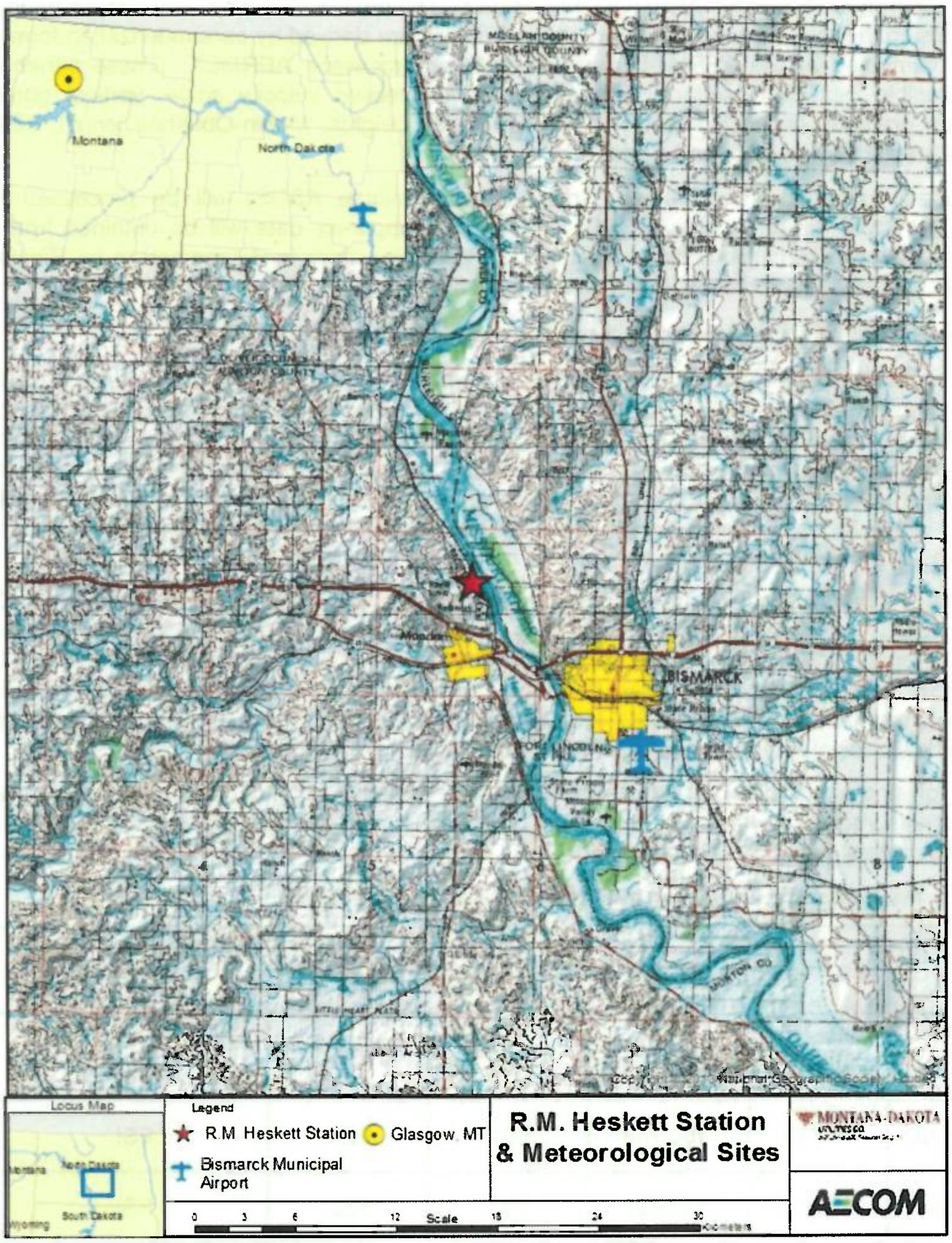
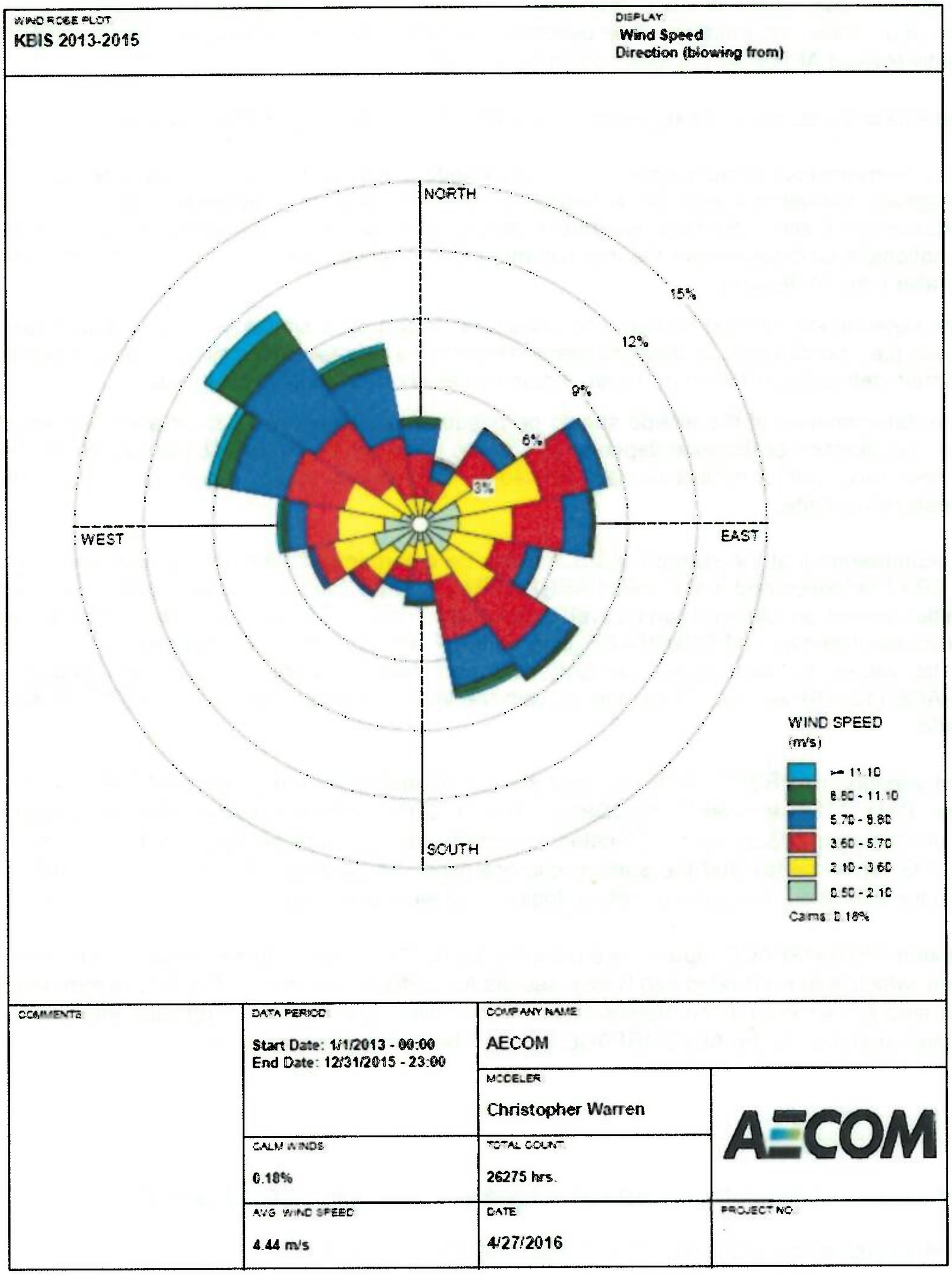


Figure 4-4: Wind Rose for Bismarck Municipal Airport, Bismarck, ND (KBIS)



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 will be developed according to the guidance provided by USEPA in the recently revised AERMOD Implementation Guide (AIG)[9].

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. US EPA has developed a tool called AERSURFACE[10] 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 will be 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[11] (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.

Recommended AERSURFACE inputs[12] are provided by NDDH. This includes using a 1-km radius circular area, which is to be divided into twelve sectors for surface roughness. The AIG recommends this circular area be centered at the meteorological station site. Since the meteorological site is at the Bismarck Municipal Airport, the AERSURFACE input will be marked as an airport.

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[9] Available at http://www3.epa.gov/ttn/scram/7thconf/aermod/aermod_implmtn_guide_3August2015.pdf.

[10] Available at http://www3.epa.gov/ttn/scram/dispersion_related.htm#aersurface.

[11] Available at http://edcftp.cr.usgs.gov/pub/data/landcover/states/.

[12] Available at https://www.ndhealth.gov/AQ/Policy/AERSURFACE%20Inputs.pdf.

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. NDDH provides guidance[13] on how to assign the seasonal category for each month of the year based upon the location of the modeling in the state. Based on this guidance, the "South Central" region seasonal classification will be used and are as follows:

> October, November, December, March = Late autumn after frost and harvest, or winter with no snow;
>
> January, February = Winter with continuous snow on ground;
>
> April, May = Transitional spring with partial green coverage or short annuals;
>
> June, July, August = Midsummer with lush vegetation; and
>
> September = Autumn with un-harvested cropland.

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 will be 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 will be taken from the Bismarck Municipal Airport.

4.3.3 AERMET Data Processing

AERMET (Version 15181) and AERMINUTE (Version 15272) will be 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 will be determined following procedures outlined below. In running AERMET, the observed airport hourly wind direction (if used to substitute for missing AERMINUTE data) will be randomized based on guidance from EPA's March 8, 2013 Use of ASOS Meteorological Data in AERMOD Dispersion Modeling memo[14]. 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

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[13] Available at https://www.ndhealth.gov/AQ/Policy/AERSURFACE%20Inputs.pdf.

[14] Available at https://www3.epa.gov/scram001/guidance/clarification/20130308_Met_Data_Clarification.pdf

options as documented in Appendices B and C, the ADJ_U* option is proposed for use in the AERMET processing.

AERMET will be 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 R.M. Heskett Station, the profile file will contain a single level of wind data (10 meters) and the temperature data only, corresponding to the Bismarck Municipal Airport observation.

4.4 Nearby Sources and Ambient Background Concentrations

4.4.1 Nearby Sources to be Modeled

NDDH will provide modeling input data for nearby background sources, if any, that the agency determines appropriate for inclusion in the modeling. The NDDH DRR 1-hour SO_2 Protocol[15] identifies a number of background sources, including the Tesoro Mandan Refinery, Milton R. Young Station, as well as a single source at the State Penitentiary.

The Tesoro Mandan Refinery will be explicitly modeled as part of the modeling for R.M. Heskett Station. Actual emissions will be modeled to the extent that such emissions can be obtained. Montana-Dakota Utilities will work with the refinery to obtain actual hourly emissions data for 2013-2015.

The State Penitentiary's coal-fired boiler was recently removed from operation as indicated in NDDH's DRR Protocol. In addition, it is over 10 km from R.M. Heskett Station and the background monitor being used to account for unmodeled sources is only 3 km from the penitentiary in a predominant downwind direction toward the northwest. Since this monitor already captures impacts from the penitentiary at a distance much less than the distance to R.M. Heskett Station and the SO_2 source has been removed and eliminated from their permit to operate, the background monitor will conservatively account for the impacts from the penitentiary background source, which will not be explicitly modeled.

The next nearest large background source is the Milton R. Young Station, which is over 30 km from R.M. Heskett Station. This location is well beyond the 20 km radius limit suggested for modeling nearby sources explicitly in the proposed Appendix W changes (80 FR 45340). The NDDH Protocol confirms that with its low emission rates Milton R. Young Station's impacts in the vicinity of R.M. Heskett Station are well below the monitored background. Therefore, the background monitor will be

[15] Protocol for Modeling Analyses Used to Address EPA's Data Requirements Rule (DRR) for 1-hour SO_2 NAAQS Designations in North Dakota. North Dakota Department of Health (NDDH). March 2016.

used to capture Milton R. Young Station's impacts in the modeling of R.M. Heskett Station and will not be modeled explicitly.

4.4.2 Regional Background Concentrations

Ambient air quality data are 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 used to characterize the area as attainment or non-attainment for 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] are proposed. The Bismarck Residential monitoring station (located at 1810 N 16th Street) concentrations observed during the 2013-2015 three-year period are listed in **Table 4-2** and **Table 4-3**.

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

Table 4-2: Bismarck Residential Station 99th Percentile Hour of the Day and by Season Concentrations (µg/m³), Hours 0-11

AVG	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Winter	19.21	13.36	14.93	16.07	14.24	16.33	21.22	23.84	11.79	14.15	20.61	27.07
Spring	9.87	9.08	9.00	7.69	7.16	8.30	7.77	9.61	18.60	12.58	15.46	9.43
Summer	4.63	4.80	5.24	5.41	4.28	2.97	11.62	10.22	10.74	12.49	14.76	11.53
Fall	7.34	6.64	7.07	5.50	8.03	8.30	10.22	11.88	13.27	12.66	11.79	18.60

Table 4-3: Bismarck Residential 99th Percentile Hour of the Day and by Season Concentrations (µg/m³), Hours 12-23

AVG	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Winter	21.66	27.16	24.98	18.60	20.26	18.17	14.76	17.47	23.41	20.26	18.95	19.13
Spring	10.04	12.49	11.18	11.35	8.47	10.22	7.77	9.96	7.60	7.51	8.73	7.16
Summer	8.91	7.34	5.59	6.72	7.07	6.03	5.85	5.59	4.37	4.10	4.02	4.37
Fall	15.55	12.49	11.62	13.45	14.41	10.13	12.31	8.21	14.06	7.34	6.29	6.38

5.0 Presentation of SO_2 Characterization Modeling Results

The modeled concentrations from the AERMOD modeling will be calculated based on the form of the 1-hour SO_2 NAAQS, with inclusion of regional background concentrations as agreed to in the final protocol. A modeling report and computer archive will be prepared that document the results of the modeling characterization study. A wind rose plot representing the input meteorological data and spatial contour plots of the modeled concentrations will be included in the modeling report.

If the total design concentration (modeled plus background 99^{th} percentile peak daily 1-hour maximum at any receptor averaged over all years modeled) is below the 1-hour SO_2 primary NAAQS of 196.5 μg/m^3, then this modeling demonstration can be used to support an attainment designation of the area in the vicinity of the Montana-Dakota Utilities Co.'s R.M. Heskett Station.

Appendix A

Additional Support Documentation for the Use of AERMOD Low Wind Options for R.M. Heskett Station

Additional Support Documentation for the Use of AERMOD Low Wind Options for R.M. Heskett Station

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:

> "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."

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[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.

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

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. 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 protocol the new version of AERMET and AERMOD with the default low wind options, with accompanying technical support provided in this appendix. This appendix includes a discussion of the issues involved in acceptance of a non-guideline modeling option and 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 current version of AERMET/AERMOD (v15181) and low wind options 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 over-prediction, and Prairie Grass showed either over-predictions 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 that would be used for 1-hour SO_2 modeling. AECOM prepared an alternative evaluation study[7] and A&WMA paper in Appendix E 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 F.

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[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.

[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.

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 low wind options, 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 low wind options. Such a similar site is the Mercer County North Dakota Evaluation Study that was included in the peer-reviewed evaluation paper by Paine et al. (2015)[5]. EPA's April 29, 2016 release of the Model Clearinghouse Review of the Use of ADJ_U* Beta Option[8] supports the use of this non-guideline beta option for tall stack sources in complex terrain. The April 29, 2016 EPA Clearinghouse memo used the Mercer County North Dakota Evaluation Study as part of the comparison analysis.

The sensitivity modeling runs using LOWWIND3 are also presented in this comparison evaluation since this option was addressed in the Mercer County, ND Evaluation Study. The comparison between the two sites using LOWWIND3 is being provided for informational purposes only, since approval of the LOWWIND3 option is not being requested at this time for use in 1-hour SO_2 DRR modeling of R.M. Heskett Station.

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. 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 likely dominated the impacts.

[8] Available at https://www3.epa.gov/ttn/scram/guidance/mch/new_mch/16-I-01_MCResponse_Region1_Schiller-04292016.pdf

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

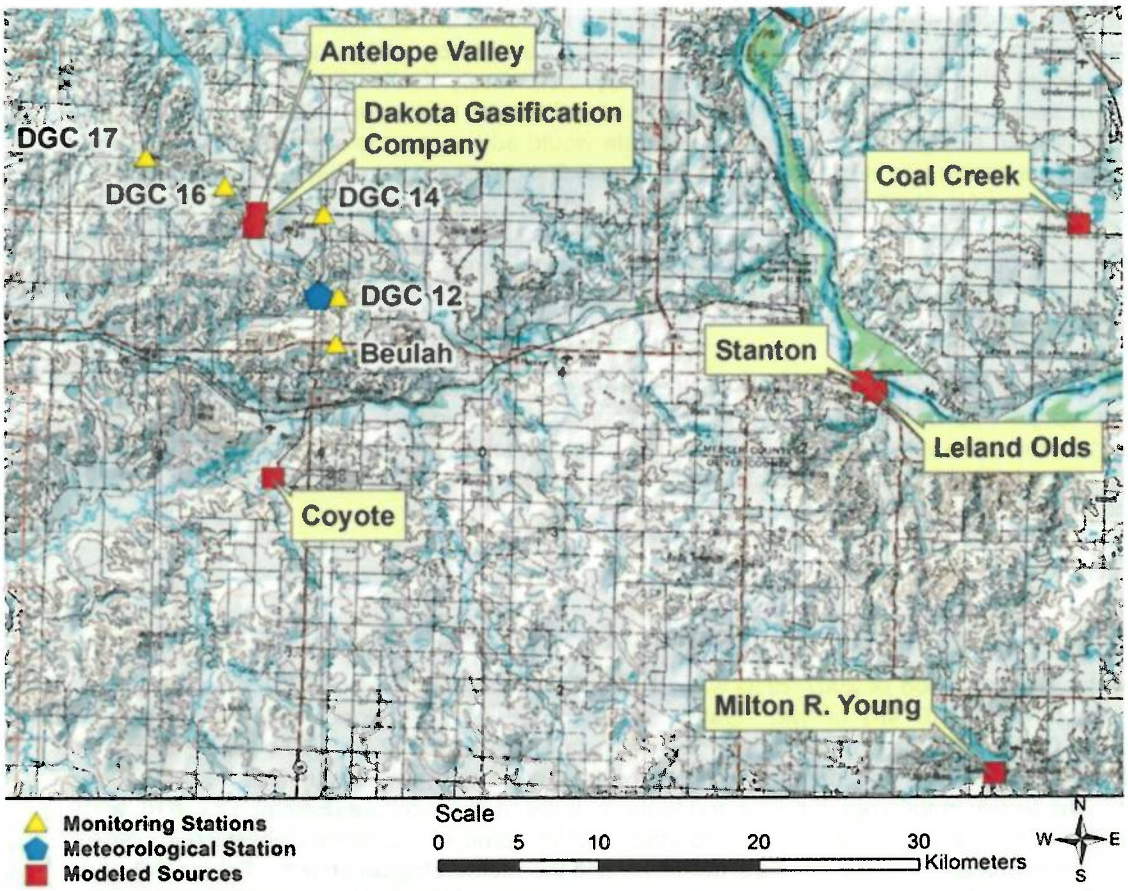


Table 1-1: Source Information for the Mercer County, ND Database

Data Base	Facility Name	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 Montana-Dakota Utilities R.M. Heskett Station and the Mercer County North Dakota Evaluation Study. R.M. Heskett Station is less than 90 km south-southeast from the facilities in Mercer County, resulting in very similar climate and terrain. Both facilities are in a river valley with elevated terrain located a few kilometers from the emission sources.

R.M. Heskett Station is situated along the west bank of the Missouri River where the topography is dominated by the Missouri Plateau (**Figure 2-1**). The Missouri Plateau consists of rolling to hilly plains, although there are occasional exceptions that include prominent buttes. One of the notable terrain features is a prominent bluff approximately 15 km west-northwest of R.M. Heskett Station. The bluff, known as Crown Butte, peaks at approximately 707 m above sea level. Crown Butte is marked with a blue diamond symbol in **Figure 2-1**. East of R.M. Heskett Station, 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 7.6 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 R.M. Heskett Station 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 R.M. Heskett Station 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 showed that this prediction overestimated by about a factor of 2. The use of the low wind options reduced the over-prediction substantially, but still resulted in a model over-prediction. Given the similarities between the two applications, we expect that the R.M. Heskett Station predicted impacts on distant high terrain are also overstated, and the use of the low wind options will mitigate these peak predictions while still resulting in somewhat modest over-predictions. Therefore, the modeling results for R.M. Heskett Station using AERMOD with low wind options would be more appropriate for this case.

Figure 2-1: Topography Map Surrounding R.M. Heskett Station

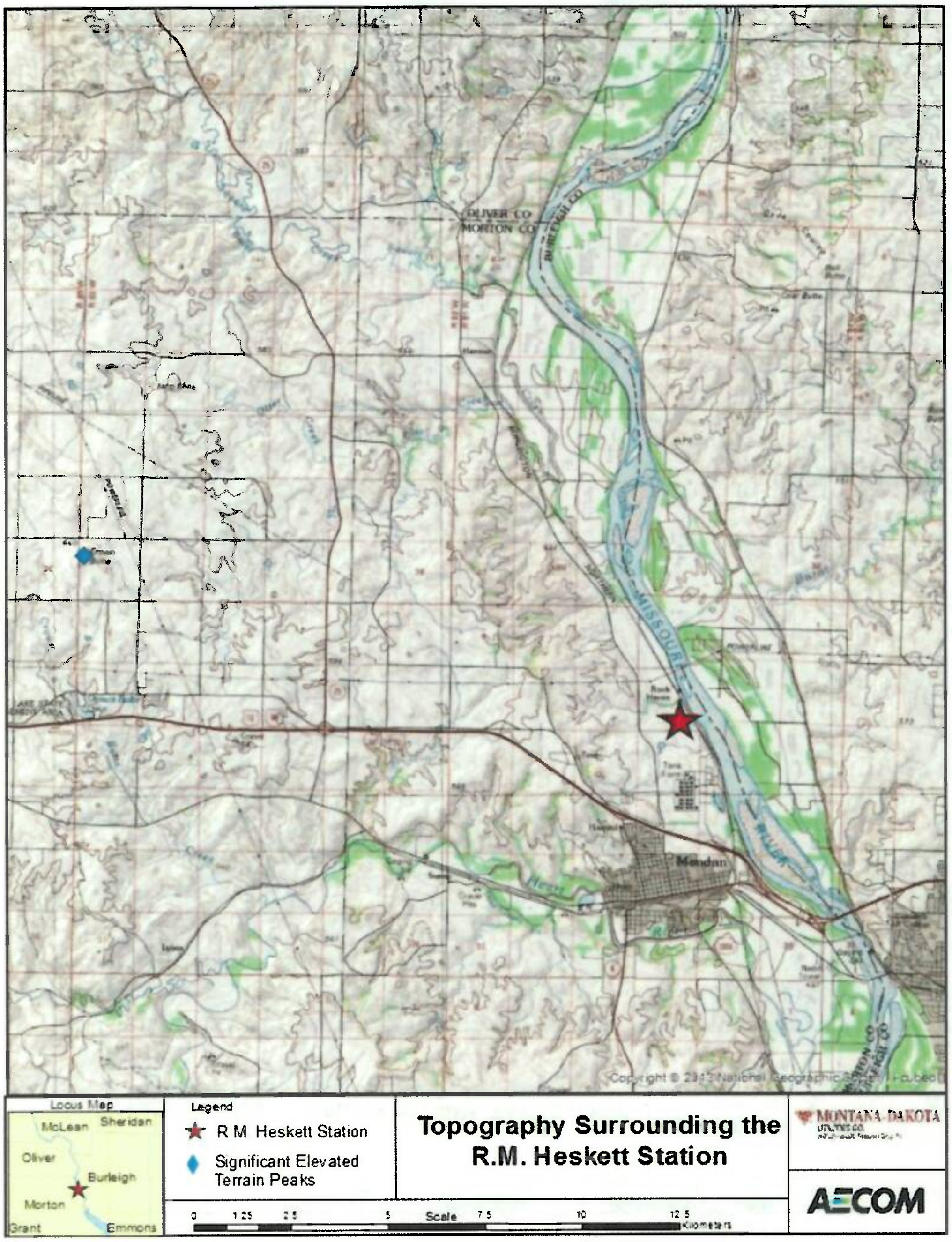
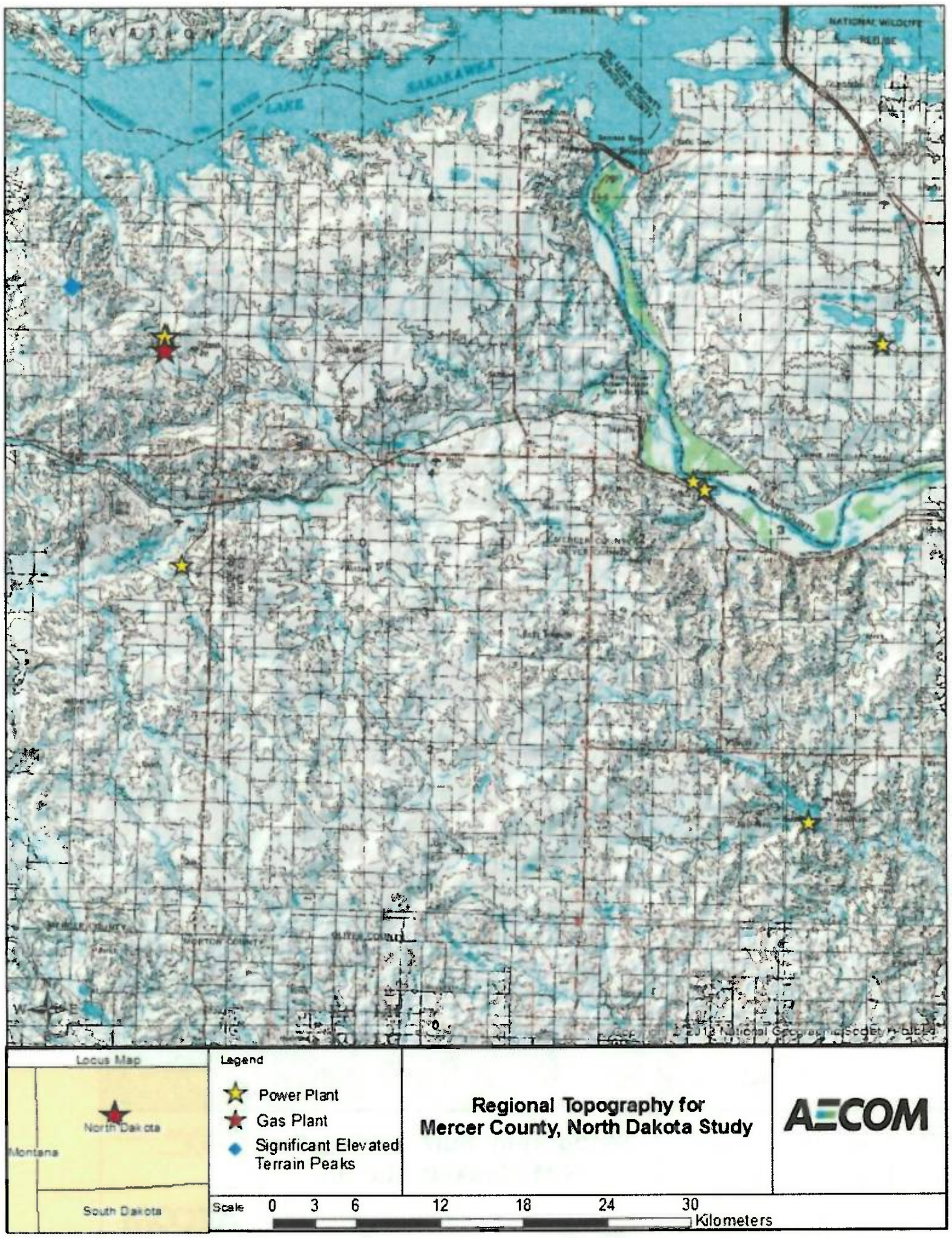


Figure 2-2: Topography Map for Mercer County, ND SO_2 Sources



3.0 Stack Parameter Similarities

As discussed in the SO_2 DRR Modeling Protocol for R.M. Heskett, the station has two boiler units (Units 1 and 2). Exhaust from both boiler stacks are vented through separate stacks with height and internal exit diameters as reported in **Table 3-1**. Both are considered to be tall stacks within a region that includes 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.

Table 3-1: R.M. Heskett Station – Physical Stack Parameters(1)

Unit	Description	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Stack Base Elevation (meters msl)	Stack Height (m)	Flue Diameter (m)
Unit 1	Spreader Stoker	356414.5	5192141.5	505.206	91.084	2.21
Unit 2	Atm. Fluid Bed	356448.5	5192035.2	505.206	91.084	3.66

(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 R.M. Heskett Station. AERMET/AERMOD version 15181 was run using the following configuration options;

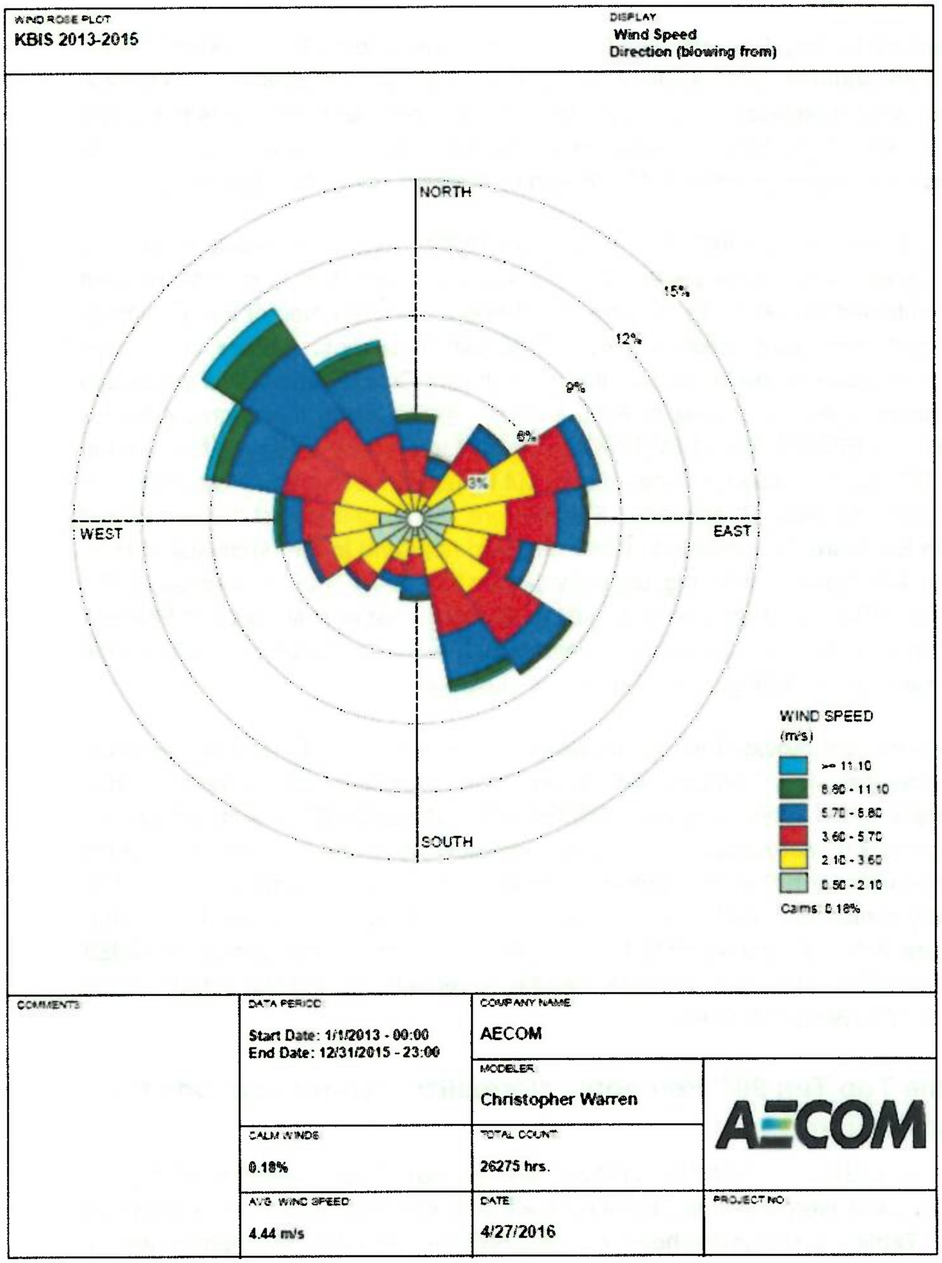
- AERMET Default / AERMOD default;
- AERMET ADJ_U* / AERMOD default;
- AERMET ADJ_U* / AERMOD LOWWIND3.

The model input configuration (domain, receptor grid, meteorological data, etc.) used in this sensitivity comparison study is identical to that presented in the 1-hr SO_2 DRR modeling protocol for R.M. Heskett Station. These input configurations include:

- Modeling using 3-years (2013-2015) for emissions and meteorological data;
- Bismarck Municipal Airport in Bismarck, ND used for surface and upper-air meteorological data (missing upper-air data substituted with Glasgow, MT);
  - Wind rose from Bismarck from 2013-2015 is shown in **Figure 4-1**.
  - Turbulence data will not be used in any of the modeling options.
- A Cartesian receptor grid:
  - 25-m receptor spacing along the R.M. Heskett Station and Tesoro Mandan Refinery boundaries for the SO_2 characterization.
  - 100-m receptor spacing extending out 5 kilometers from the grid center (located near the Heskett stacks).
  - 250-m receptor spacing between 5.0 and 10 kilometers from the grid center.
  - 500-m receptor spacing will be used beyond 10 kilometers (out to 20 km).

Since this sensitivity study focuses on the impacts of R.M. Heskett Station, model-predicted impacts presented in Section 4.1 are based on hourly SO_2 emission rates from R.M. Heskett Station alone. Therefore, no background has been included in the sensitivity comparison results.

Figure 4-1: Wind Rose for Bismarck Municipal Airport, Bismarck, ND (KBIS)



4.1 Results of the Maximum 99th Percentile Normalized Concentrations for R.M. Heskett Station

The 4th highest (99th percentile) daily 1-hour peak SO_2 concentrations for both R.M. Heskett Station and North Dakota Study are summarized in **Table 4-2**. For this comparative modeling, the emission rates for R.M. Heskett were normalized by a constant factor, consistent with EPA's Monitor Technical Assistance Document guidance[9]. Ambient background SO_2 concentrations were not included in the modeling comparison for either R.M. Heskett or Mercer County, ND database.

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 R.M. Heskett Station is at the aforementioned Crown Butte. **Figure 4-2** 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 at the location of the more distant Crown Butte with a secondary area of high concentrations to the southwest of R.M. Heskett Station along the nearby complex terrain. The results from of AERMET ADJ-U*/AERMOD default (**Figure 4-3**) continued to show the 4th highest daily 1-hour SO_2 concentration at Crown Butte, but there is a more gradual concentration gradient near this bluff under the ADJ_U* scenario. Furthermore, the magnitudes of the normalized concentrations at Crown Butte are comparable to those depicted near and to the northwest of R.M. Heskett Station. **Figure 4-4** shows that 4th highest daily 1-hour SO_2 concentration using AERMET ADJ_U*/AERMOD LOWWIND3 model options occur just to the northwest of R.M. Heskett Station's fenceline. While a secondary maximum of higher concentrations continues to be predicted by the model at Crown Butte, there are no tight gradient signatures observed.

Q-Q plots paired by receptor are provided for the predicted 3-year averaged 4th highest maximum daily 1-hour SO_2 concentrations. **Figure 4-5** shows the predicted concentrations from AERMET/AERMOD default option run versus the AERMET ADJ_U*/AERMOD Default options run. Concentrations that correspond with receptors in flat terrain follow along the 1:1 ratio line, where those in the complex terrain have higher concentrations from the default modeling scenario. This behavioral pattern is very similar to that observed in the evaluation study presented in EPA's April 29, 2016 Memo. **Figure 4-6** plots the AERMET/AERMOD Default option run versus AERMET ADJ_U*/AERMOD LOWWIND3 option run. A similar trend is observed to that of the default versus ADJ_U* for the default to LOWWIND3 Q-Q Plot.

4.2 Results of the Top Ten 99th Percentile Normalized Concentrations for R.M. Heskett Station

Using default options for AERMET/AERMOD v15181, the top ten 3-year average 4th highest maximum daily 1-hour impacts were predicted to all coincide with elevated terrain associated with Crown Butte (**Fig. 4-7**). **Table 4-2** shows the hours corresponding to these top ten impacts, with all of them occurring during low wind speed, stable conditions. This process is repeated in **Tables 4-3** and **4-4** for the non-regulatory low wind option modeling scenarios of AERMET ADJ_U*/AERMOD

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

v15181 and AERMET ADJ_U*/AERMOD LOWWIND3 v15181, respectfully. The top ten impacts for AERMET ADJ_U*/AERMOD default indicate a mix between daytime and nighttime hours. The top three 4th highest impacts were still occurring under low wind conditions with receptor locations near Crown Butte. The majority of the top ten receptor locations for the ADJ_U* scenario reside near R.M. Heskett Station, as shown in **Figure 4-8**. Using the LOWWIND3 non-regulatory option in AERMOD, **Table 4-4** shows top ten impacts occurring primarily during daytime hours under moderate wind conditions. The receptor locations of the top ten from the LOWWIND3 modeling scenario all occur less than 1 km from R.M. Heskett Station in flat terrain **(Figure 4-9)**.

4.3 Comparison of the Results of the Top Ten 99th Percentile Normalized Concentrations for R.M. Heskett Station between Default and Low Wind Options

a. Top Ten 99th Percentile Default versus ADJ_U Model Options*

The top ten 3-year averaged 4th highest maximum daily 1-hour SO_2 impacts for each of the non-regulatory modeling scenarios are compared against the regulatory default run. **Table 4-5** compares the 3-year averaged 4th highest maximum daily 1-hour concentrations from default to ADJ_U* for the receptors that correspond to the top ten impacts from the default run. The surface roughness (u*) values from the default run ranges between 0.03 m/s to 0.05 m/s. When the non-default ADJ_U* option is used, the corresponding u* values increase with values ranging from 0.07 m/s to 0.10 m/s. As a result, the predicted 3-year averaged 4th highest concentrations at the ten receptors around Crown Butte are reduced by 46% - 61%.

As previously mentioned, the location of the receptors corresponding to the top ten 3-year averaged 4th highest maximum daily 1-hour SO_2 concentrations are split between those at Crown Butte and less than 1 km of R.M. Heskett Station (**Fig. 4-8**). The predicted 4th highest concentrations for default and ADJ_U* are provided in **Table 4-6** based on the top ten receptors from the ADJ_U* run. For the receptors that are located at Crown Butte, the change in predicted concentrations is similar to those compared in the previous default run. However those receptors that are close to R.M. Heskett Station, in the flat terrain, show that the use of the beta ADJ_U* option in AERMET has no effect on the predicted concentrations.

b. Top Ten 99th Percentile Default versus ADJ_U with LOWWIND3 Model Options*

Table 4-7 compares the 3-year averaged 4th highest maximum daily 1-hour concentrations from default to ADJ_U* and LOWWIND3 for the receptors that correspond to the top ten impacts from the default run. When the corrective non-default ADJ_U* with LOWWIND3 options are used, the corresponding u* values are comparable to those for the ADJ_U* run (without LOWWIND3). The predicted 3-year averaged 4th highest concentrations at the ten receptors around Crown Butte are reduced by 61% - 67% for the ADJ_U* and LOWWIND3 options relative to default options.

All receptors corresponding to the top ten 3-year averaged 4th highest maximum daily 1-hour SO_2 concentrations are located less than 1 km of R.M. Heskett Station (**Fig. 4-9**). The predicted 4th highest concentrations for default and ADJ_U* are provided in **Table 4-8** based on the top ten receptors from the ADJ_U* with LOWWIND3 run. As expected, the u* values are very similar between default and ADJ_U* with LOWWIND3, the concentrations do decrease slightly, between 7% - 16%. This decrease in predicted concentrations can be attributed in large part to the higher minimum horizontal turbulence (sigma-v), allowing for more lateral dispersion of the plume in the LOWWIND3 algorithm under low wind conditions.

Table 4-1: Model-Predicted 4th Highest Daily Peak 1-hour SO_2 Concentrations for R.M. Heskett Station and Mercer County, ND

Model Options	R.M. Heskett Station Predicted Daily 1-hour Highest 99th Percentile SO_2 Concentrations (µg/m³)[1,2]	Mercer County, ND Predicted Daily 1-hour Highest 99th Percentile SO_2 Concentrations (µg/m³)[2]
AERMET; AERMOD Default v15181	100.20	174.49
AERMET w/ ADJ_U*; AERMOD v15181	44.09	122.30
AERMET w/ ADJ_U*; AERMOD LOWWIND3 v15181	35.75	102.09

[1] Model-predicted concentrations based on normalized emission rates.
[2] SO_2 predicted concentrations do not include any background contributions.

Figure 4-2: Isopleth Map of the 99th Percentile Normalized SO_2 Concentrations Using AERMET/AERMOD Default options for R.M. Heskett Station

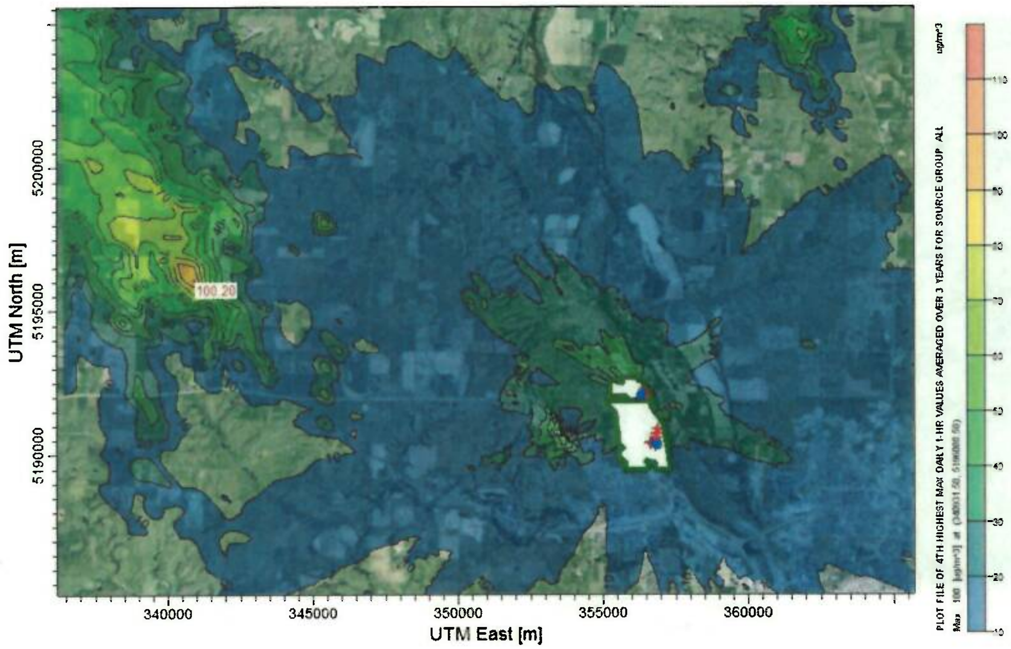


Figure 4-3: Isopleth Map of the 99th Percentile Normalized SO_2 Concentrations Using AERMET ADJ_U*/AERMOD Default options for R.M. Heskett Station

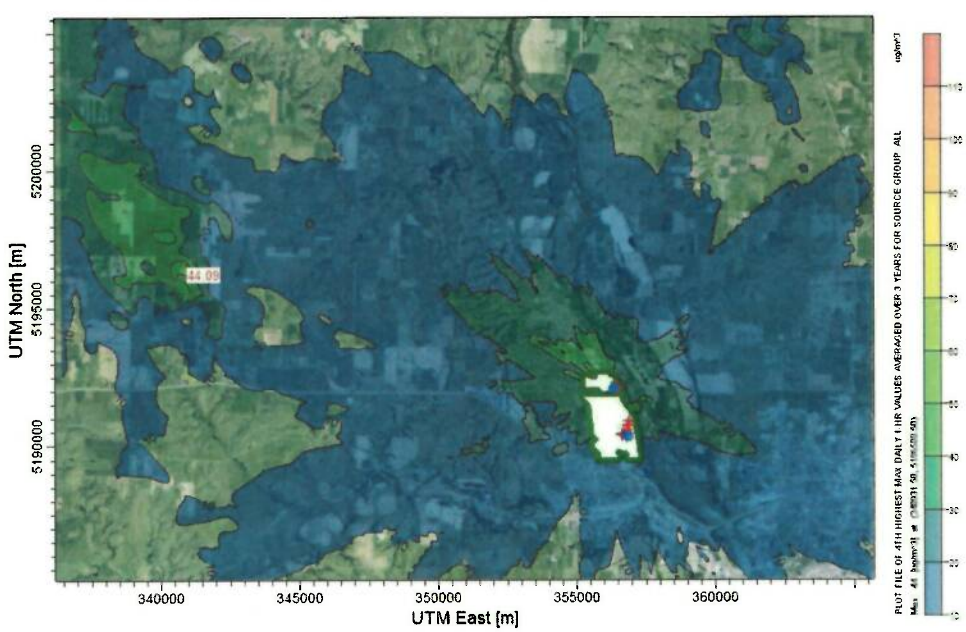


Figure 4-4: Isopleth Map of the 99th Percentile SO_2 Concentrations Using AERMET ADJ_U*/AERMOD LOWWIND3 options for R.M. Heskett Station

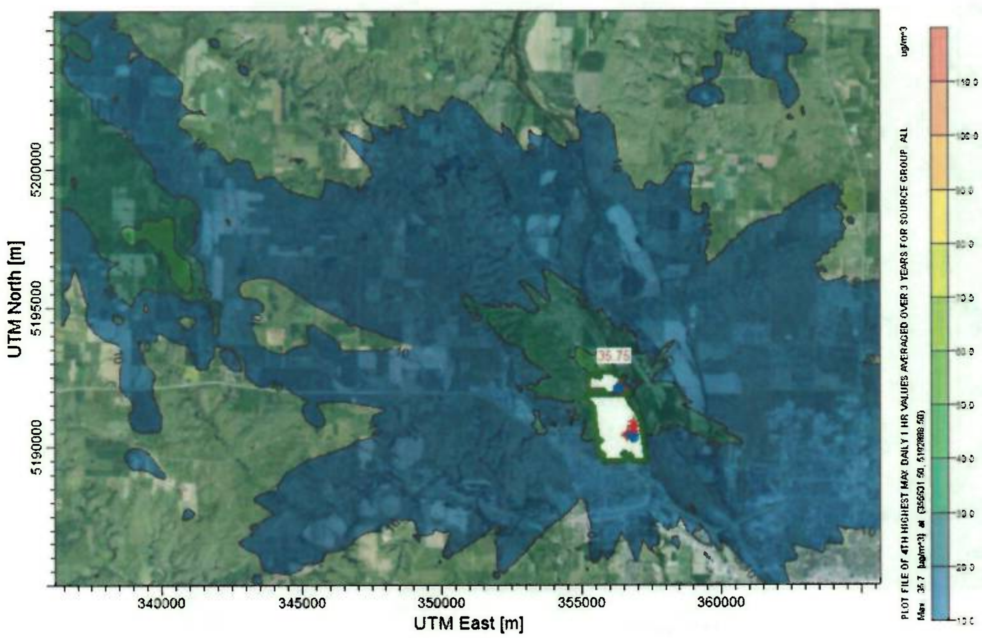


Figure 4-5: Q-Q Plot paired by Receptor of Predicted 3-year Averaged 99th Percentile Peak Daily 1-hour SO_2 Concentrations with AERMET/AERMOD Default Options versus AERMET ADJ_U*/AERMOD Default Options.

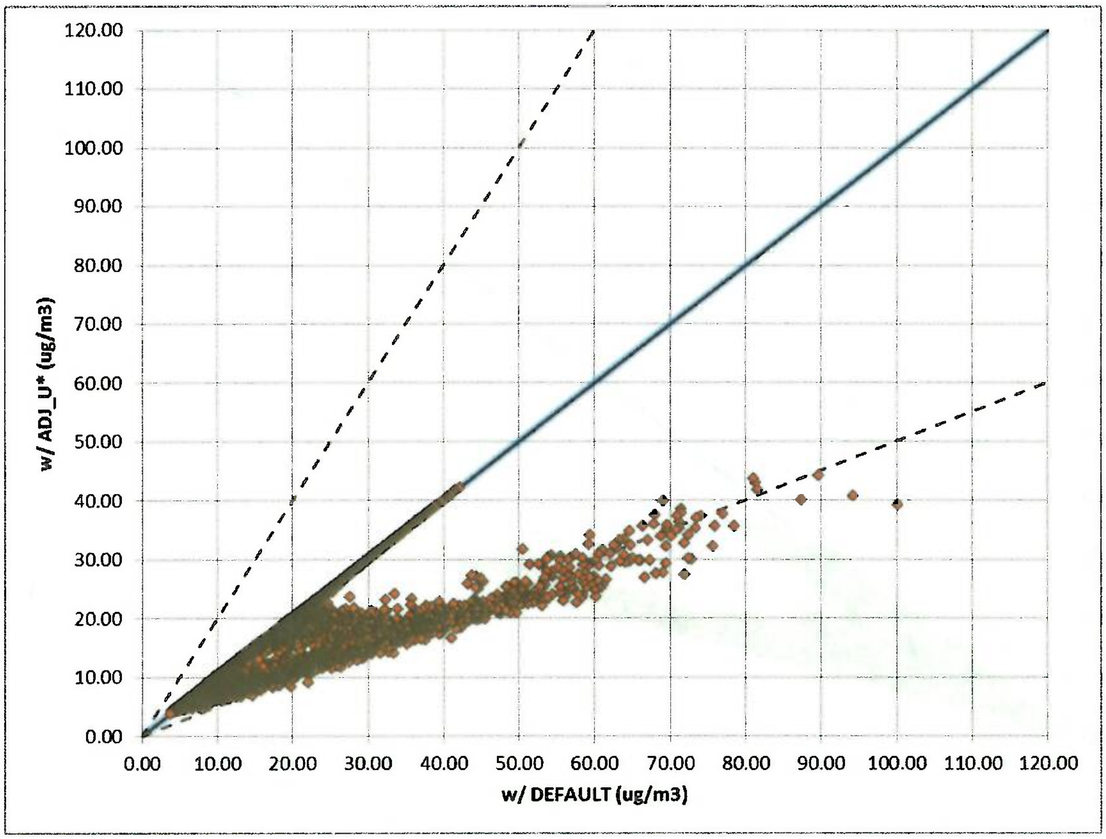


Figure 4-6: Q-Q Plot paired by Receptor of Predicted 3-year Averaged 99th Percentile Peak Daily 1-hour SO_2 Concentrations with AERMET/AERMOD Default Options versus AERMET ADJ_U*/AERMOD LOWWIND3 Options.

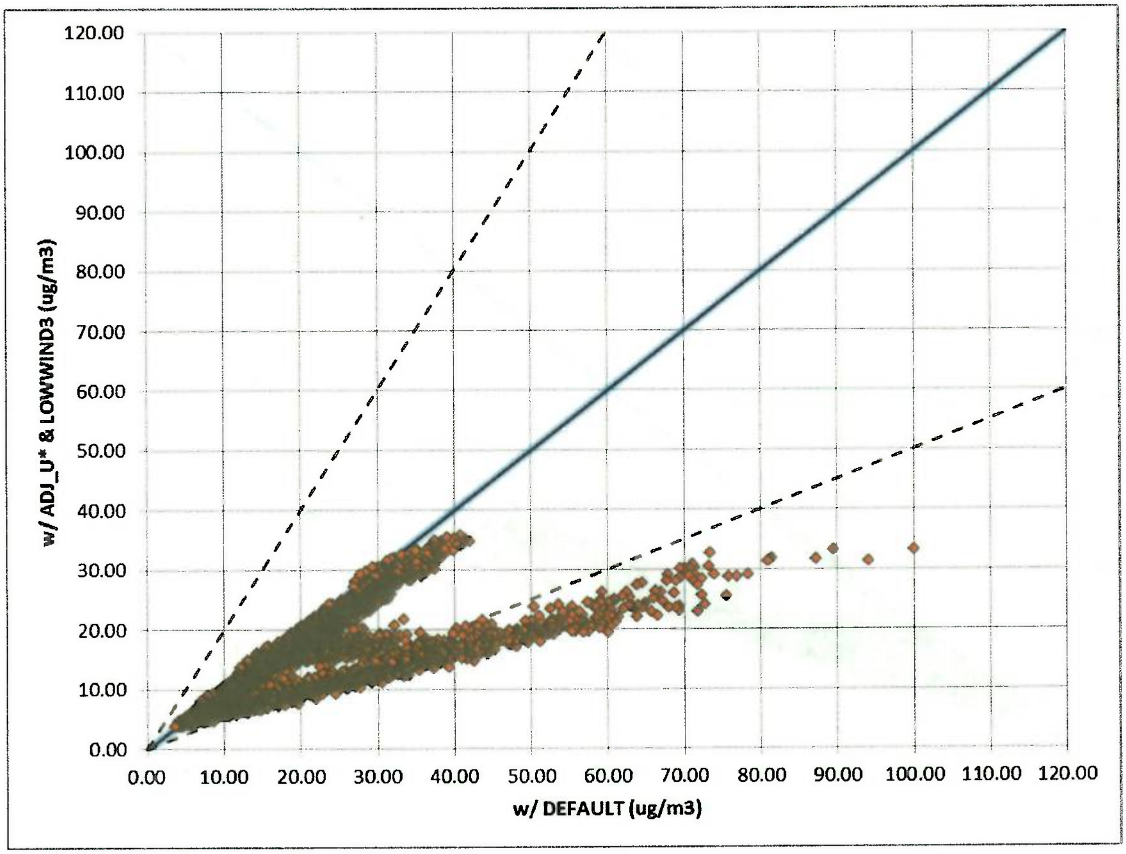


Table 4-2: 4th Highest Daily Peak 1-hour SO_2 Concentrations ($\mu g/m^3$) of the Top Ten 3-Year Averages for v15181 AERMET/AERMOD Default Options.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Year	4th-highest Max. Daily 1-hour Concentration (ug/m3)	U* (m/s)	Hour of Day	Wind Speed (m/s)	Monin-Obukhov Length (m)
1st Highest	340931.50	5196088.50	2013	120.4	0.038	8	1.23	2.8
			2014	100.7	0.061	22	2.21	4.3
			2015	79.5	0.026	3	0.96	1.9
2nd Highest	340431.50	5196588.50	2013	118.9	0.038	8	1.23	2.8
			2014	88.3	0.039	20	1.28	3.0
			2015	75.6	0.050	23	1.64	3.9
3rd Highest	340931.50	5196588.50	2013	100.1	0.028	24	1.01	2.0
			2014	96.0	0.035	1	1.06	2.8
			2015	73.2	0.029	5	0.94	2.2
4th Highest	340431.50	5196088.50	2013	108.1	0.039	1	1.28	3.1
			2014	77.5	0.044	9	1.59	3.1
			2015	76.7	0.065	7	2.38	4.6
5th Highest	339931.50	5197588.50	2013	76.8	0.045	23	1.48	3.5
			2014	73.4	0.033	7	1.20	2.4
			2015	94.6	0.066	23	2.15	4.9
6th Highest	340931.50	5195588.50	2013	72.1	0.049	1	1.60	3.7
			2014	96.9	0.067	7	2.17	5.1
			2015	75.0	0.026	3	0.96	1.9
7th Highest	340431.50	5197588.50	2013	86.9	0.037	24	1.21	3.9
			2014	75.8	0.020	3	0.65	1.5
			2015	80.5	0.029	5	0.94	2.2
8th Highest	338431.50	5197588.50	2013	83.2	0.055	2	2.01	5.4
			2014	79.1	0.032	23	1.03	2.4
			2015	73.4	0.063	18	2.28	4.7
9th Highest	338431.50	5198088.50	2013	73.4	0.045	23	1.48	3.5
			2014	68.7	0.039	20	1.28	3.0
			2015	89.1	0.066	23	2.15	4.9
10th Highest	338931.50	5199588.50	2013	87.2	0.048	20	1.76	3.5
			2014	63.5	0.040	5	1.30	3.0
			2015	77.1	0.041	23	1.48	4.1

Table 4-3: 4th Highest Daily Peak 1-hour SO_2 Concentrations (µg/m³) of the Top Ten 3-Year Averages for v15181 AERMET ADJ_U*/AERMOD Default Options.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Year	4th-highest Max. Daily 1-hour Concentration (ug/m3)	U* (m/s)	Hour of Day	Wind Speed (m/s)	Monin-Obukhov Length (m)
1st Highest	340931.50	5196588.50	2013	56.9	0.093	6	1.69	12.9
			2014	42.3	0.092	20	1.28	16.8
			2015	33.1	0.085	18	1.16	17.1
2nd Highest	340431.50	5197588.50	2013	46.9	0.094	24	1.48	14.9
			2014	39.4	0.128	8	2.28	18.3
			2015	44.9	0.092	8	1.67	12.9
3rd Highest	340931.50	5195588.50	2013	35.3	0.093	1	1.60	13.6
			2014	50.8	0.094	21	1.59	13.7
			2015	42.8	0.078	10	1.33	13.8
4th Highest	355531.50	5192788.50	2013	33.6	0.466	12	6.36	-75.8
			2014	74.7	0.120	13	1.37	-1.9
			2015	18.1	0.433	17	5.79	-48.8
5th Highest	339931.50	5197588.50	2013	46.5	0.099	2	2.01	12.7
			2014	35.0	0.046	10	0.84	14.3
			2015	43.9	0.119	23	2.15	16.4
6th Highest	355431.50	5192888.50	2013	34.1	0.466	12	6.36	-75.8
			2014	73.5	0.120	13	1.37	-1.9
			2015	17.5	0.332	17	4.19	-20.7
7th Highest	355431.50	5192788.50	2013	33.1	0.124	9	1.11	-1.9
			2014	74.4	0.120	13	1.37	-1.9
			2015	16.7	0.332	17	4.19	-20.7
8th Highest	355631.50	5192688.50	2013	32.9	0.150	12	1.76	-2.3
			2014	74.2	0.120	13	1.37	-1.9
			2015	17.1	0.474	16	5.95	-34.6
9th Highest	355631.50	5192788.50	2013	35.1	0.124	9	1.11	-1.9
			2014	70.8	0.129	10	1.48	-1.9
			2015	17.6	0.372	10	4.75	-24.2
10th Highest	355331.50	5192888.50	2013	33.8	0.150	12	1.76	-2.3
			2014	73.1	0.120	13	1.37	-1.9
			2015	16.0	0.383	11	6.16	-140.0

Table 4-4: 4th Highest Daily Peak 1-hour SO_2 Concentrations ($\mu g/m^3$) of the Top Ten 3-Year Averages for v15181 AERMET ADJ_U*/AERMOD LOWWIND3 Options.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Year	4th-highest Max. Daily 1-hour Concentration (ug/m3)	U* (m/s)	Hour of Day	Wind Speed (m/s)	Monin-Obukhov Length (m)
			2013	33.1	0.136	10	1.64	-2.8
1st Highest	355531.50	5192888.50	2014	58.5	0.120	13	1.37	-1.9
			2015	15.7	0.450	13	5.80	-27.3
			2013	33.9	0.124	9	1.11	-1.9
2nd Highest	355331.50	5193088.50	2014	57.1	0.113	11	1.38	-3.1
			2015	15.1	0.433	17	5.79	-48.8
			2013	33.3	0.466	12	6.36	-75.8
3rd Highest	355431.50	5192988.50	2014	57.6	0.113	11	1.38	-3.1
			2015	15.0	0.459	19	6.13	-113.9
			2013	32.2	0.466	12	6.36	-75.8
4th Highest	355331.50	5192988.50	2014	57.9	0.120	13	1.37	-1.9
			2015	15.3	0.501	13	6.29	-34.1
			2013	30.0	0.316	14	3.69	-14.5
5th Highest	355631.50	5192688.50	2014	60.3	0.120	13	1.37	-1.9
			2015	15.1	0.543	13	6.13	-42.6
			2013	31.0	0.124	9	1.11	-1.9
6th Highest	355431.50	5192888.50	2014	59.6	0.120	13	1.37	-1.9
			2015	14.7	0.332	17	4.19	-20.7
			2013	32.4	0.466	12	6.36	-75.8
7th Highest	355731.50	5192688.50	2014	57.7	0.120	13	1.37	-1.9
			2015	14.9	0.445	14	5.44	-23.9
			2013	30.8	0.382	12	4.71	-27.0
8th Highest	355631.50	5192788.50	2014	59.0	0.120	13	1.37	-1.9
			2015	15.2	0.433	17	5.79	-48.8
			2013	34.0	0.136	10	1.64	-2.8
9th Highest	355731.50	5192788.50	2014	54.9	0.148	11	1.72	-2.2
			2015	15.7	0.372	10	4.75	-24.2
			2013	33.4	0.135	9	1.42	-3.9
10th Highest	355631.50	5192888.50	2014	55.5	0.148	11	1.72	-2.2
			2015	15.4	0.372	10	4.75	-24.2

Table 4-5: Comparison of Predicted Concentrations with default options versus with ADJ_U* at receptors with the Top Ten 3-Year Averages 4th –Highest Maximum Daily 1-Hour Concentrations for AERMET/AERMOD Default Options.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Elevation (m)	3-Year Average Concentration AERMET w/ Default (ug/m3)	3-Year Average Concentration AERMET w/ ADJ_U* (ug/m3)	Percent Change (%)	AERMET w/ Default Avg. u* (m/s)	AERMET w/ ADJ_U* Avg. u* (m/s)
1st Highest	340931.50	5196088.50	656.35	100.2	39.2	-61%	0.042	0.092
2nd Highest	340431.50	5196588.50	657.88	94.3	40.8	-57%	0.042	0.097
3rd Highest	340931.50	5196588.50	678.73	89.7	44.1	-51%	0.031	0.090
4th Highest	340431.50	5196088.50	659.19	87.4	40.1	-54%	0.049	0.103
5th Highest	339931.50	5197588.50	664.56	81.6	41.8	-49%	0.048	0.088
6th Highest	340931.50	5195588.50	653.28	81.3	43.0	-47%	0.047	0.088
7th Highest	340431.50	5197588.50	674.69	81.1	43.7	-46%	0.029	0.105
8th Highest	338431.50	5197588.50	659.98	78.5	35.6	-55%	0.050	0.093
9th Highest	338431.50	5198088.50	663.59	77.1	37.7	-51%	0.050	0.088
10th Highest	338931.50	5199588.50	675.00	75.9	35.6	-53%	0.043	0.074

Table 4-6: Comparison of Predicted Concentrations with default options versus with ADJ_U* at receptors with the Top Ten 3-Year Averages 4th –Highest Maximum Daily 1-Hour Concentrations for AERMET ADJ_U*/AERMOD Default Options.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Elevation (m)	3-Year Average Concentration AERMET w/ Default (ug/m3)	3-Year Average Concentration AERMET w/ ADJ_U* (ug/m3)	Percent Change (%)	AERMET w/ Default Avg. u* (m/s)	AERMET w/ ADJ_U* Avg. u* (m/s)
1st Highest	340931.50	5196588.50	678.73	89.7	44.1	-51%	0.031	0.090
2nd Highest	340431.50	5197588.50	674.69	81.1	43.7	-46%	0.029	0.105
3rd Highest	340931.50	5195588.50	653.28	81.3	43.0	-47%	0.047	0.088
4th Highest	355531.50	5192788.50	514.43	42.1	42.1	0%	0.340	0.340
5th Highest	339931.50	5197588.50	664.56	81.6	41.8	-49%	0.048	0.088
6th Highest	355431.50	5192888.50	516.09	41.7	41.7	0%	0.306	0.306
7th Highest	355431.50	5192788.50	518.90	41.4	41.4	0%	0.192	0.192
8th Highest	355631.50	5192688.50	512.31	41.4	41.4	0%	0.248	0.248
9th Highest	355631.50	5192788.50	509.28	41.2	41.2	0%	0.208	0.208
10th Highest	355331.50	5192888.50	519.27	41.0	41.0	0%	0.218	0.218

Table 4-7: Comparison of Predicted Concentrations with default options versus with ADJ_U* and LOWWIND3 at receptors with the Top Ten 3-Year Averages 4th –Highest Maximum Daily 1-Hour Concentrations for AERMET/AERMOD Default Options.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Elevation (m)	3-Year Average Concentration AERMET w/ Default (ug/m3)	3-Year Average Concentration AERMET w/ ADJ_U* + LOWWIND3 (ug/m3)	Percent Change (%)	AERMET w/ Default Avg. u* (m/s)	AERMET w/ ADJ_U* + LOWWIND3 Avg. u* (m/s)
1st Highest	340931.50	5196088.50	656.35	100.2	33.3	-67%	0.042	0.108
2nd Highest	340431.50	5196588.50	657.88	94.3	31.4	-67%	0.042	0.084
3rd Highest	340931.50	5196588.50	678.73	89.7	33.2	-63%	0.031	0.082
4th Highest	340431.50	5196088.50	659.19	87.4	31.7	-64%	0.049	0.093
5th Highest	339931.50	5197588.50	664.56	81.6	31.9	-61%	0.048	0.094
6th Highest	340931.50	5195588.50	653.28	81.3	31.5	-61%	0.047	0.089
7th Highest	340431.50	5197588.50	674.69	81.1	31.4	-61%	0.029	0.078
8th Highest	338431.50	5197588.50	659.98	78.5	29.1	-63%	0.050	0.097
9th Highest	338431.50	5198088.50	663.59	77.1	28.7	-63%	0.050	0.094
10th Highest	338931.50	5199588.50	675.00	75.9	28.7	-62%	0.043	0.098

Table 4-8: Comparison of Predicted Concentrations with default options versus with ADJ_U* at receptors with the Top Ten 3-Year Averages 4th –Highest Maximum Daily 1-Hour Concentrations for AERMET ADJ_U*/AERMOD LOWWIND3 Options.

Rank	UTM-14N [NAD-83] East (m)	UTM-14N [NAD-83] North (m)	Elevation (m)	3-Year Average Concentration AERMET w/ Default (ug/m3)	3-Year Average Concentration AERMET w/ ADJ_U* + LOWWIND3 (ug/m3)	Percent Change (%)	AERMET w/ Default Avg. u* (m/s)	AERMET w/ ADJ_U* + LOWWIND3 Avg. u* (m/s)
1st Highest	355531.50	5192888.50	510.48	40.9	35.7	-13%	0.349	0.235
2nd Highest	355331.50	5193088.50	514.80	39.2	35.4	-10%	0.236	0.223
3rd Highest	355431.50	5192988.50	511.85	40.1	35.3	-12%	0.239	0.346
4th Highest	355331.50	5192988.50	518.45	40.6	35.2	-13%	0.323	0.362
5th Highest	355631.50	5192688.50	512.31	41.4	35.1	-15%	0.248	0.326
6th Highest	355431.50	5192888.50	516.09	41.7	35.1	-16%	0.306	0.192
7th Highest	355731.50	5192688.50	509.36	39.7	35.0	-12%	0.347	0.344
8th Highest	355631.50	5192788.50	509.28	41.2	35.0	-15%	0.208	0.312
9th Highest	355731.50	5192788.50	508.28	37.6	34.8	-7%	0.342	0.219
10th Highest	355631.50	5192888.50	506.92	38.4	34.8	-9%	0.212	0.218

Figure 4-7: Locations of Receptors for the Top Ten 99th Percentile 3-year Averaged Daily Peak 1-hour SO_2 Concentrations Using AERMET/AERMOD Default Options.

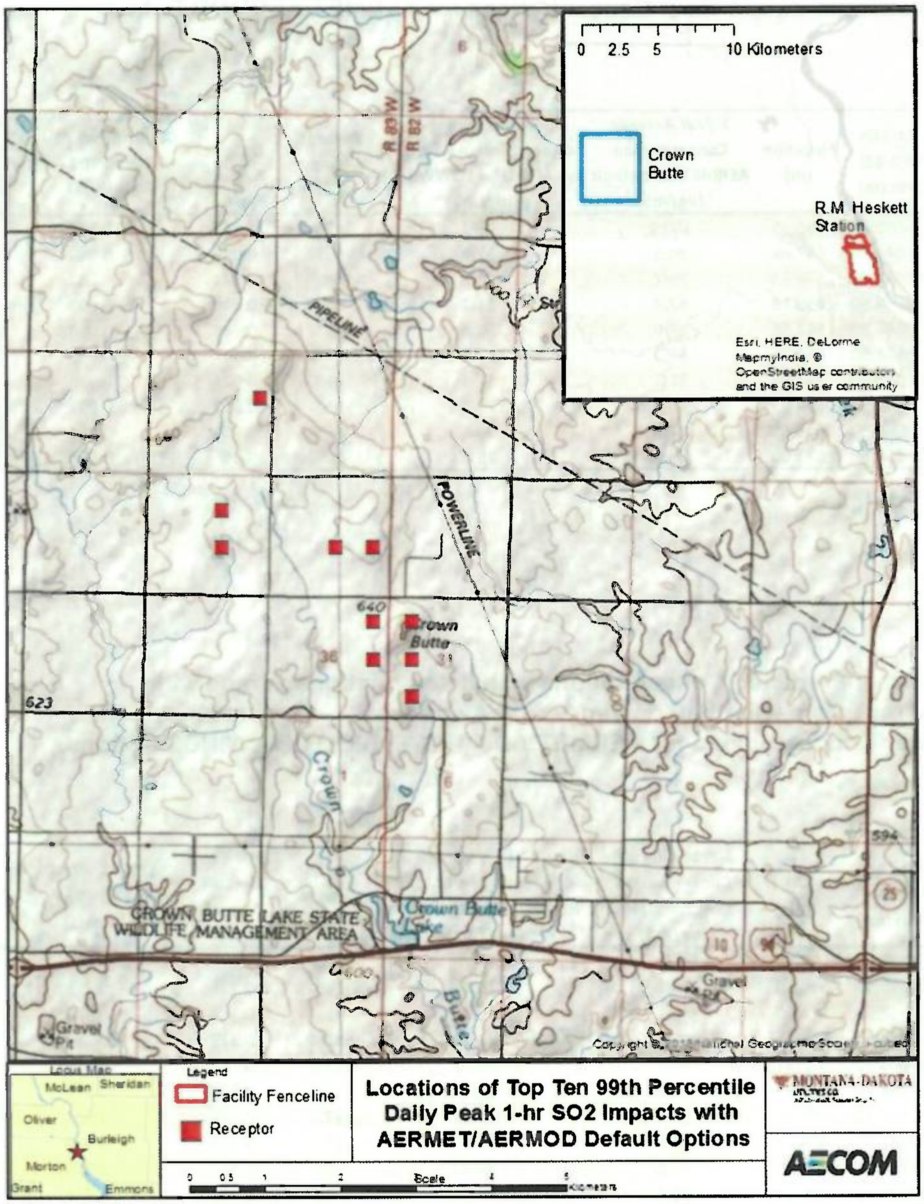


Figure 4-8: Locations of Receptors for the Top Ten 99th Percentile 3-year Averaged Daily Peak 1-hour SO_2 Concentrations Using AERMET ADJ_U*/AERMOD Default Options.

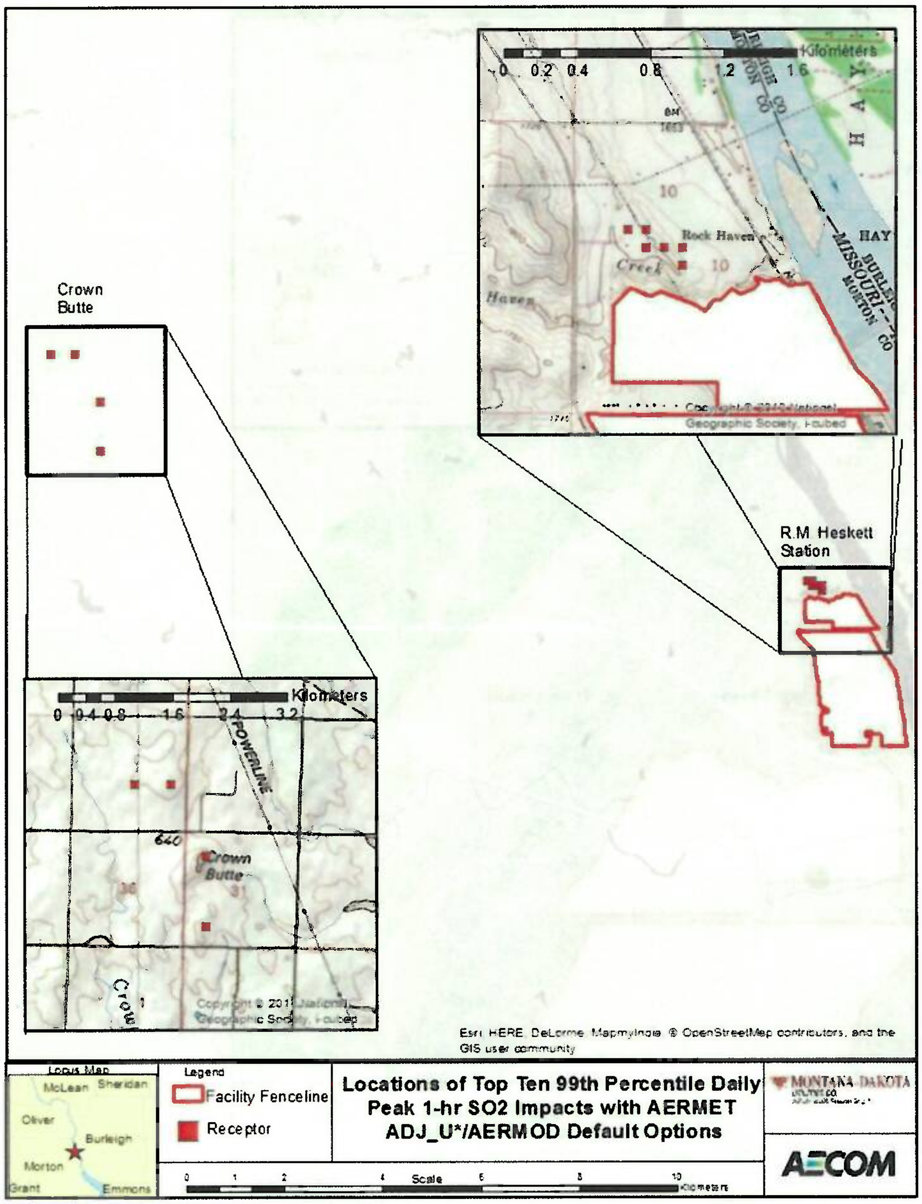
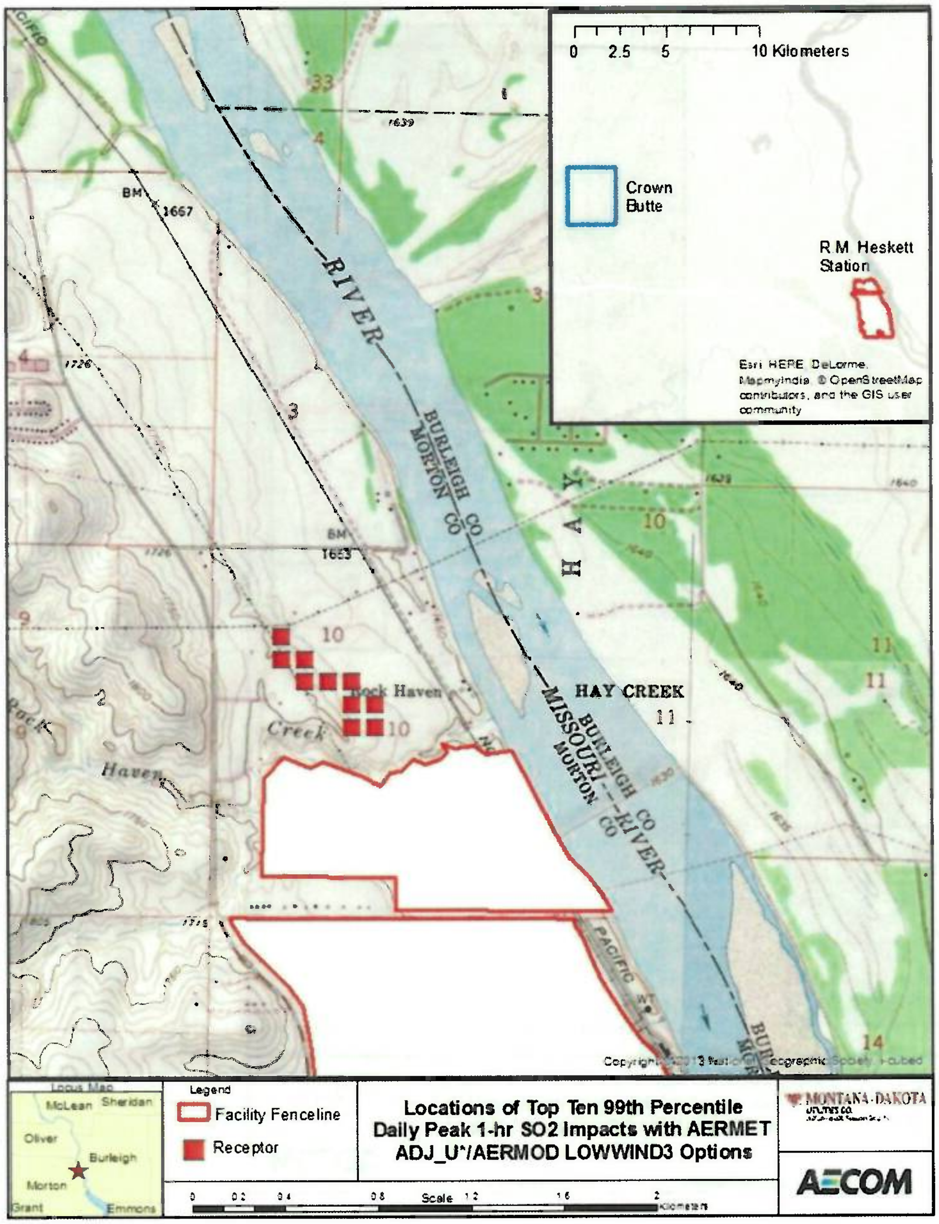


Figure 4-9: Locations of Receptors for the Top Ten 99th Percentile 3-year Averaged Daily Peak 1-hour SO_2 Concentrations Using AERMET ADJ_U*/AERMOD LOWWIND3 Options.



4.4 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 4-9** and graphically plotted in **Figure 4-10**. These charts indicate that at all the sites; the model-predicted values are higher than the observed. The overall results indicate the following:

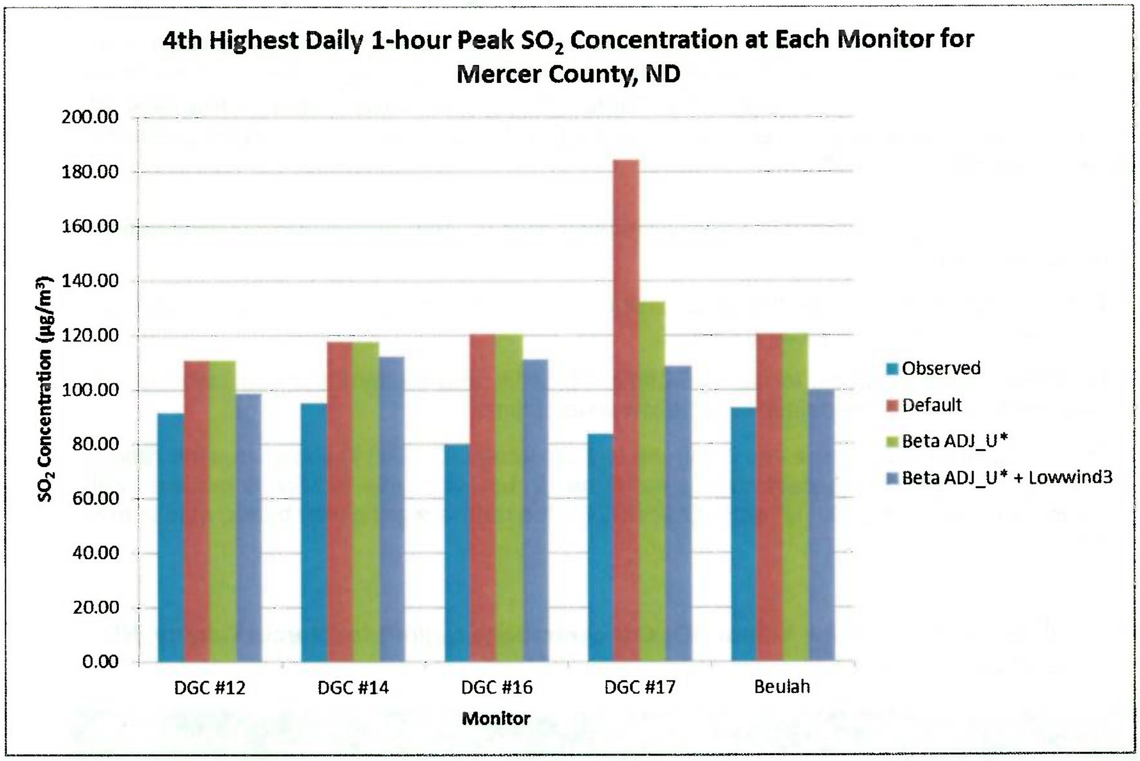
- The highest design concentration from all monitor sites for both default and low wind options are higher than observed.
- The AERMOD v15181 default highest design concentration from all monitor sites is greater than the ones using the low wind options.
- For the monitors in simple terrain (DGC#12, 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 4-9: 4th Highest Daily Peak 1-hour SO_2 Concentrations ($\mu g/m^3$) 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 $\mu g/m^3$ added to model-predicted concentrations.

Figure 4-10: Histogram of the 4th Highest Daily Peak 1-hour SO_2 Concentrations from Mercer County, ND Evaluation Study



5.0 Evaluation Comparison Conclusions

A model evaluation of AERMOD's low wind options was conducted in order to demonstrate an "apples-to-apples" comparison between R.M. Heskett Station and Mercer County North Dakota evaluation database for 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 R.M. Heskett Station show very similar behavioral patterns 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 kilometers away from the source.
- The peak impacts for AERMOD default options occurred in stable, light wind conditions, which are the conditions that 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 Mercer County, ND and R.M. Heskett cases.
- When the low wind options are used, the concentrations are more homogeneous between the flat terrain and high terrain areas for R.M. Heskett, as was observed in the Mercer County, ND database.

Receptors in the flat terrain showed that the use of the beta ADJ_U* option in AERMET in conjunction with AERMOD default options had no effect on the predicted concentrations for the evaluation studies R.M. Heskett Station, Mercer County North Dakota, and EPA's April 29, 2016 memo. 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 R.M. Heskett Station.

This discussion of terrain setting and source similarities, in addition to a model sensitivity comparison approach (as requested by EPA) is provided to EPA as documentation in support of the request to use AERMET/AERMOD ADJ_U* low wind option for use in 1-hour SO_2 DRR modeling of R.M. Heskett Station. The documentation also includes a discussion of the LOWWIND3 option for informational purposes.

The R.M. Heskett Station submittal indicates that the regulatory default options in AERMET version 15181 and AERMOD version 15181 lead to controlling concentrations at receptors on Crown Butte at elevations from 656 meters to 678 meters. These concentrations consistently occur during low-wind speed and stable boundary conditions. **Figure 4-5** of the submittal indicates that default u* values are very low (0.03 m/s to 0.05 m/s) for hours during which concentrations at the top ten receptors in the default modeling are highest. At those receptor locations, using the ADJ_U* option increases 3-year average default u* values by 100% to 133% (to 0.07 m/s to 0.10 m/s). As a result of the increase in default u* from the use of the ADJ_U* option, 3-year average 4^{th} highest concentrations at these receptors decreased by 46% to 61%, from 75.9 μg/m³ to 100.2 μg/m³ to 35.6 μg/m³ to 44.1 μg/m³).

The use of the ADJ_U* options shifted the majority of the controlling concentrations from the more remote ten receptors at Crown Butte to a cluster of six receptors within 1 kilometer of R.M. Heskett Station (see **Table 4-6** and **Figure 4-8**). At these receptors, there were insignificant changes in default u* values and relevant concentration values between the regulatory default and alternative modeling configuration. This indicates that stable low wind speed conditions are not controlling at these receptors. For these six receptors, the 3-year average default u* values range from 0.03 m/s to 0.34 m/s for peak concentrations, which range from 41.0 µg/m³ to 42.1 µg/m³.

The analysis in the R.M. Heskett submittal indicates that the ADJ_U* option only has significant effects in the modeling domain at receptors with elevations at or above the height of release. Specifically, the analysis of the top ten 4th highest 3-year averaged predicted concentrations showed that stable conditions with low wind speeds are the controlling meteorological conditions for receptors with elevations above 656 meters, and that concentrations at these receptors are often lower by more than 46% under the ADJ_U* formulation than under the regulatory default formulation. For the top ten 4th highest 3-year average receptors below 656 meters, in the analysis, there is little to no change in concentration, indicating that stable conditions with low wind speeds are not controlling at elevations below the release height.

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

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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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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

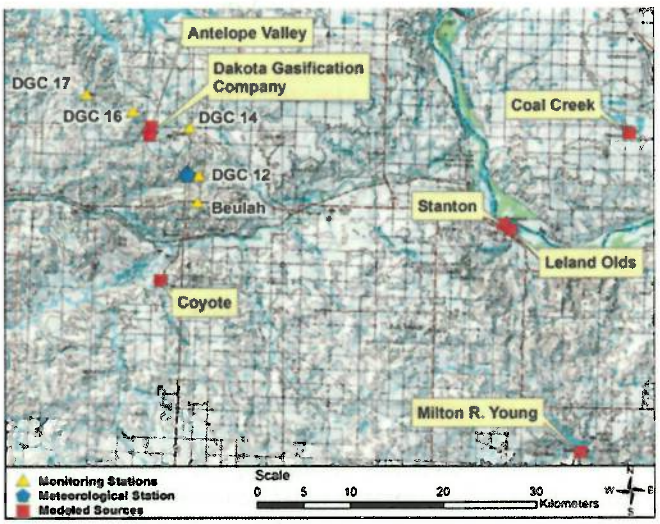

Figure 1. Map of North Dakota model evaluation layout.

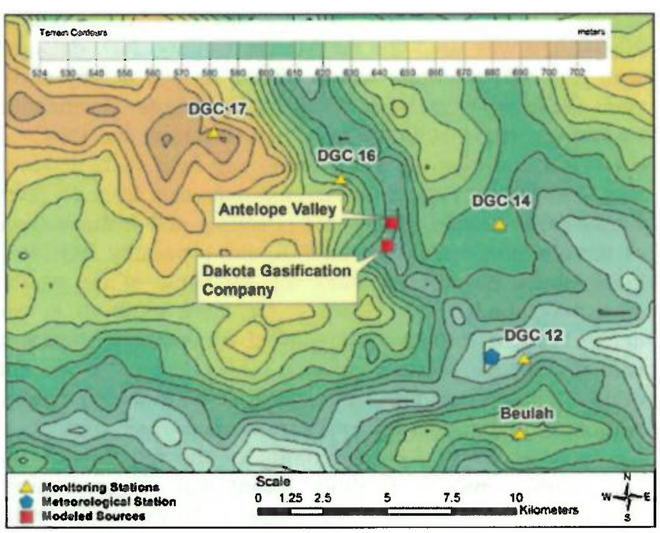

Figure 2. Terrain around the North Dakota monitors.

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

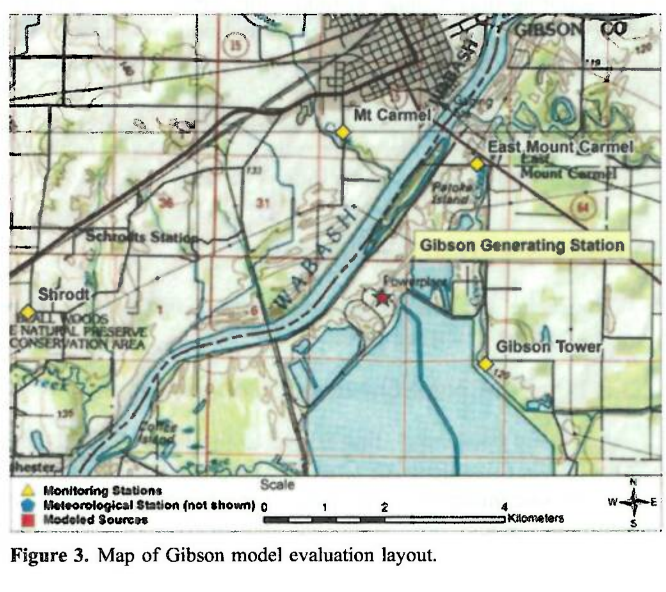

Figure 3. Map of Gibson model evaluation layout.

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 $\mu g/m^3$ 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 10$\mu g/m^3$) 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:

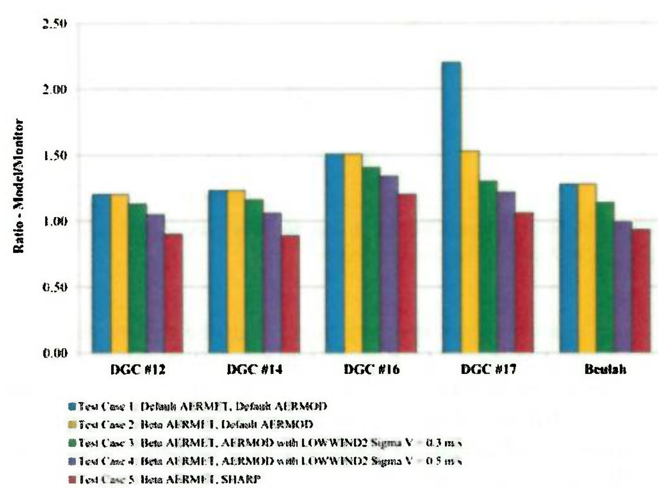

Figure 4. North Dakota ratio of monitored to modeled design concentration values at specific monitors.

- 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

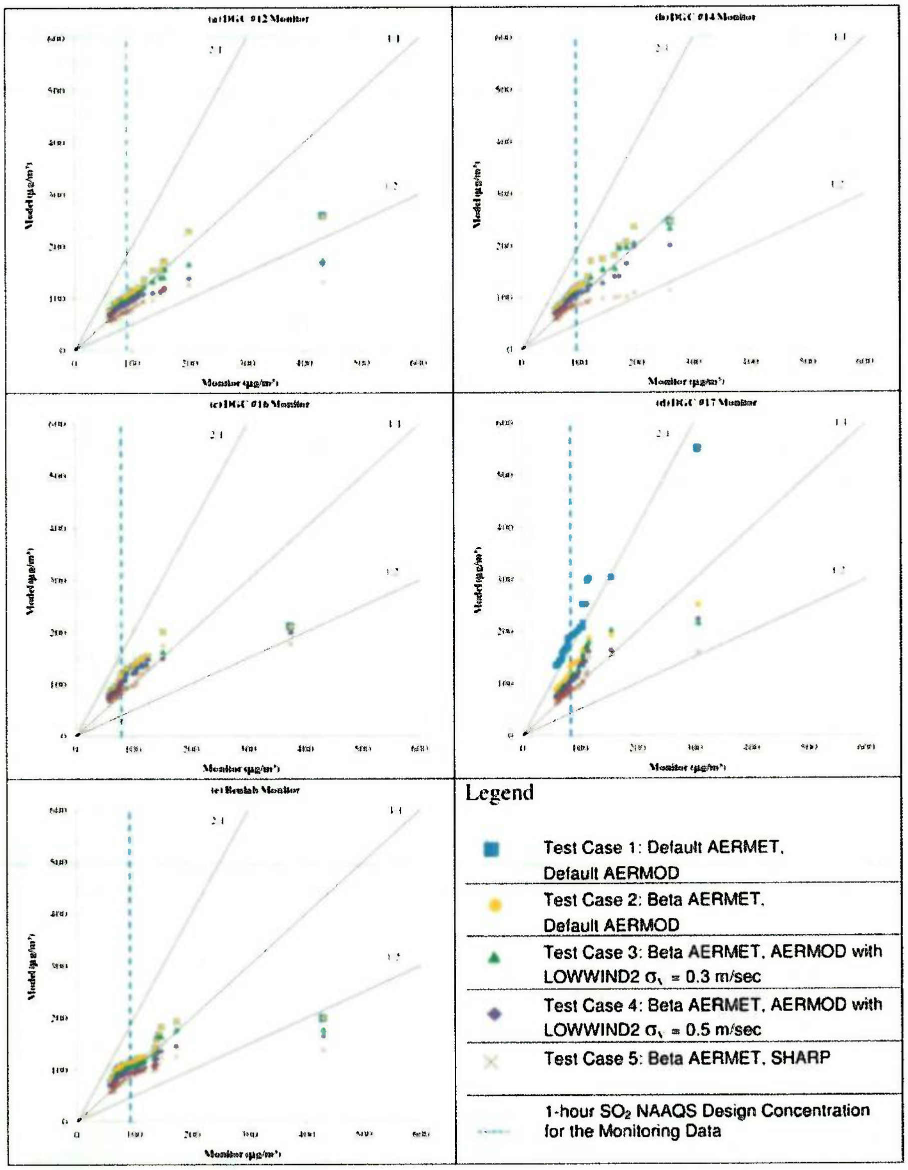

Figure 5. North Dakota Q-Q plots: top 50 daily maximum 1-hr SO_2 concentrations: (a) DGC #12 Monitor. (b) DGC#14 monitor. (c) DGC#16 monitor. (d) DGC#17 monitor. (e) Beulah monitor.

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.

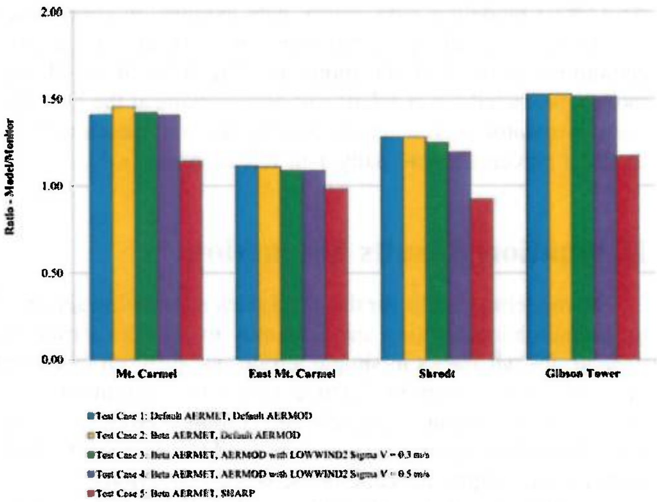

Figure 6. Gibson ratio of monitored to modeled design concentration values at specific monitors.

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.

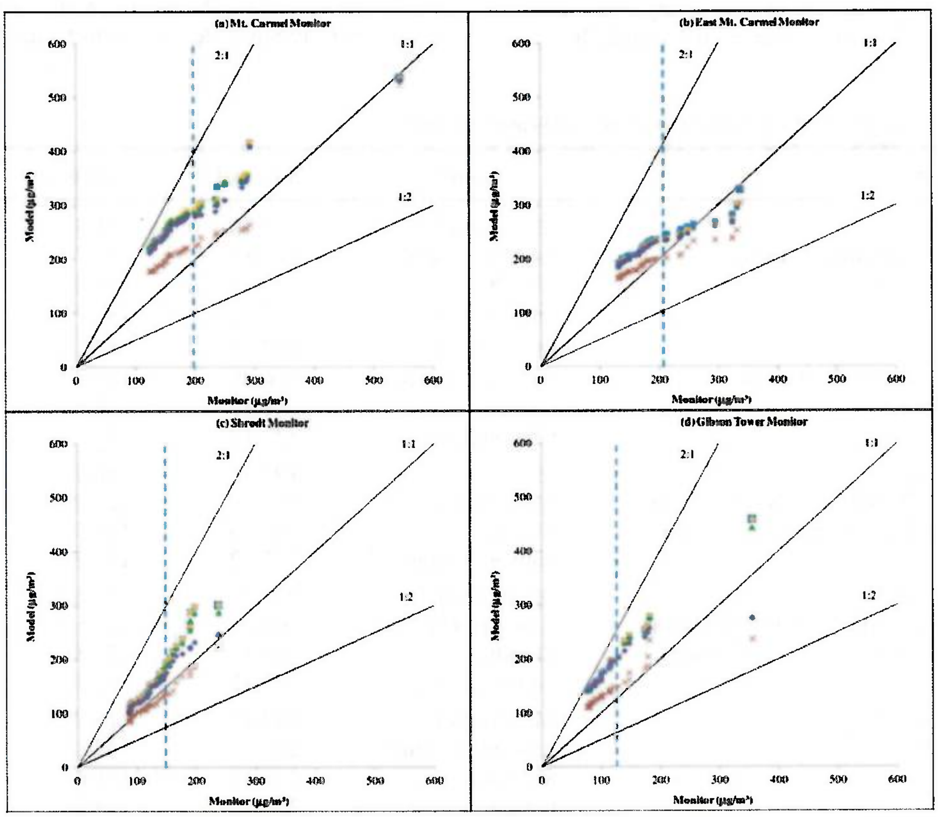

Figure 7. Gibson Q-Q plots: top 50 daily maximum 1-hour SO_2 concentrations. (a) Mt. Carmel monitor. (b) East Mt. Carmel monitor. (c) Shrodt monitor. (d) Gibson tower monitor. For the legend, see Figure 5.

- 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

Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases with AERMOD LOWWIND3 Option

(Manuscript submitted for publication to the Journal of the Air & Waste Management Association, revised May 6, 2016; authored by Robert Paine and Olga Samani)

Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases with AERMOD LOWWIND3 Option

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Abstract:

The analysis documented in this paper addresses evaluations of the two field study databases using a new AERMOD modeling option ("LOWWIND3") for low wind conditions made available by the United States Environmental Protection Agency (EPA) in July 2015. These results are provided to supplement our published (Paine et al., 2015) evaluation results in the Journal of the Air & Waste Management Association (JA&WMA) using the previous AERMOD low wind option ("LOWWIND2").

AERMOD was tested on the same two field study databases as before, involving tall stacks, several SO2 monitors, and hourly emissions data. Several technical options were tested, including 1) a default mode with no low wind treatment for both AERMET (the meteorological pre-processor) and AERMOD (the dispersion model), and 2) AERMET with a low wind adjustment for computing the friction velocity (u*) and other planetary boundary layer parameters more accurately in low wind speed conditions ("ADJ_U*" option). In addition, the new tests reported here also involve the use of the AERMOD dispersion model with the updated low wind ("LOWWIND3") option that provides a higher minimum value for the standard deviation of the lateral wind speed component (sigma-v) than the default option provides.

The newly available LOWWIND3 option shows results within 10% of those

	for the LOWWIND2 option, with slightly reduced over-predictions for both databases. As such, these evaluations indicate that use of the ADJ_U* with the LOWWIND3 option provides nearly equivalent, but slightly improved, AERMOD model performance among the options tested, while retaining a slight over-prediction bias for these two databases.

Implications

AERMOD evaluations for two tall stack databases in areas of both flat and elevated terrain were updated using the EPA-proposed low wind options for AERMOD (ADJ_U* and LOWWIND3). AERMOD runs with the low wind options showed improvement in model performance (especially in higher terrain areas) over the default options, helping to reduce some of the over-prediction biases currently present in regulatory default AERMOD while retaining a slight over-prediction bias. The LOWWIND3 results are generally within 10% of the LOWWIND2 results previously reported by Paine et al. (2015), indicating a nearly equivalent outcome while showing a slightly lower over-prediction tendency.

Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases with AERMOD LOWWIND3 Option

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Abstract

The analysis documented in this paper addresses evaluations of the two field study databases using a new AERMOD modeling option ("LOWWIND3") for low wind conditions made available by the United States Environmental Protection Agency (EPA) in July 2015. These results are provided to supplement our published (Paine et al., 2015) evaluation results in the Journal of the Air & Waste Management Association (JA&WMA) using the previous AERMOD low wind option ("LOWWIND2").

AERMOD was tested on the same two field study databases as before, involving tall stacks, several SO_2 monitors, and hourly emissions data. Several technical options were tested, including 1) a default mode with no low wind treatment for both AERMET (the meteorological pre-processor) and AERMOD (the dispersion model), and 2) AERMET with a low wind adjustment for computing the friction velocity (u*) and other planetary boundary layer parameters more accurately in low wind speed conditions ("ADJ_U*" option). In addition, the new tests reported here also involve the use of the AERMOD dispersion model with the updated low wind ("LOWWIND3") option that provides a higher minimum value for the standard deviation of the lateral wind speed component (sigma-v) than the default option provides.

The newly available LOWWIND3 option shows results within 10% of those for the LOWWIND2 option, with slightly reduced over-predictions for both databases. As such, these evaluations indicate that use of the ADJ_U* with the LOWWIND3 option provides nearly equivalent, but slightly improved, AERMOD model performance among the options tested, while retaining a slight over-prediction bias for these two databases.

Introduction

In a proposed rulemaking published in the July 29, 2015 Federal Register EPA (2015a), the United States Environmental Protection Agency (EPA) released a revised version of AERMOD

(15181), which replaced AERMOD version 14134. Because AERMOD is used in the United States as well as several countries throughout the world, updates and refinements to this model proposed by the EPA are of widespread interest.

EPA proposed refinements to its preferred short-range model, AERMOD, involving the handling of low wind conditions. These refinements involve an adjustment to the computation of the friction velocity ("ADJ_U*") in the AERMET meteorological pre-processor and a higher minimum lateral wind speed standard deviation, sigma-v (σ_v), as incorporated into the new "LOWWIND3" option in the AERMOD dispersion model. These low wind AERMOD options continue to be regarded by EPA as experimental ("beta") options pending further evaluation and public comment.

Paine et al. (2015) described the evaluation of the combined ADJ_U* and LOWWIND2 options as implemented in AERMOD version 14134 on two tall-stack databases. The 2015 paper provides a comprehensive discussion of the field databases and evaluation testing. This update supplements the 2015 paper by comparing the performance of the model with EPA-proposed options (with LOWWIND3 in addition to LOWWIND2) based on the same two databases. In addition to the two databases evaluated here, Paine at al. (2016) have since evaluated the AERMOD low wind options at two other sites (Lovett and Clifty Creek), which supplements EPA evaluations (EPA, 2015b) of the same options on three separate databases.

Scientific Justification for AERMOD Low Wind Options

During low wind speed (LWS) conditions, the dispersion of pollutants is limited by diminished fresh air dilution. Paine et al. (2015) discuss challenges and modeling approaches for steady-state plume model formulation approaches that are summarized here. 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 the 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 EPA's preferred model, AERMOD (Cimorelli et al., 2005), is the standard deviation of the crosswind component, σ_v, which, in the absence of direct measurements, can be parameterized as being proportional to the friction velocity, u_* (Smedman, 1988; Mahrt, 1998). These investigators found that there was a minimum, non-zero value of σ_v that can be attributed to wind meandering over the course of a given hour. While at higher wind speeds, small-scale turbulence is the main source of variance, longer-scale sub-hourly lateral meandering motions appear to exist in all conditions. Hanna (1990) found that the hourly-averaged σ_v has a non-zero minimum value of about 0.5 ms^{-1} as the wind speed approaches zero. Chowdhury et al. (2014) noted that a minimum σ_v of 0.5 ms^{-1} is a part of the formulation for the advanced puff model SCICHEM. 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 hourly averaged horizontal wind component variances as noted by Hanna (1990) over all types of terrain. The use of a "floor" for the σ_v input to hourly steady-state plume models like AERMOD is important not only for parameterizations that could result in very low computed σ_v values, but also for measurement systems that have starting speeds above the minimum σ_v values for calm conditions noted above.

Thus, the simulation of pollutant dispersion in LWS conditions is challenging. These conditions are addressed by AERMOD in a unique manner. As stated 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)."

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 parameterized as being directly proportional to the magnitude of the friction velocity unless there are direct turbulence measurements. Therefore, the formulation of the friction velocity calculation and the specification of a minimum σ_v value were also considered by Paine et al. (2015). It is noted that the friction velocity also affects the internally-calculated vertical temperature gradient, which affects plume rise and plume-terrain interactions, and these are especially important in elevated terrain situations. The formulation of the friction velocity has been separately researched by Qian and Venkatram (2011). This research led to an adjustment of friction velocity computation in AERMET as proposed by EPA. However, this paper focuses upon an updated treatment in AERMOD of the specification of the minimum σ_v ("LOWWIND3") as well as how the meander weighted component is determined in AERMOD.

Paine et al. (2015) conducted an evaluation with two tall-stack databases with the AERMOD "LOWWIND2" option. Since that time, EPA proposed an updated "LOWWIND3" option. Both options are similar, but certain aspects of LOWWIND3 include additional changes that EPA has proposed. Both options adopt a minimum σ_v of 0.3 ms^{-1}, which is an increase from the current default value of 0.2 ms^{-1}, but still less than the above-referenced 0.5 ms^{-1}. The differences between LOWWIND2 and LOWWIND3 are as follows:

- The LOWWIND2 option reduced the time scale for the meander component from the original AERMOD formulation specification for 24 hours to 12 hours, but LOWWIND3 has restored the meander time scale to 24 hours.
- The LOWWIND3 option eliminated the computation of upwind concentrations that the meander component allowed under other options. This is more typical of the behavior of most steady-state Gaussian models.
- The LOWWIND3 option assumes a travel time to the model receptor as along the actual wind direction as opposed to directly toward the receptor, wherever it is located (which LOWWIND2 does). The LOWWIND3 treatment is also more consistent with typical steady-state plume model formulations.

In essence, the LOWWIND3 option has restored certain features of the original AERMOD formulation that were removed by the LOWWIND2 option, while improving other features of the model's treatment of dispersion under low wind conditions. However, since both LOWWIND2 and LOWWIND3 options limit the minimum σ_v value to 0.3 ms^{-1}, the differences in model predictions between the two model options is expected to be small.

Modeling Options and Databases for Testing

The field study databases, meteorological data, emissions, and receptors used in this analysis are identical to those used in the Paine et al. (2015) analysis. The field study databases include 1) Mercer County, a North Dakota database featuring five SO_2 monitors within 10 kilometers 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 kilometers of the Gibson Generating Station in southwest Indiana. Both sites feature regionally representative 10-meter meteorological databases, with no significant terrain obstacles between the meteorological site and the emission sources. Figure 1 and Figure 2 show a layout of the North Dakota and Gibson sources, monitors, and the meteorological station, respectively.

Figure 1.

Figure 2.

The test cases provided in this updated evaluation are listed below. Note that the results for Test Cases 1, 2, and 3 have already been reported by Paine et al. (2015).

Test Case 1: AERMET and AERMOD in default mode.

Test Case 2: ADJ_U* low wind beta option for AERMET and default option for AERMOD.

Test Case 3: ADJ_U* low wind beta option for AERMET and the LOWWIND2 option for AERMOD.

Test Case 4: ADJ_U* low wind beta option for AERMET and the LOWWIND3 option for AERMOD.

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

- They feature multiple years of hourly SO_2 monitoring at several sites.
- Emissions are predominantly from tall stack sources for which hourly continuous emission monitoring data is available.
- There is representative meteorological data from a single-level tower, such as is typical of airport-type data.

AERMOD was applied using hourly meteorological data to predict hourly concentrations at the location of the respective SO_2 monitors.

"Equivalence" Range for Modeling Results

When comparing the modeled and measured SO_2 concentrations, it is important to be aware that the monitored values have an up to 10% uncertainty in accordance with tolerance specified in the quality control checks and span checks of EPA air quality motoring procedures (EPA, 2013b). Therefore, it is appropriate to consider modeling results for the LOWWIND2 and LOWWIND3 evaluation tests that are within 10% of the monitoring values to be "equivalent."

North Dakota Database Model Evaluation Procedures and Results

AERMOD was run for the test cases listed above for the North Dakota databases to compute the 99th percentile of the daily 1-hour maximum concentration value averaged over four years ("design concentration") to match the statistical form of the United States ambient air quality standard. Model receptors were placed at the location of the five ambient monitors. A regional background of 10 $\mu g/m^3$ was added to the AERMOD model predictions, as determined from a review of rural monitors unaffected by local sources. This background concentration is small in comparison to modeled concentration and as such has little effect on the interpretation of the results.

A plot of the predicted-to-observed ratios for the North Dakota evaluation database is provided in Figure 3. The evaluation results for the four test cases indicate that the predicted-to-observed ratios are consistently greater than 1.0 and AERMOD consistently over-predicts with use of both the proposed ADJ_U* and the LOWWIND3 options. The results for the new model with the LOWWIND3 option (Test Case 4) are within 10% of the LOWWIND2 results (Test Case 3), indicating results that are essentially equivalent. However, the LOWWIND3 low wind option (Test Case 4) shows a lower degree of over-prediction relative to the default option (Test Case 1). The changes in the design concentration over the monitors range from 5 to 41%. Of particular note is the large improvement at the monitor in higher terrain (DGC #17), with a 41% reduction in the predicted-to-observed ratio. This improvement is primarily due to the effect of ADJ_U* with an additional improvement from LOWWIND3. Supplemental data (that can be accessed at the publisher's website) contains the tables and quantile-quantile plots of the top 50 (unpaired) predictions and observations for Test Case 1 and Test Case 4. Test Case 2 and Test Case 3 results were previously reported by Paine et al. (2015).

Figure 3

To understand the conditions during which the highest measured concentrations occurred, the top 25 observed hourly concentrations were reviewed. This indicated that majority of impacts at monitor DGC#12, DGC#14, and Beulah occurred during unstable conditions. The observed top 25 hourly concentrations at DGC#16 DGC#17 were evenly split between unstable and stable conditions. In comparison, the peak predicted concentrations with both the default and low wind options at DGC#12, DGC#14, DGC#16, and Beulah were all associated with unstable daytime conditions. For the high terrain monitor, DGC#17, AERMOD-predicted concentrations with the default options were due to mostly stable conditions, but with the low wind options, the controlling dispersion conditions had many more unstable hours.

Gibson Generating Station Database Model Evaluation Procedures and Results

AERMOD was also evaluated with the four test cases as described above to compute the design concentration at the four ambient monitors. A regional background of 18 $\mu g/m^3$ was added to the AERMOD modeled predictions, determined from monitors with of no plant impacts. The background concentration is a small fraction of the modeled concentration and has little effect on the results.

A plot of the predicted-to-observed ratios is provided Figure 4. The plot shows that these ratios are consistently greater than 1.0. The results for the new model with LOWWIND3 option (Test Case 4) are within 10% of the LOWWIND2 option (Test Case 3) and thus are essentially equivalent. As in the case of the Mercer County, North Dakota study, the EPA-proposed LOWWIND3 low wind option (Test Case 4) provided modest improvements, ranging from 1 to 9% in performance relative to the default option (Test Case 1) for Gibson, while consistently showing an over-prediction tendency at each monitor. Supplemental data (that can be accessed at the publisher's website contains the tables and quantile-quantile plots of the top 50 (unpaired) predictions and observations for Test Case 1 and Test Case 4. Test Case 2 and Test Case 3 results were already reported by Paine et al. (2015).

Figure 4

Our review of the top 25 hourly concentrations indicates that all of observed highest impacts at Shrodt and Gibson Tower monitors occurred during unstable conditions. The observed peak concentrations at Mt. Carmel include many stable condition hours, but at East Mt. Carmel are mostly due to unstable conditions. The conditions at which peak modeled concentrations were predicted with either default or low wind options are consistent with the observed conditions.

Conclusions

The model evaluation results for the new version of AERMOD (version 15181), using the two databases previously evaluated in Paine et al. (2015) that had used an older version of AERMOD, showed that the EPA-proposed low wind options (ADJ_U* and LOWWIND3) consistently perform better than the default option, while still over-predicting the 99th percentile daily 1-hour concentration, the statistical form of the United States 1-hour SO_2 ambient standard. The LOWWIND3 results are generally within 10% of the LOWWIND2 results previously reported by Paine et al. (2015), representing an essentially equivalent outcome. The present study also indicates that LOWWIND3 resulted in a slightly smaller over-prediction tendency than LOWWIND2.

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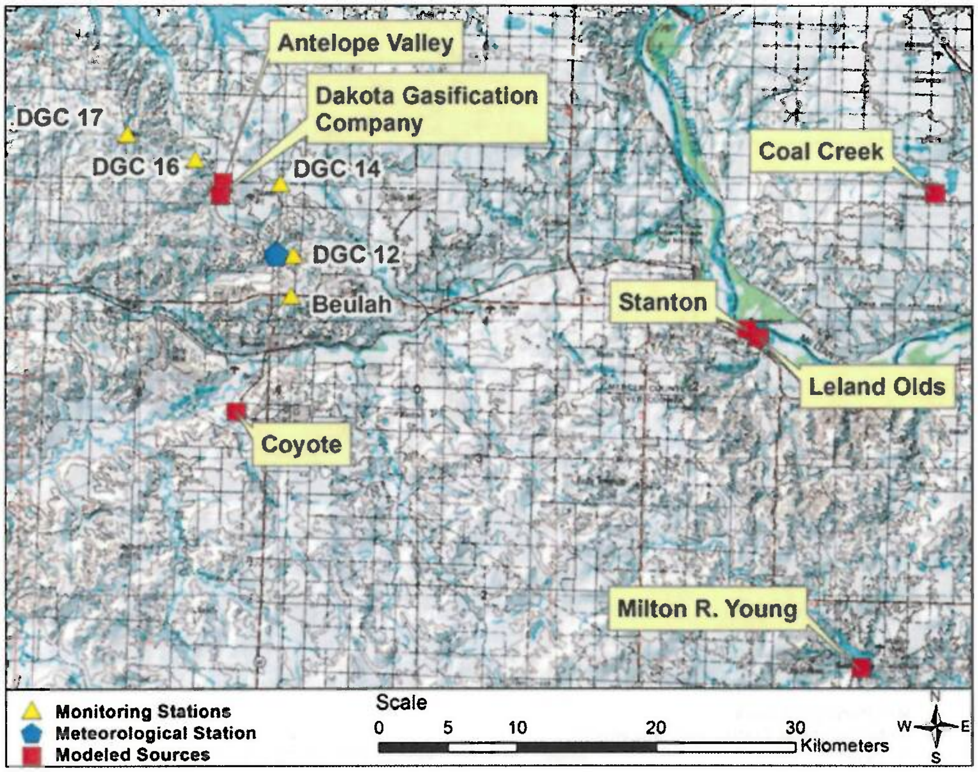


Figure 1. Map of North Dakota Model Evaluation Layout
63x50mm (300 x 300 DPI)

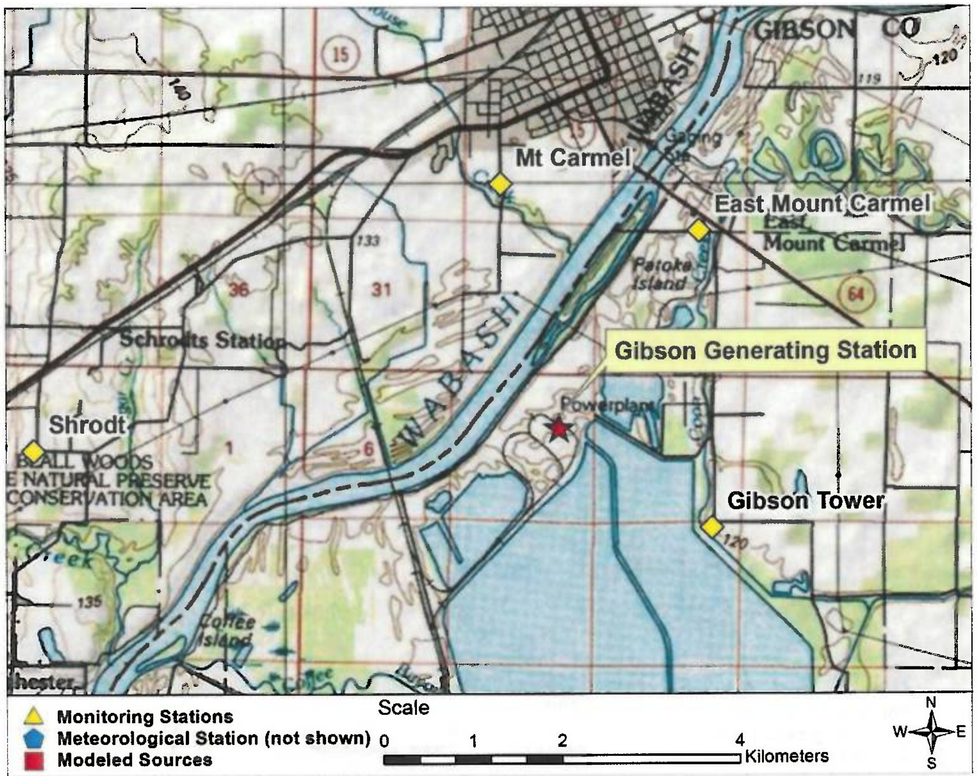


Figure 2. Map of Gibson Model Evaluation Layout
199x160mm (300 x 300 DPI)

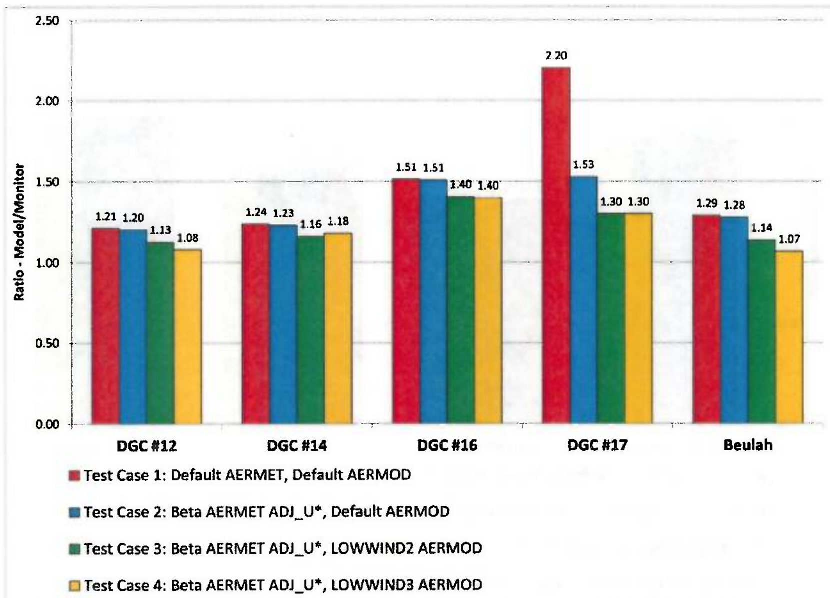


Figure 3. North Dakota Ratio of Monitored to Modeled Design Concentration Values at Specific Monitors
279x215mm (300 x 300 DPI)

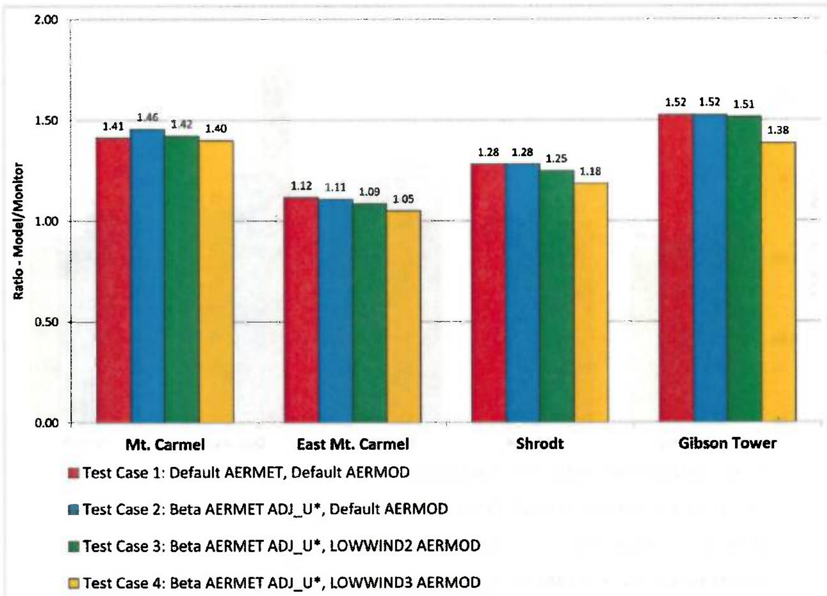
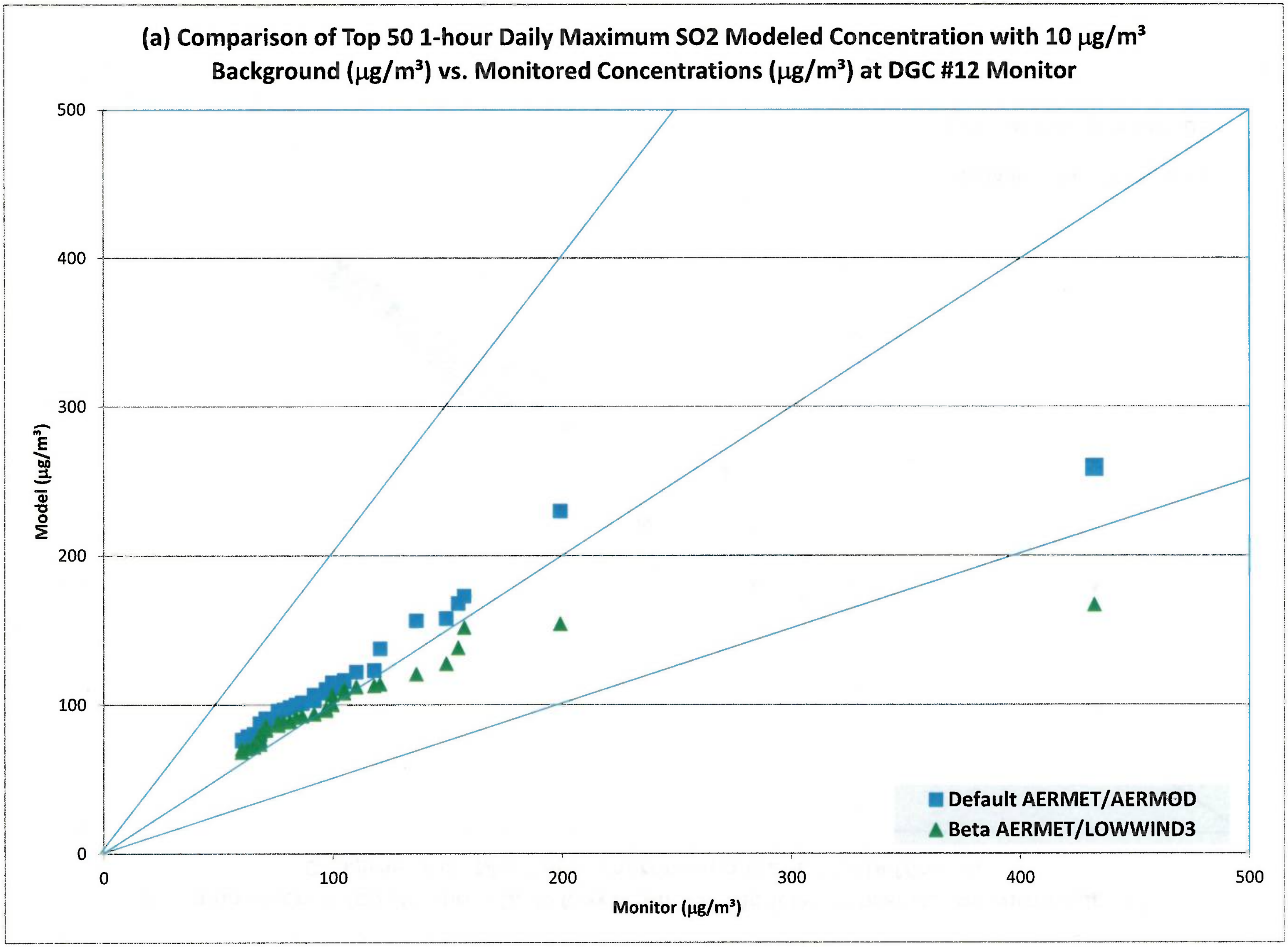
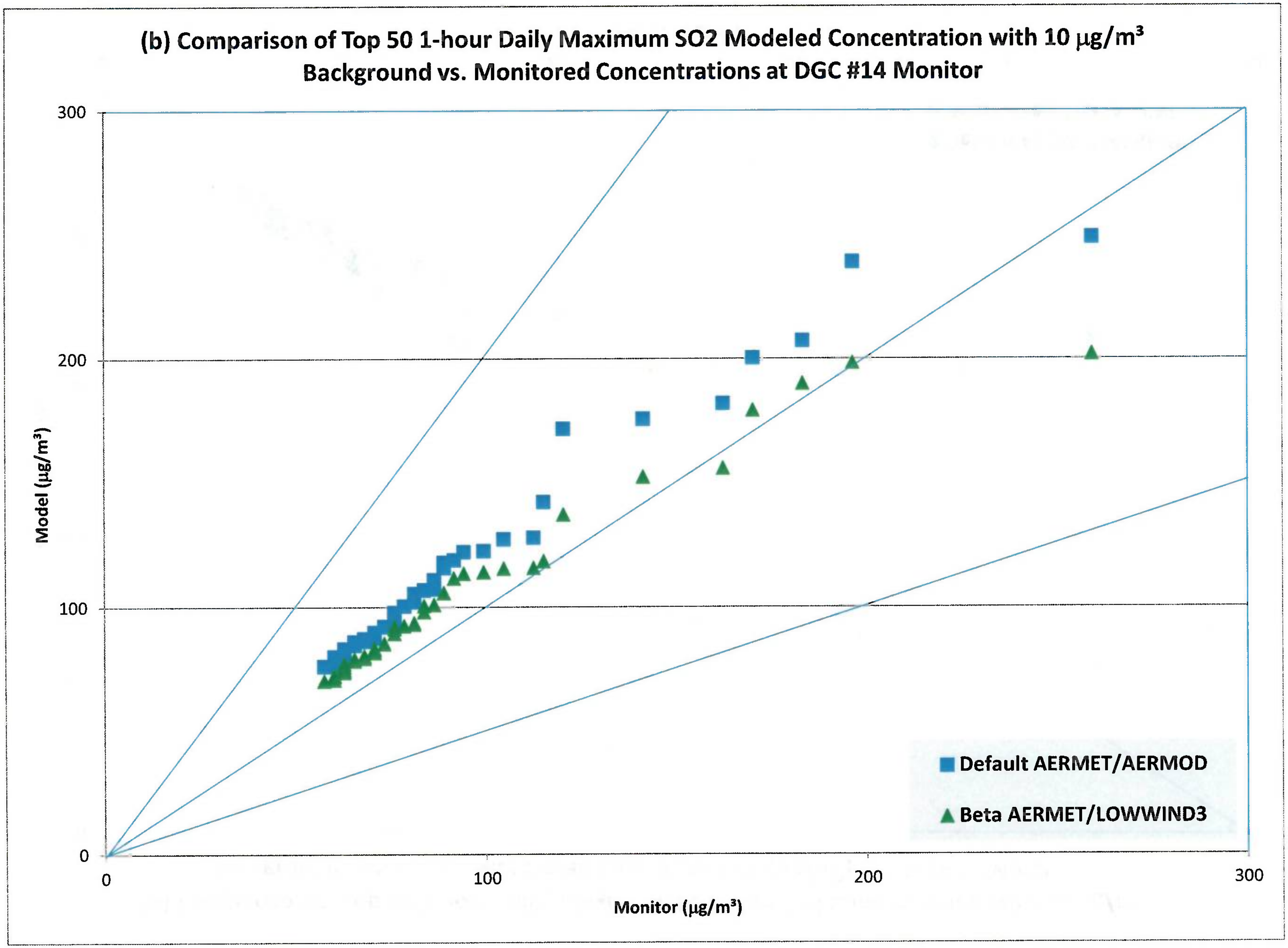


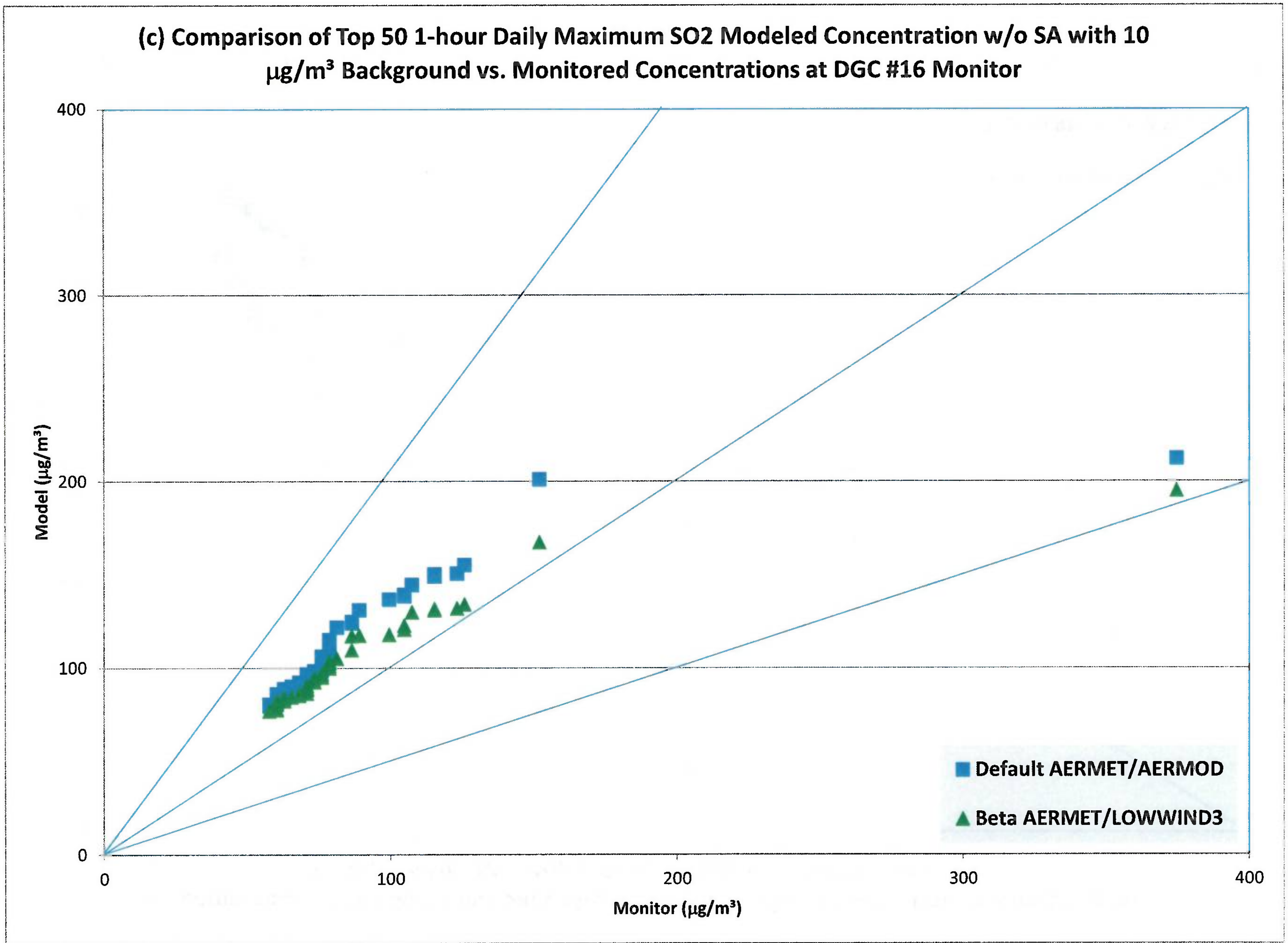
Figure 4. Gibson Ratio of Monitored to Modeled Design Concentration Values at Specific Monitors
279x215mm (300 x 300 DPI)

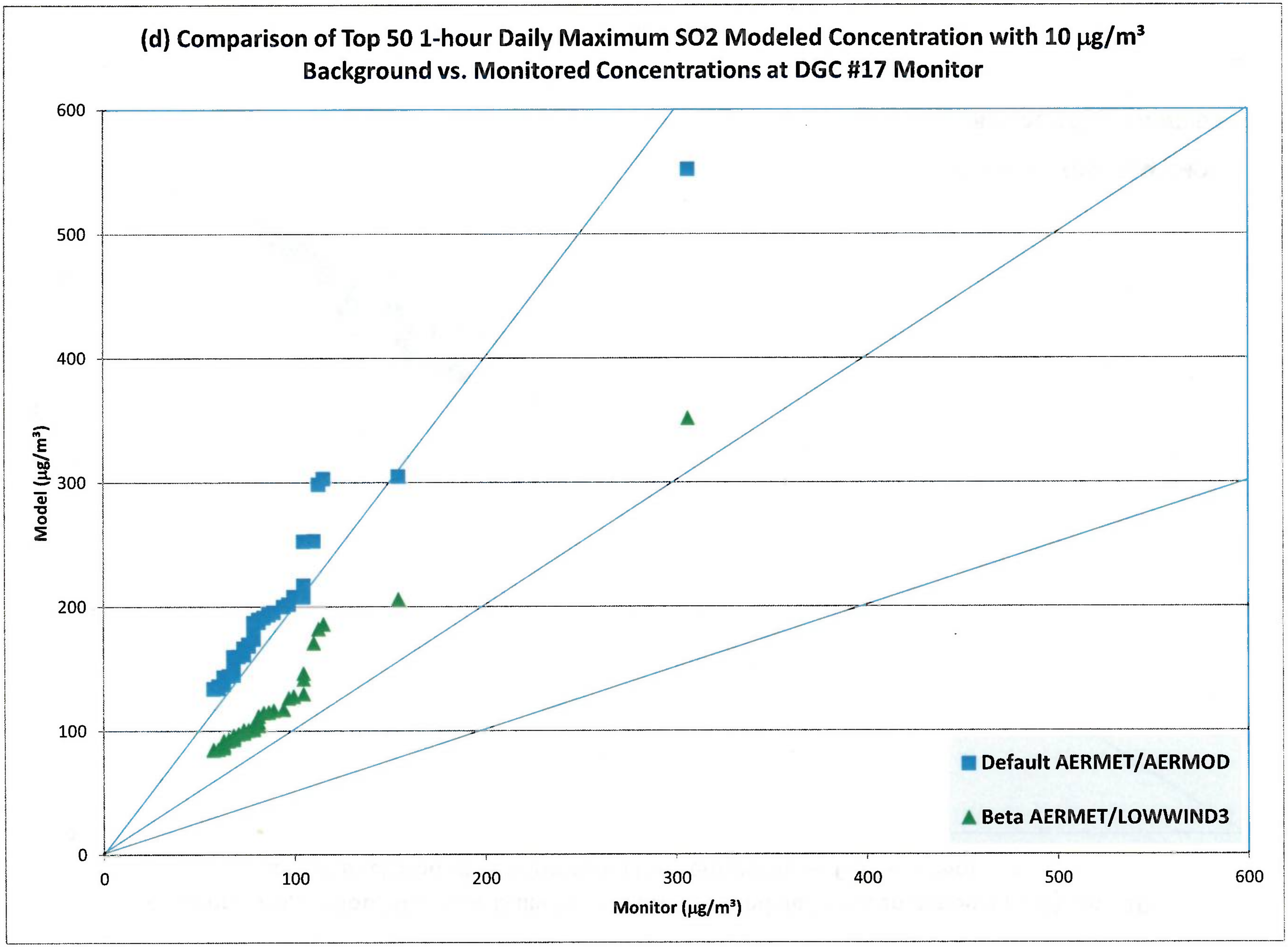
North Dakota: Top 50 1-hour SO2 Daily Max Monitoring and Predicted Concentrations

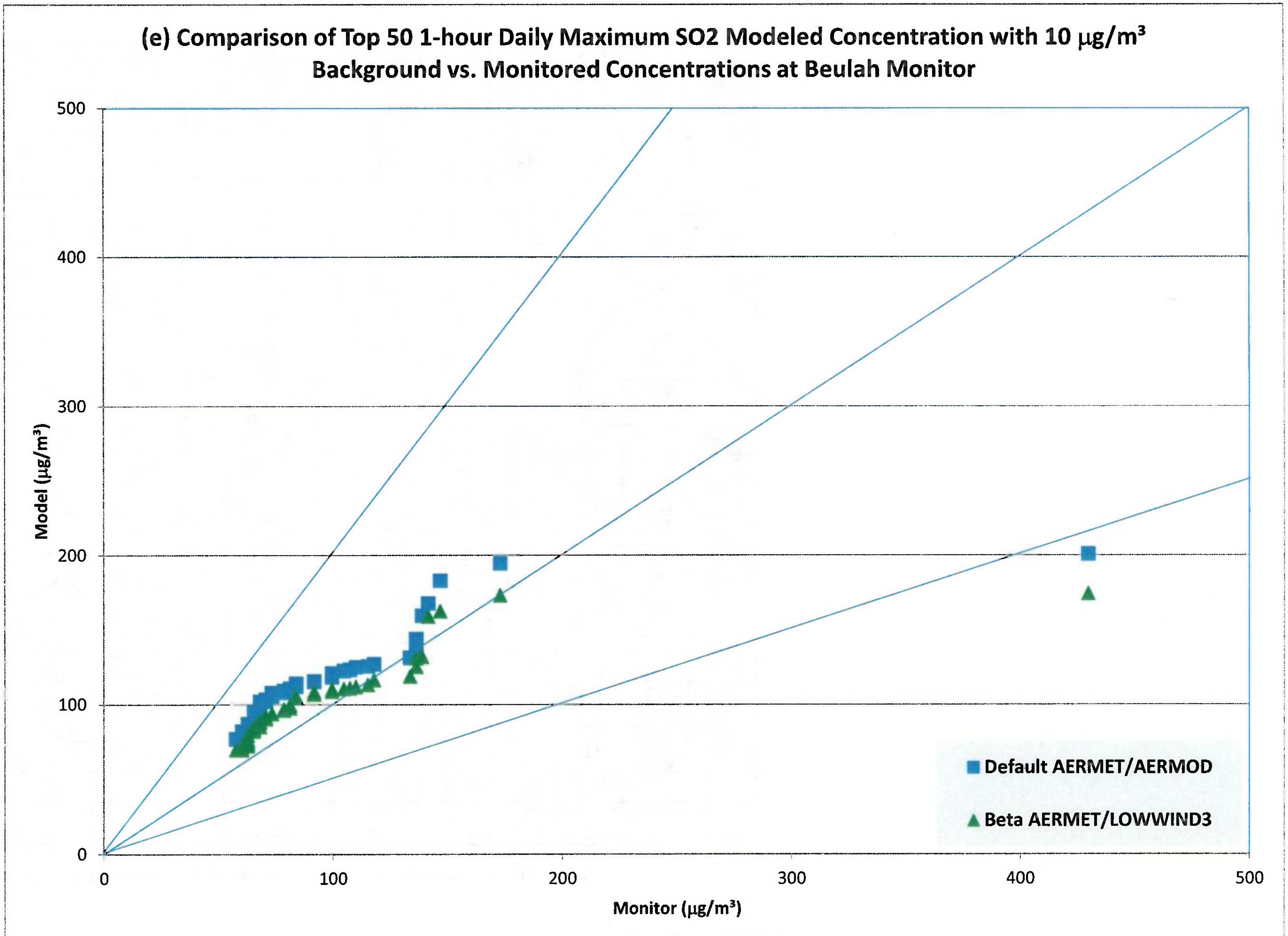
DGC12	DGC14	DGC16	DGC17	Beulah	DGC12	DGC14	DGC16	DGC17	Beulah	DGC12	DGC14	DGC16	DGC17	Beulah
Monitored					Default AERMET/AERMOD					Beta AERMET/LOWWIND3				
432.28	259.37	374.64	306.52	429.66	259.01	248.84	212.05	551.94	200.73	166.74	201.85	194.87	351.53	174.11
199.11	196.49	151.95	154.57	172.91	229.73	238.94	200.87	304.74	194.42	154.14	198.35	167.19	206.04	173.04
157.19	183.39	125.75	115.27	146.71	172.70	207.22	155.15	303.06	182.88	151.71	190.11	133.92	185.82	162.41
154.57	170.29	123.13	112.65	141.47	167.90	200.40	150.47	298.39	167.62	138.15	179.26	131.82	182.08	158.78
149.33	162.43	115.27	110.03	138.85	157.80	182.01	150.07	252.86	159.41	127.36	155.87	131.40	170.61	131.91
136.23	141.47	115.27	104.79	136.23	156.30	175.78	149.06	252.56	143.96	120.38	152.45	130.75	146.31	131.00
120.51	120.51	107.41	104.79	136.23	137.49	171.87	144.49	217.09	136.07	113.69	137.24	129.71	141.65	125.14
117.89	115.27	104.79	104.79	133.61	122.95	142.37	139.13	207.90	131.34	112.55	118.38	122.71	129.70	118.79
110.03	112.65	104.79	99.55	117.89	121.89	128.02	138.50	207.88	126.99	112.03	115.74	120.53	127.77	116.34
110.03	104.79	99.55	96.93	115.27	121.85	127.34	136.66	202.01	125.58	111.89	115.45	117.65	126.34	113.08
104.79	99.55	89.08	94.31	110.03	116.27	122.63	131.00	200.13	125.02	110.77	114.05	117.29	117.17	111.73
104.79	94.31	86.46	89.08	107.41	115.54	122.25	124.74	195.49	123.38	107.65	113.47	117.05	116.36	110.95
99.55	91.70	86.46	86.46	104.79	114.72	118.94	124.08	193.71	122.51	106.49	111.57	109.56	114.90	110.48
99.55	89.08	81.22	83.84	99.55	113.13	117.93	121.73	191.25	120.89	100.45	105.72	105.07	114.63	110.20
99.55	89.08	78.60	81.22	99.55	110.86	115.83	115.10	189.60	118.51	99.86	105.67	103.42	111.62	108.71
96.93	86.46	78.60	81.22	91.70	110.37	110.88	114.81	188.90	115.61	97.40	100.99	102.78	107.06	108.43
96.93	86.46	78.60	81.22	91.70	107.84	107.29	109.31	188.18	115.40	96.06	100.83	102.43	104.39	106.84
91.70	83.84	78.60	81.22	83.84	106.55	107.03	109.02	187.51	113.99	93.90	100.55	101.12	104.06	105.18
91.70	83.84	78.60	78.60	83.84	105.59	106.84	108.73	187.13	112.11	93.78	98.07	99.78	103.94	104.57
91.70	81.22	75.98	78.60	81.22	102.74	105.44	106.19	183.14	110.71	93.46	93.56	96.96	103.59	99.57
86.46	81.22	75.98	78.60	81.22	101.42	102.13	105.41	180.84	110.22	92.44	93.02	96.86	101.99	97.61
86.46	78.60	75.98	78.60	78.60	100.91	100.44	103.18	176.71	109.35	92.33	92.35	96.05	101.27	96.86
83.84	75.98	75.98	78.60	78.60	99.91	97.86	102.59	173.95	108.13	91.54	92.00	95.28	101.00	96.17
81.22	75.98	75.98	75.98	73.36	98.30	95.78	99.84	169.81	107.74	88.78	91.95	95.26	100.71	93.94
81.22	75.98	75.98	75.98	73.36	98.12	94.48	98.56	168.47	105.48	88.69	91.22	94.99	100.49	93.78
78.60	75.98	73.36	73.36	70.74	96.61	93.19	98.26	166.45	103.44	88.40	89.23	94.55	100.43	91.74
75.98	73.36	73.36	73.36	70.74	95.84	92.18	97.30	166.44	103.15	87.88	85.37	92.45	99.59	90.97
75.98	73.36	70.74	73.36	70.74	93.29	92.08	96.78	165.91	102.19	87.09	85.14	90.53	98.99	90.39
75.98	70.74	70.74	73.36	68.12	92.69	89.80	95.78	161.63	102.04	86.07	83.28	89.13	98.10	88.75
70.74	70.74	70.74	70.74	68.12	90.80	88.71	95.27	159.85	99.01	86.03	82.54	88.74	97.44	88.30
70.74	70.74	70.74	68.12	68.12	89.01	87.52	93.63	159.71	98.25	83.88	81.58	88.31	96.15	88.29
70.74	68.12	70.74	68.12	68.12	87.93	87.27	93.55	158.85	95.70	82.71	80.34	86.39	95.58	88.08
68.12	68.12	68.12	68.12	68.12	87.42	86.47	92.27	151.20	95.39	80.00	80.15	86.11	95.32	85.24
68.12	68.12	68.12	68.12	65.50	87.15	86.40	92.15	148.91	95.32	79.82	79.45	85.71	95.19	84.97
68.12	68.12	68.12	68.12	65.50	86.55	86.24	91.23	148.58	93.92	77.28	79.33	85.31	94.57	84.49
68.12	65.50	65.50	68.12	65.50	83.92	86.09	90.10	146.02	93.46	77.19	79.07	84.26	94.52	84.12
68.12	65.50	62.88	68.12	65.50	83.89	85.96	88.85	145.13	88.85	76.41	78.53	84.01	93.04	83.33
68.12	65.50	62.88	65.50	65.50	80.74	84.58	88.81	144.41	87.97	75.39	78.41	83.66	92.63	82.20
68.12	65.50	62.88	65.50	62.88	80.45	84.58	87.52	144.31	87.12	73.35	78.27	82.34	91.98	79.64
65.50	62.88	60.26	62.88	62.88	80.30	83.13	86.02	143.28	85.49	72.79	77.14	82.30	91.92	76.69
65.50	62.88	60.26	62.88	62.88	80.28	82.85	84.53	140.77	85.28	71.85	76.03	81.80	91.73	76.42
65.50	62.88	60.26	62.88	62.88	79.51	82.14	84.12	140.39	85.01	71.72	75.04	81.48	91.65	75.34
65.50	62.88	60.26	62.88	62.88	79.28	81.93	83.89	140.31	82.94	71.55	74.83	81.04	88.98	74.23
65.50	62.88	60.26	62.88	62.88	79.21	81.37	82.40	139.52	82.78	71.47	74.24	80.77	88.63	73.39
62.88	62.88	60.26	62.88	62.88	78.68	80.23	82.05	138.74	82.50	70.62	73.65	80.56	87.75	72.40
62.88	60.26	60.26	62.88	60.26	77.60	80.07	81.75	137.58	82.22	70.47	72.44	78.10	86.34	71.97
60.26	60.26	60.26	60.26	60.26	76.40	80.02	80.81	136.15	81.50	70.37	71.94	77.78	85.14	71.51
60.26	60.26	60.26	60.26	60.26	76.12	78.94	80.54	134.37	77.99	68.41	70.63	77.53	84.87	70.13
60.26	60.26	57.64	57.64	60.26	76.04	76.73	80.39	133.96	77.42	68.03	70.57	76.98	84.80	69.74
60.26	57.64	57.64	57.64	57.64	75.82	76.09	79.62	133.90	76.97	68.02	70.14	76.92	84.36	69.72


(a) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 10 μg/m³ Background (μg/m³) vs. Monitored Concentrations (μg/m³) at DGC #12 Monitor
Model (μg/m³)
Monitor (μg/m³)
0
100
200
300
400
500
Default AERMET/AERMOD
Beta AERMET/LOWWIND3


(b) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 10 μg/m³
Background vs. Monitored Concentrations at DGC #14 Monitor
Model (μg/m³)
Monitor (μg/m³)
300
200
100
0
Default AERMET/AERMOD
Beta AERMET/LOWWIND3

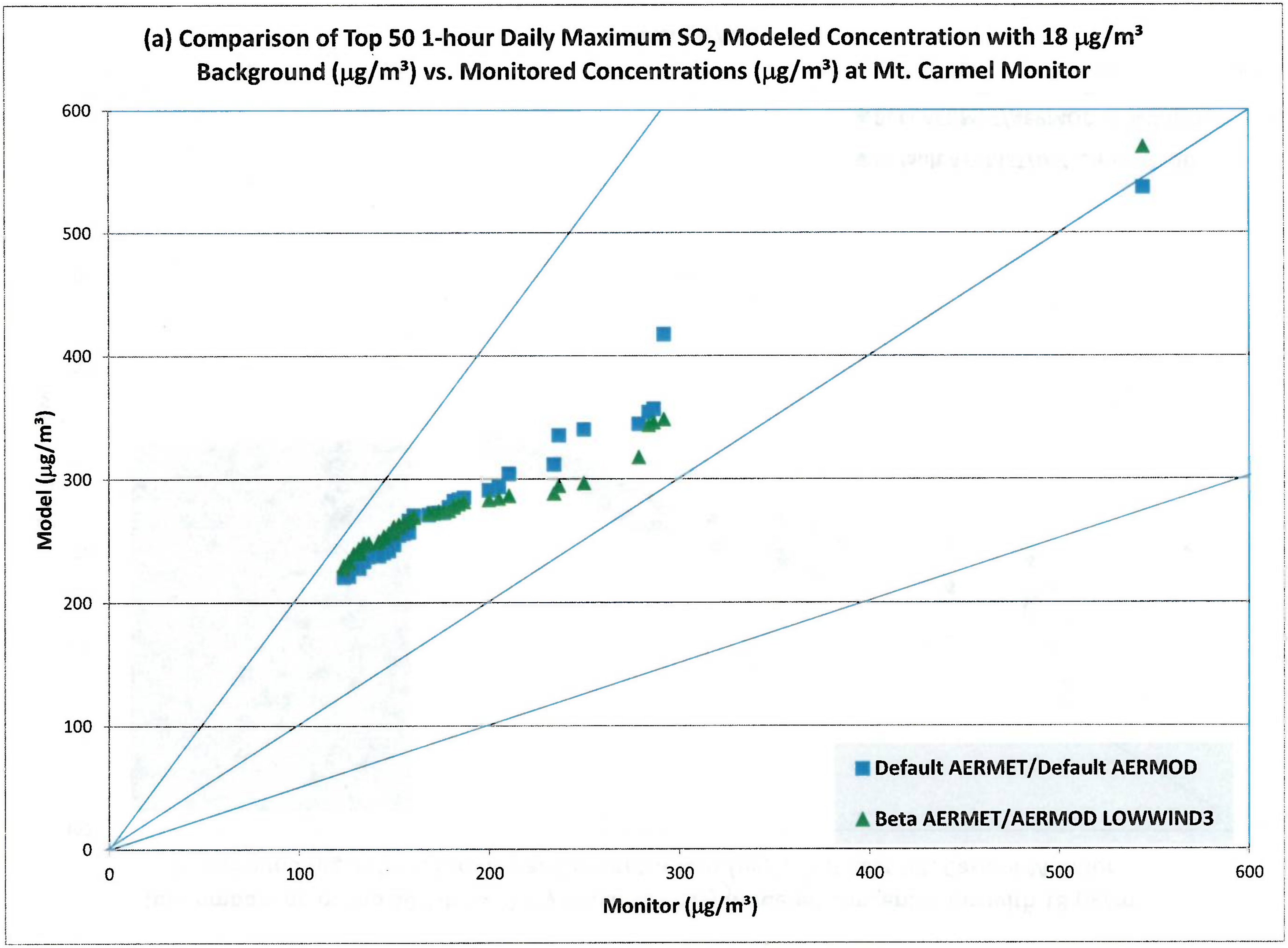

(c) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration w/o SA with 10 µg/m³ Background vs. Monitored Concentrations at DGC #16 Monitor
Model (µg/m³)
400
300
200
100
0
0
100
200
300
400
Monitor (µg/m³)
Default AERMET/AERMOD
Beta AERMET/LOWWIND3

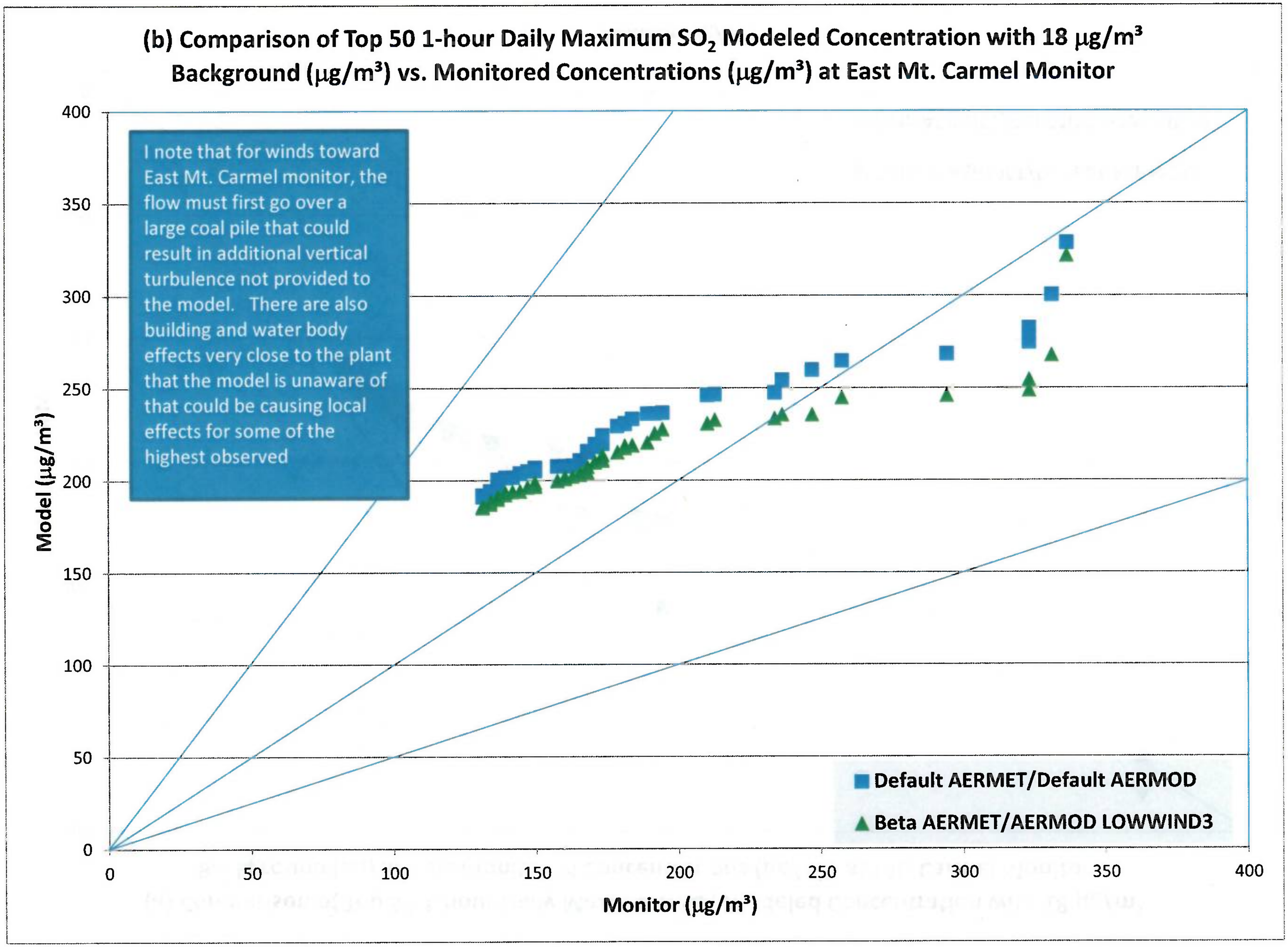

(d) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 10 μg/m³ Background vs. Monitored Concentrations at DGC #17 Monitor
Model (μg/m³)
Monitor (μg/m³)
0
100
200
300
400
500
600
Default AERMET/AERMOD
Beta AERMET/LOWWIND3

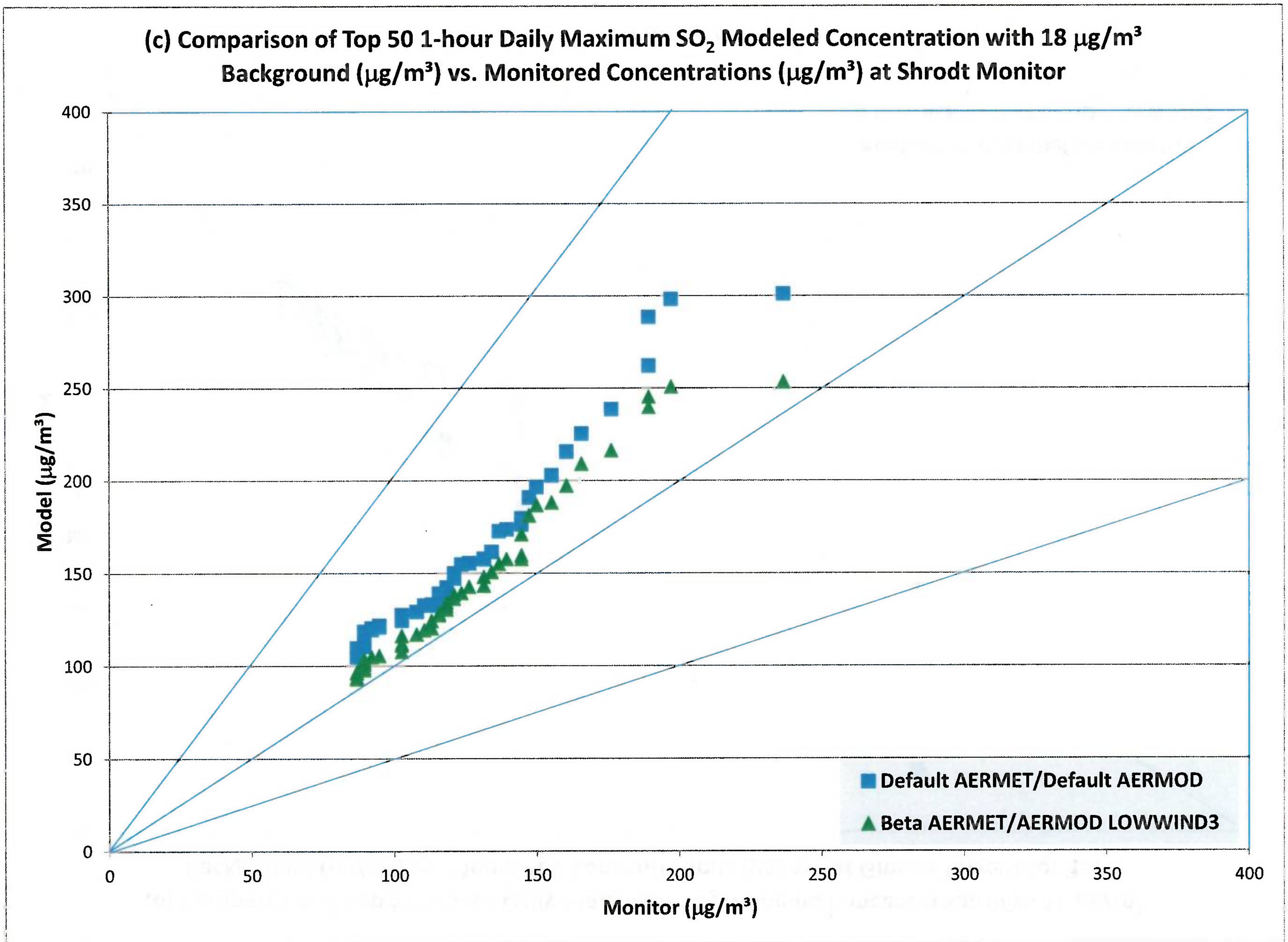

(e) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 10 μg/m³ Background vs. Monitored Concentrations at Beulah Monitor
Model (μg/m³)
Monitor (μg/m³)
0
100
200
300
400
500
Default AERMET/AERMOD
Beta AERMET/LOWWIND3

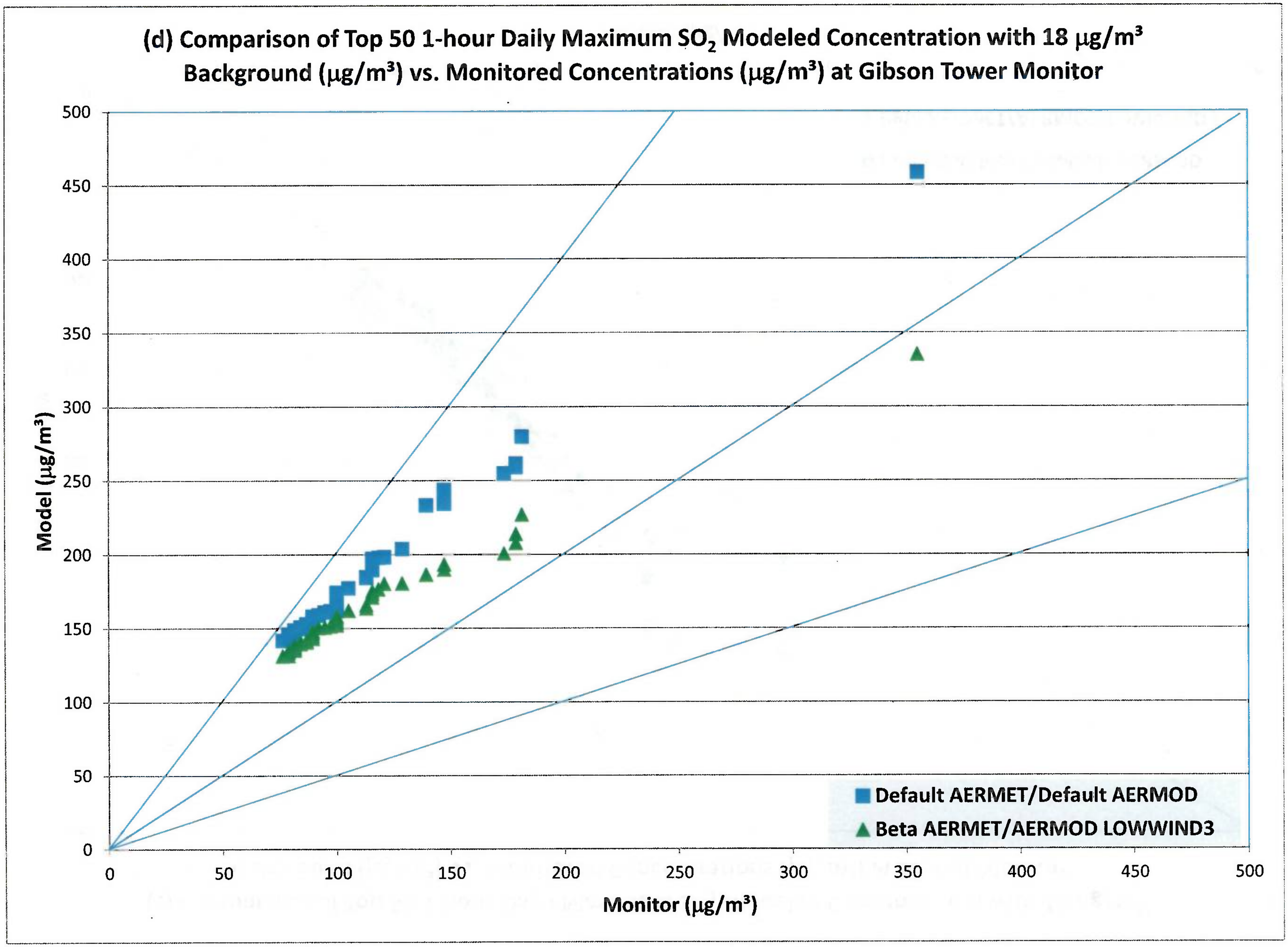
Gibson: Top 50 1-hour SO2 Daily Max Monitoring and Predicted Concentrations

Mt Carmel	East Mt Carmel	Shrodt	Gibson Tower	Mt Carmel	East Mt Carmel	Shrodt	Gibson Tower	Mt Carmel	East Mt Carmel	Shrodt	Gibson Tower
Monitored				Default AERMET/Default AERMOD				Beta AERMET/AERMOD LOWWIND3			
544.41	336.64	236.70	355.05	536.86	328.53	301.02	458.35	569.88	321.62	253.14	335.27
291.93	331.38	197.25	181.47	417.42	300.35	298.21	279.77	348.25	267.64	250.57	227.02
286.67	323.49	189.36	178.84	356.67	282.41	288.44	261.51	345.80	254.45	245.15	213.82
284.04	323.49	189.36	178.84	354.22	274.70	262.03	259.16	343.66	248.66	239.52	207.70
278.78	294.56	176.21	173.58	344.57	268.44	238.58	255.06	317.56	245.80	216.19	200.70
249.85	257.74	165.69	147.28	340.20	264.68	225.35	243.77	296.46	244.67	209.01	193.10
236.70	247.22	160.43	147.28	335.40	259.67	215.55	234.48	294.47	235.53	197.18	189.79
234.07	236.70	155.17	139.39	311.70	254.25	202.82	233.38	288.22	235.48	188.06	186.40
210.40	234.07	149.91	128.87	304.17	247.45	196.54	203.94	286.35	233.44	186.77	180.39
205.14	213.03	147.28	120.98	293.44	246.60	190.89	198.42	284.10	232.70	181.10	180.30
199.88	210.40	144.65	118.35	290.86	246.12	179.54	197.89	283.10	230.72	171.01	176.37
186.73	194.62	144.65	115.72	284.85	236.55	176.31	197.29	281.63	227.63	159.52	175.21
184.10	191.99	144.65	115.72	283.32	236.27	176.30	191.47	279.70	225.33	157.64	173.27
181.47	189.36	139.39	115.72	282.04	236.10	173.64	189.69	278.62	220.43	157.55	171.10
181.47	184.10	136.76	113.09	279.48	233.32	172.74	184.82	277.22	218.96	155.05	165.66
178.84	181.47	134.13	113.09	277.21	230.93	161.48	184.45	274.10	218.61	150.55	163.67
176.21	181.47	131.50	105.20	272.80	230.55	157.88	177.40	274.00	217.49	147.96	161.98
173.58	178.84	131.50	99.94	272.66	229.49	157.58	174.25	273.78	215.22	143.17	158.14
170.95	173.58	126.24	99.94	272.40	224.43	155.53	174.10	272.57	213.73	142.56	156.70
168.32	173.58	123.61	99.94	271.12	223.37	154.81	171.22	272.19	211.43	139.28	155.00
160.43	173.58	120.98	99.94	270.49	219.95	149.98	170.38	270.15	210.67	138.43	154.23
160.43	170.95	120.98	99.94	269.84	219.72	147.32	164.04	268.91	210.17	136.19	153.52
157.80	170.95	118.35	99.94	266.20	218.59	142.35	161.80	267.16	210.02	134.31	152.13
157.80	170.95	118.35	97.31	257.08	218.27	141.73	161.78	266.09	209.67	132.28	151.57
155.17	168.32	118.35	94.68	255.87	215.89	140.46	161.07	264.35	207.37	130.42	150.54
152.54	168.32	115.72	92.05	254.98	215.36	139.07	159.10	262.73	204.28	128.11	150.38
152.54	165.69	115.72	89.42	254.51	210.95	135.08	158.13	261.17	204.09	127.43	148.19
149.91	165.69	113.09	89.42	252.72	210.64	133.13	157.29	261.17	203.05	124.32	147.09
149.91	163.06	113.09	89.42	252.46	208.13	132.67	156.62	257.96	202.12	120.19	146.55
149.91	160.43	110.46	89.42	246.81	207.81	132.62	155.37	256.26	201.69	119.26	144.83
147.28	160.43	107.83	89.42	245.63	207.78	129.24	153.21	255.99	200.86	116.96	143.11
147.28	157.80	102.57	86.79	242.00	207.70	127.45	153.14	255.77	199.75	116.24	141.58
144.65	149.91	102.57	86.79	240.76	206.81	126.50	153.12	253.25	198.73	112.19	141.55
144.65	149.91	102.57	86.79	240.21	205.31	125.50	153.09	252.32	197.17	111.05	141.05
142.02	149.91	102.57	86.79	239.88	205.30	124.57	152.89	249.41	196.72	107.61	140.62
142.02	147.28	94.68	84.16	237.73	205.07	121.66	150.95	248.84	196.36	105.49	140.42
136.76	144.65	94.68	84.16	236.94	203.74	121.00	149.88	247.55	194.09	105.48	139.50
134.13	142.02	92.05	81.53	236.26	201.72	120.33	148.70	247.41	193.87	104.76	138.53
134.13	139.39	92.05	81.53	234.89	201.61	119.51	147.63	246.70	193.47	104.76	138.28
134.13	139.39	89.42	81.53	233.33	201.50	118.56	147.15	246.36	192.16	103.46	137.55
131.50	136.76	89.42	81.53	233.33	200.43	117.17	147.13	243.04	191.30	102.15	136.71
131.50	136.76	89.42	81.53	231.41	198.55	114.50	146.65	242.88	190.31	100.93	135.64
131.50	136.76	89.42	81.53	229.94	198.19	114.37	146.37	242.08	190.02	100.69	135.08
131.50	136.76	89.42	78.90	227.80	196.78	110.63	146.12	239.98	189.84	98.98	134.62
128.87	134.13	89.42	78.90	227.53	194.16	110.47	146.01	239.08	188.59	97.78	134.43
126.24	134.13	86.79	78.90	224.43	194.10	109.60	145.97	233.19	188.44	96.60	133.93
126.24	134.13	86.79	78.90	222.28	192.93	108.28	145.66	233.00	187.14	96.18	133.91
126.24	131.50	86.79	78.90	221.32	191.96	107.13	143.05	232.21	185.87	93.91	133.56
123.61	131.50	86.79	78.90	220.36	191.26	106.00	141.85	229.57	185.67	93.43	131.43
123.61	131.50	86.79	76.27	220.36	191.18	104.82	141.79	227.57	185.12	92.93	131.06


(a) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 18 µg/m³ Background (µg/m³) vs. Monitored Concentrations (µg/m³) at Mt. Carmel Monitor
Model (µg/m³)
Monitor (µg/m³)
0
100
200
300
400
500
600
Default AERMET/Default AERMOD
Beta AERMET/AERMOD LOWWIND3


(b) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 18 µg/m³ Background (µg/m³) vs. Monitored Concentrations (µg/m³) at East Mt. Carmel Monitor
I note that for winds toward East Mt. Carmel monitor, the flow must first go over a large coal pile that could result in additional vertical turbulence not provided to the model. There are also building and water body effects very close to the plant that the model is unaware of that could be causing local effects for some of the highest observed
Model (µg/m³)
Monitor (µg/m³)
0
50
100
150
200
250
300
350
400
Default AERMET/Default AERMOD
Beta AERMET/AERMOD LOWWIND3


(c) Comparison of Top 50 1-hour Daily Maximum SO_2 Modeled Concentration with 18 μg/m³ Background (μg/m³) vs. Monitored Concentrations (μg/m³) at Shrodt Monitor
Model (μg/m³)
Monitor (μg/m³)
0
50
100
150
200
250
300
350
400
Default AERMET/Default AERMOD
Beta AERMET/AERMOD LOWWIND3


(d) Comparison of Top 50 1-hour Daily Maximum SO_2 Modeled Concentration with 18 µg/m³ Background (µg/m³) vs. Monitored Concentrations (µg/m³) at Gibson Tower Monitor
Model (µg/m³)
Monitor (µg/m³)
0
50
100
150
200
250
300
350
400
450
500
Default AERMET/Default AERMOD
Beta AERMET/AERMOD LOWWIND3

Appendix D

E-mail from EPA Regarding Placement of Receptors for DRR Modeling

Paine, Bob

From:	Thurman, James <Thurman.James@epa.gov>
Sent:	Tuesday, January 26, 2016 1:10 PM
To:	Paine, Bob
Cc:	Wallace, Larry
Subject:	RE: question regarding placement of model receptors for SO2 concentration characterization

Bob,
The same policy as below generally fits the case you describe.

James

James A. Thurman, Ph.D.
U.S. EPA/OAQPS/AQAD
Air Quality Modeling Group (C439-01)
109 T.W. Alexander Drive
Research Triangle Park, NC 27711
Phone: (919) 541-2703
Fax: (919) 541-0044
Email: thurman.james@epa.gov

From: Paine, Bob [mailto:bob.paine@aecom.com]
Sent: Tuesday, January 26, 2016 9:30 AM
To: Thurman, James <Thurman.James@epa.gov>
Cc: Wallace, Larry <Wallace.Larry@epa.gov>
Subject: RE: question regarding placement of model receptors for SO2 concentration characterization

Thanks, James. One question on receptor placement that has come up recently on this same topic is steep terrain, especially in generally inaccessible areas with no nearby power. What is EPA's policy on placing receptors for the SO2 characterization in such areas?

Bob

From: Thurman, James [mailto:Thurman.James@epa.gov]
Sent: Tuesday, January 26, 2016 8:56 AM
To: Paine, Bob
Cc: Wallace, Larry
Subject: RE: question regarding placement of model receptors for SO2 concentration characterization

Bob,
Yes that is correct.

James

James A. Thurman, Ph.D.
U.S. EPA/OAQPS/AQAD
Air Quality Modeling Group (C439-01)
109 T.W. Alexander Drive

Research Triangle Park, NC 27711
Phone: (919) 541-2703
Fax: (919) 541-0044
Email: thurman.james@epa.gov

From: Paine, Bob [mailto:bob.paine@aecom.com]
Sent: Tuesday, January 26, 2016 8:53 AM
To: Thurman, James <Thurman.James@epa.gov>
Cc: Wallace, Larry <Wallace.Larry@epa.gov>
Subject: question regarding placement of model receptors for SO2 concentration characterization

James, I was provided some notes from a call conducted with you, Scott Mathias, and Andy Chang of EPA by UARG's Ambient Standards and Nonattainment Committees by teleconference on April 20, 2015, to answer questions concerning EPA's plans concerning designations of areas for the 1-hour SO2 NAAQS.

One area of discussion that was reported from the call was the placement of receptors in the modeling for SO2 concentration characterization. The UARG call notes indicated that EPA stated that for purposes of the area designation process, receptors should not be sited where a monitor could not be placed. Accordingly, receptors are not to be placed over water (rivers, lakes, ponds, and swamps), in a different country, on the secured property of another industrial source, on a roadway, railroad track, or similar pathway used by vehicles, or on active landfills or dredge spoils areas.

Is that a correct interpretation of EPA's policy?

Regards,

Bob Paine, CCM, QEP
Associate Vice President
Environment
D 978.905.2352
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Appendix E

AERMOD Low Wind Speed Improvements: Status Report and New Evaluations

AERMOD Low Wind Speed Improvements: Status Report and New Evaluations

Paper # 935

Robert J. Paine, Christopher J. Warren, and Olga Samani
AECOM, 250 Apollo Drive, Chelmsford, MA 01824

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

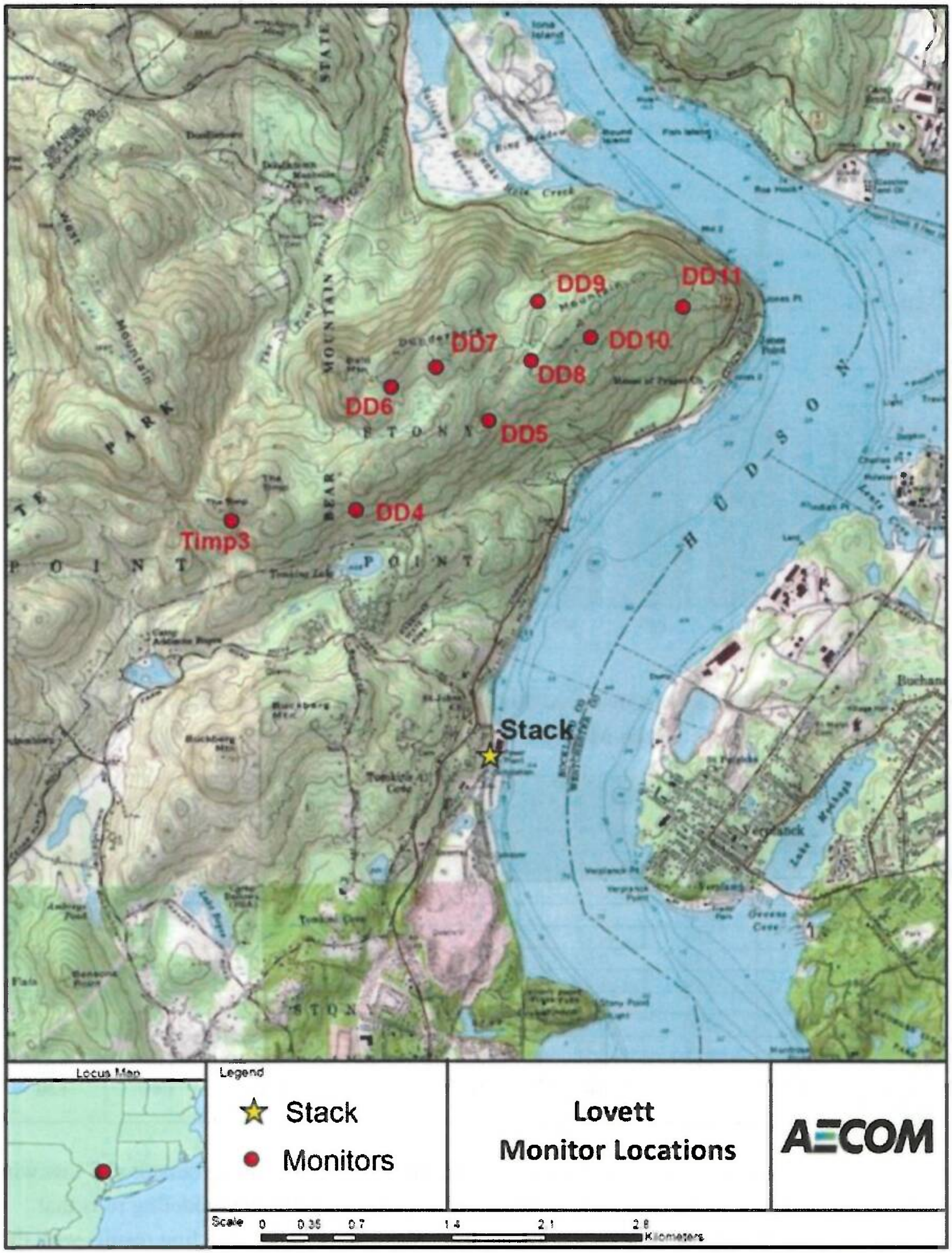


Figure 3 Histogram of the 4th Highest Daily Peak 1-hour SO_2 Concentrations

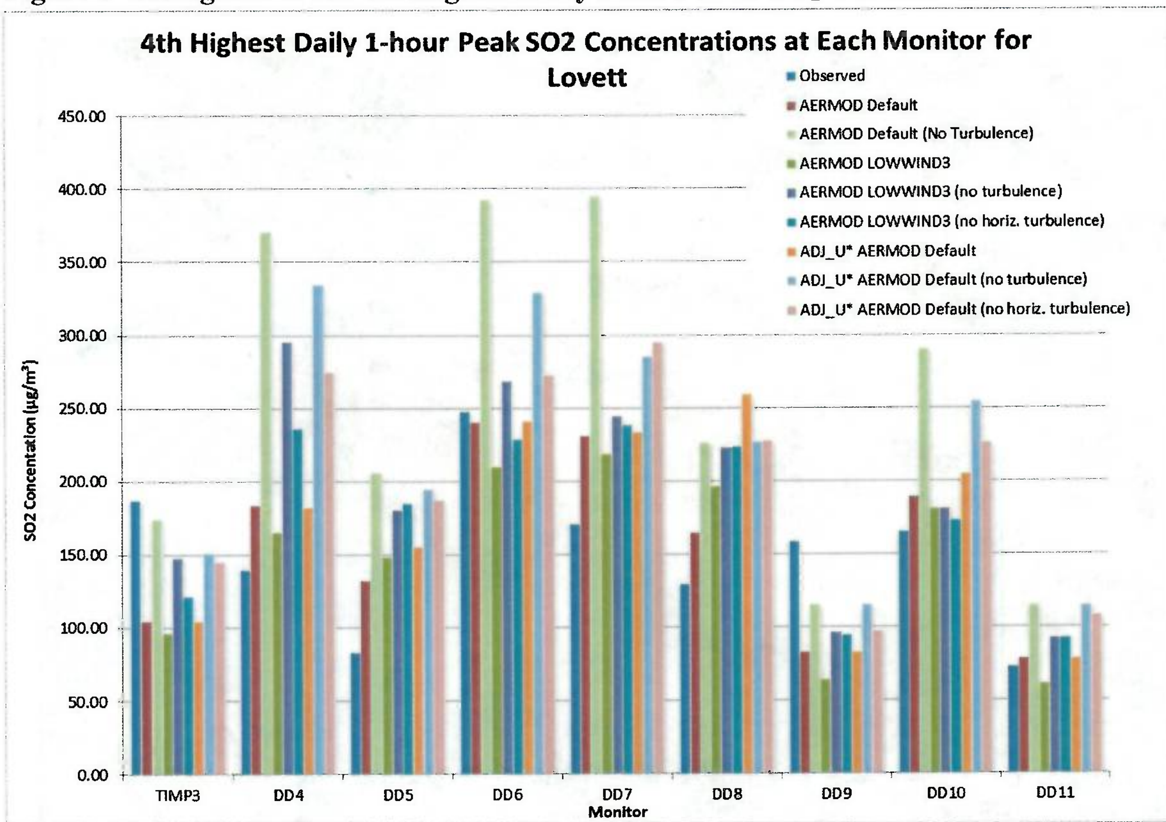


Table 1 Ratio of Predicted-to-Observed Robust 4th Highest Daily Peak Concentration (R4HC; 99th Percentile) for Each Monitor at Lovett

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)

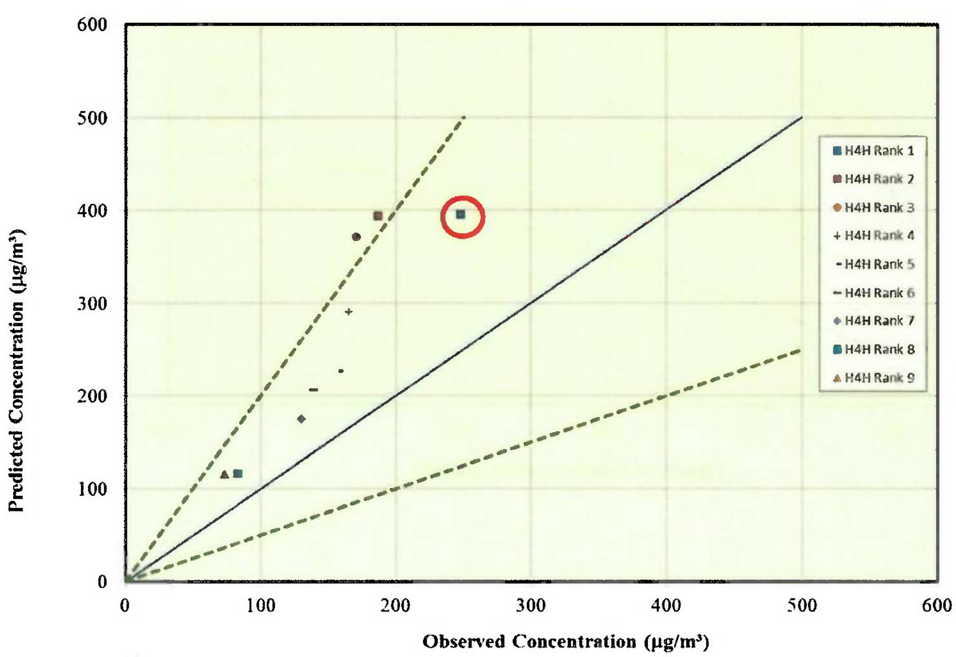


Figure 5 Q-Q Plot of the Ranked 4th Highest (99th Percentile) Daily 1-hour SO_2 Concentrations for Each Monitor Using AERMOD LOWWIND3 (No Turbulence)

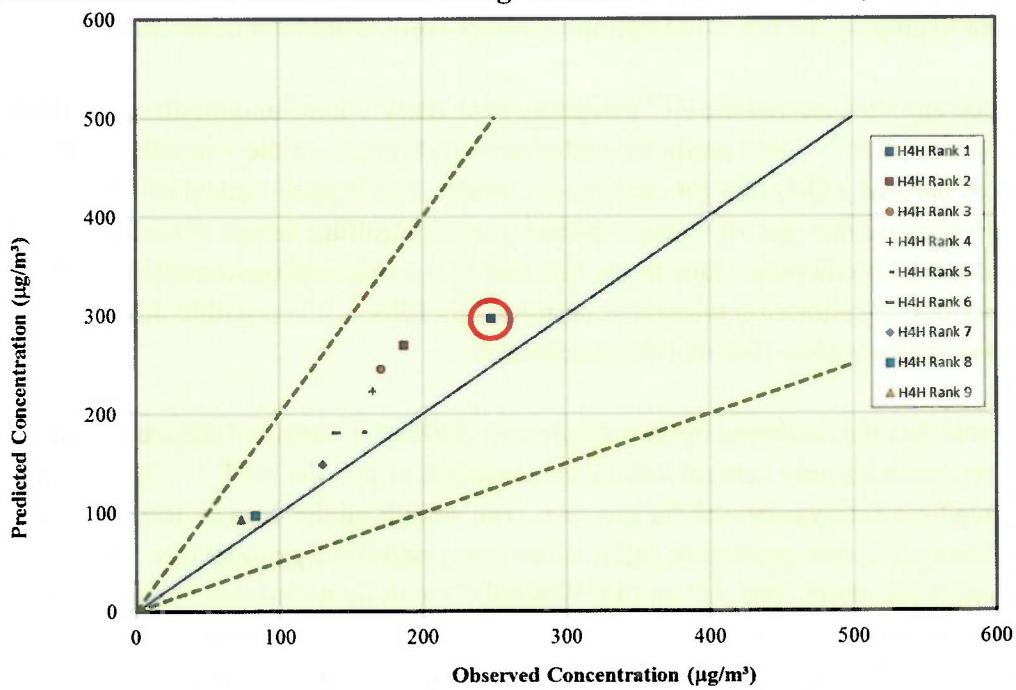
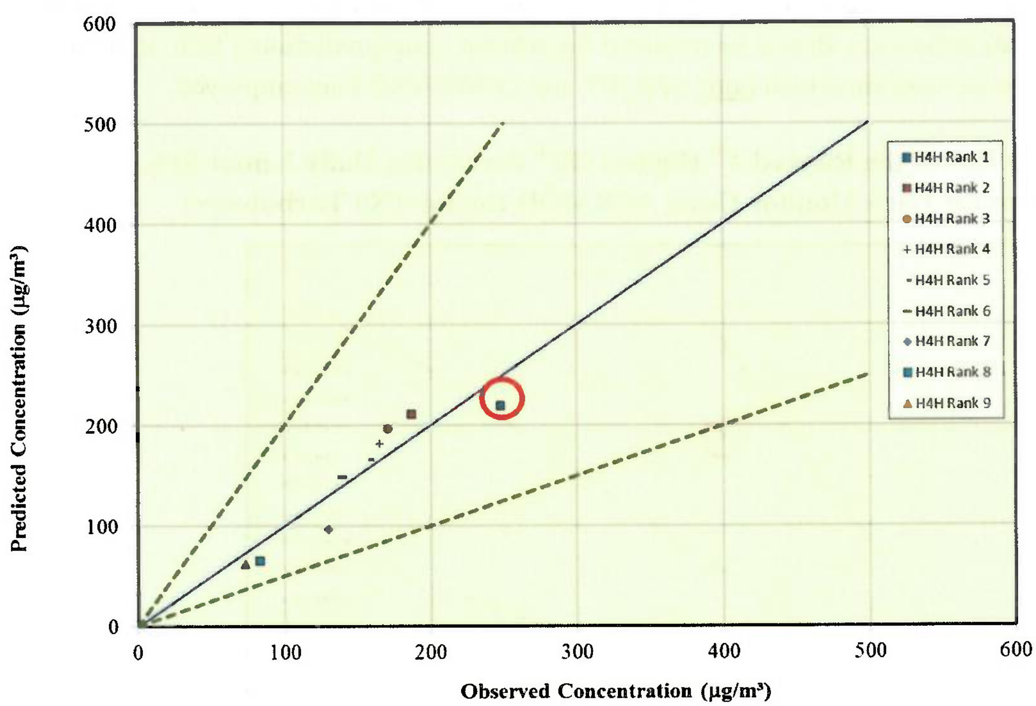


Figure 6 Q-Q Plot of the Ranked 4th Highest (99th Percentile) Daily 1-hour SO_2 Concentrations for Each Monitor Using ADJ_U* and LOWWIND3 (All Turbulence Used)



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

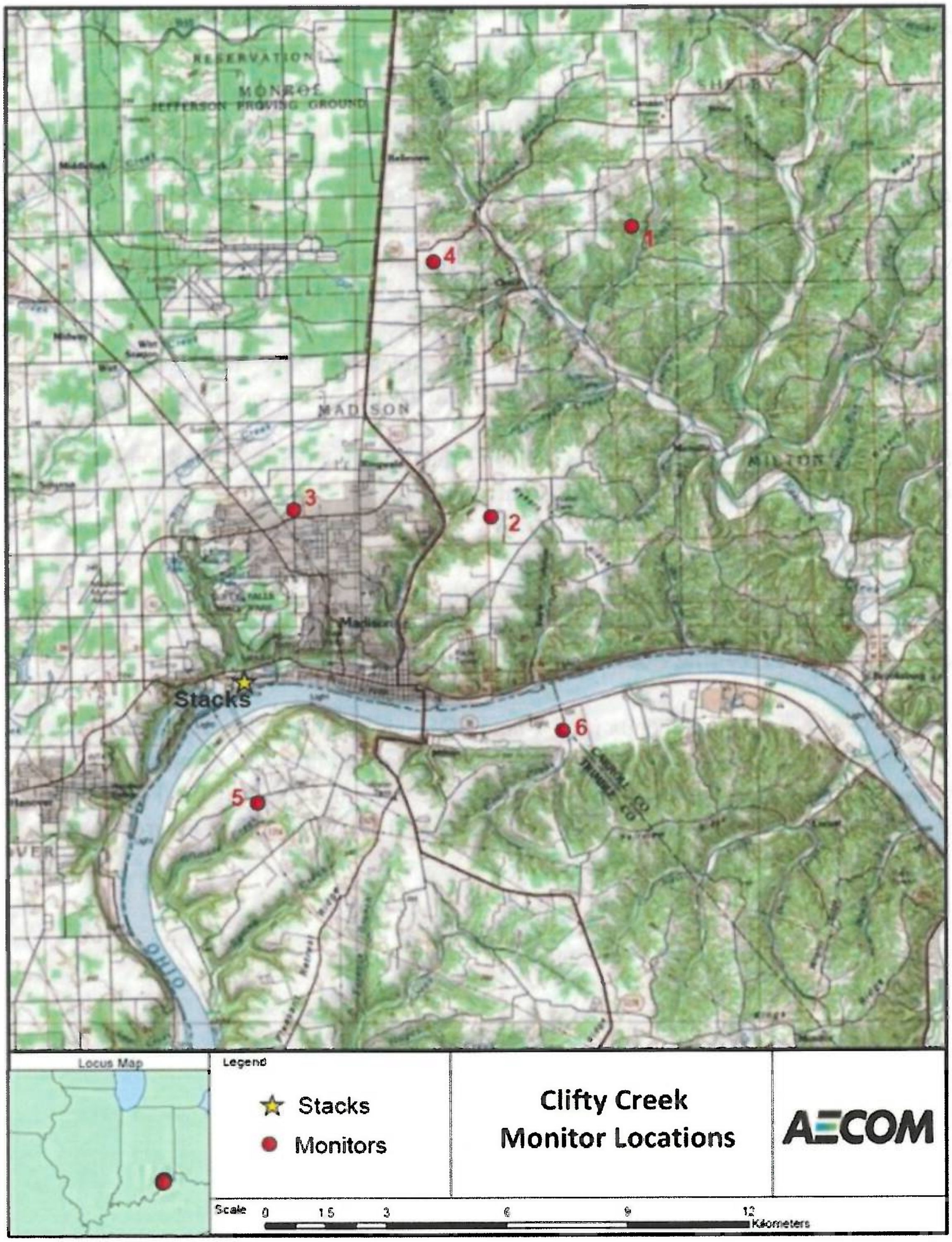
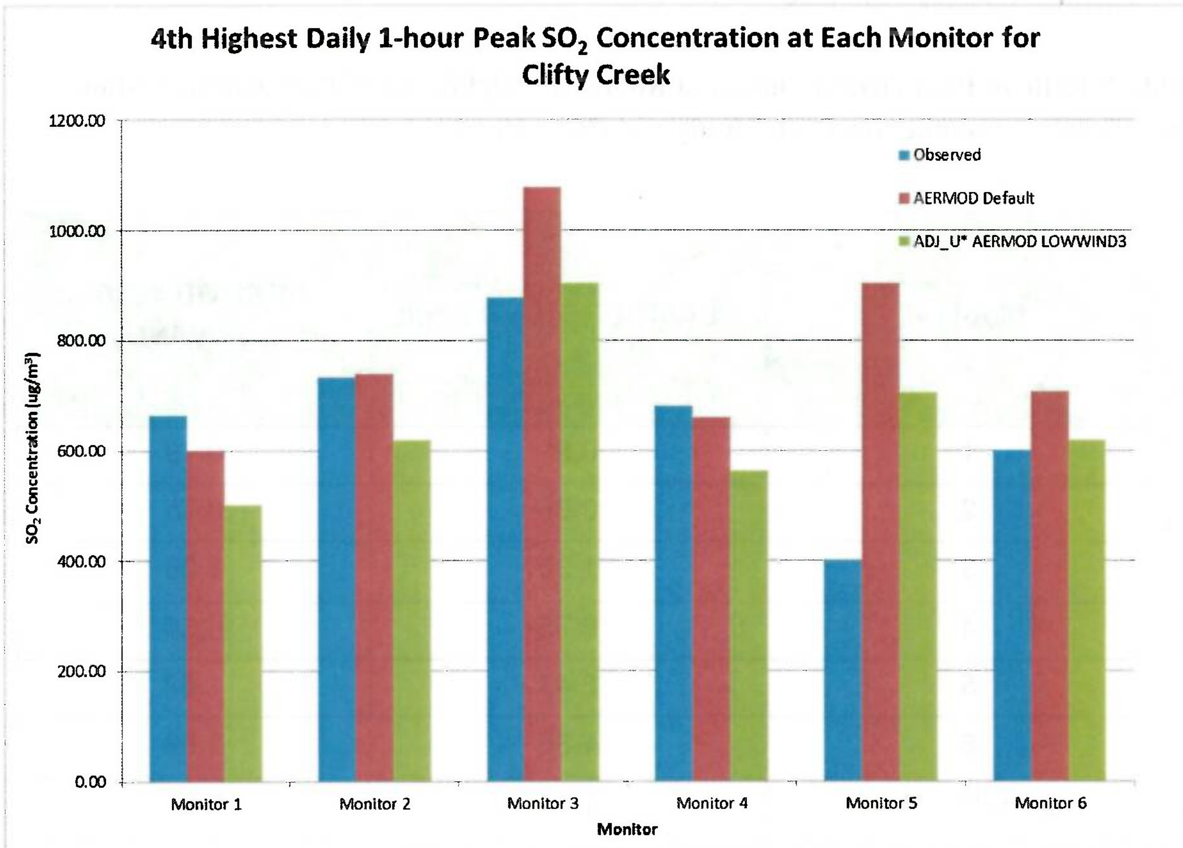


Figure 8 Histogram of the 4th Highest Daily Peak 1-hour SO_2 Concentrations



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

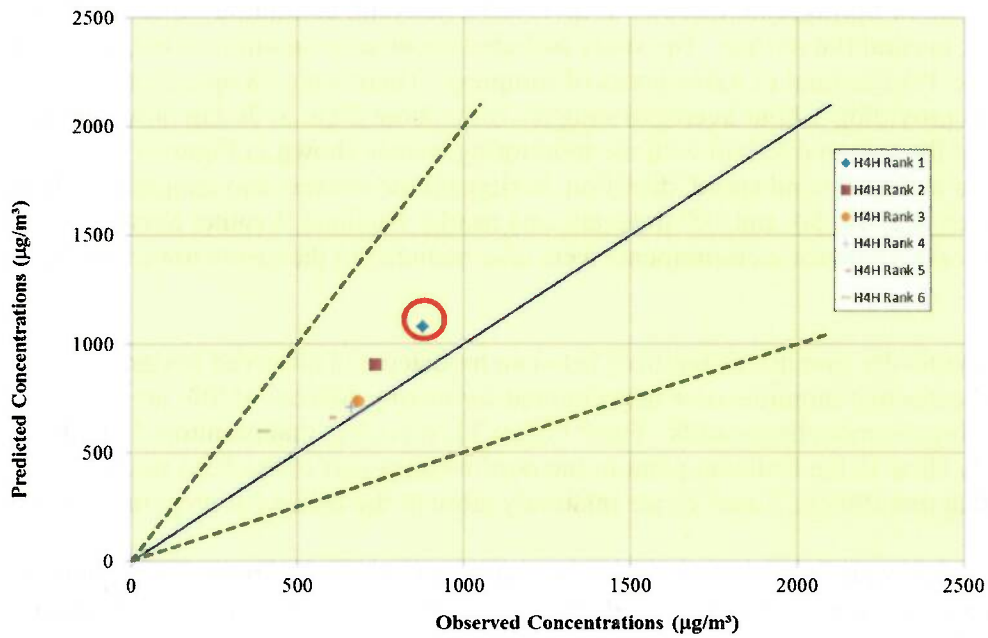
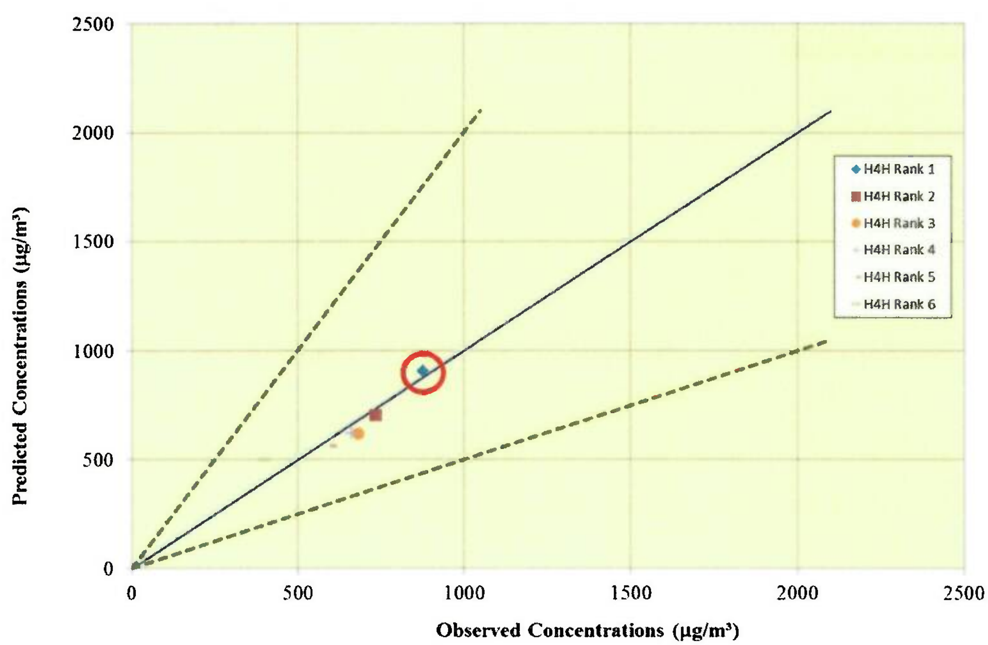


Figure 10 Q-Q Plot of the Ranked 4th Highest (99th Percentile) Daily 1-hour SO_2 Concentrations for Each Monitor Using ADJ_U* and LOWWIND3



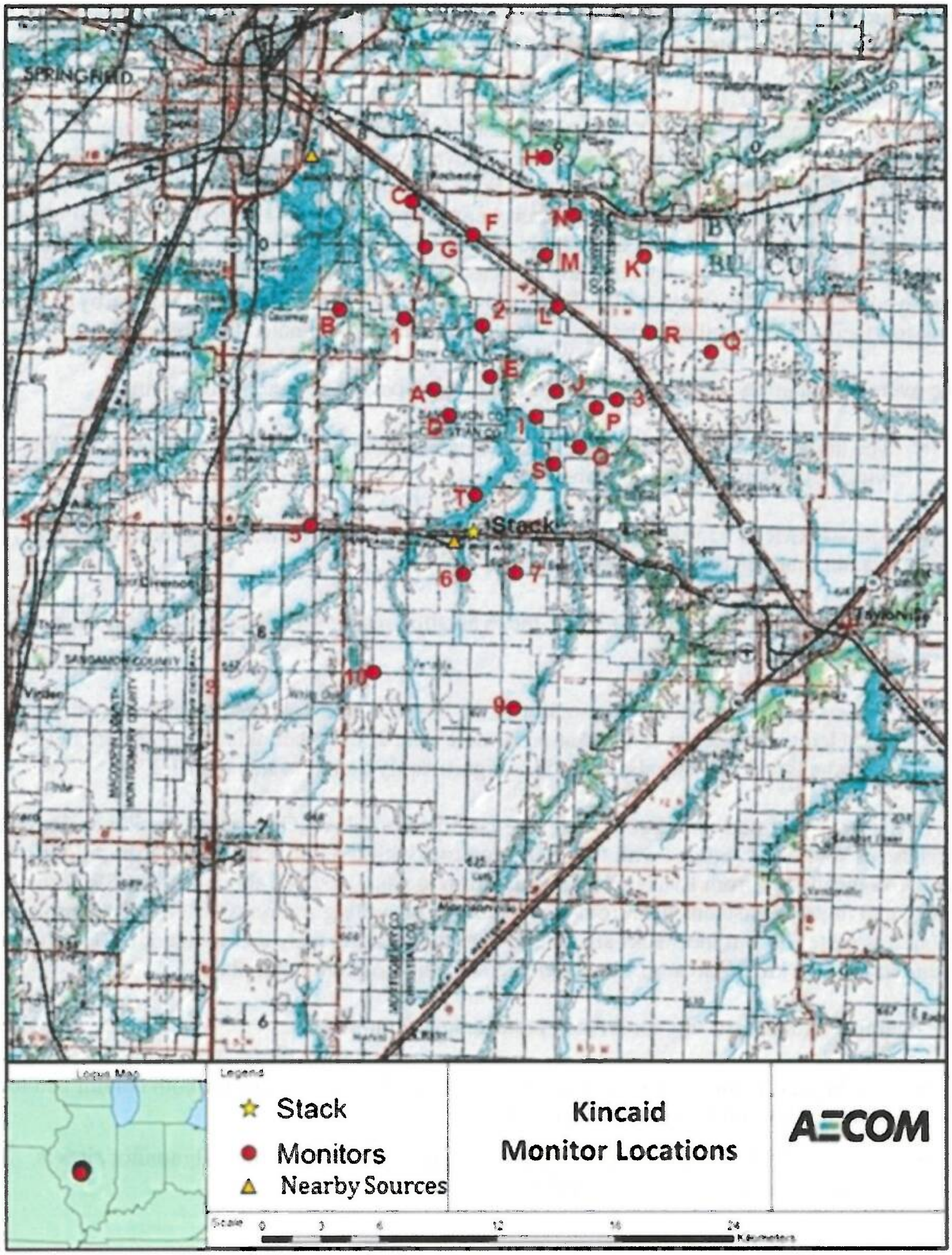
KINCAID FIELD STUDY

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.

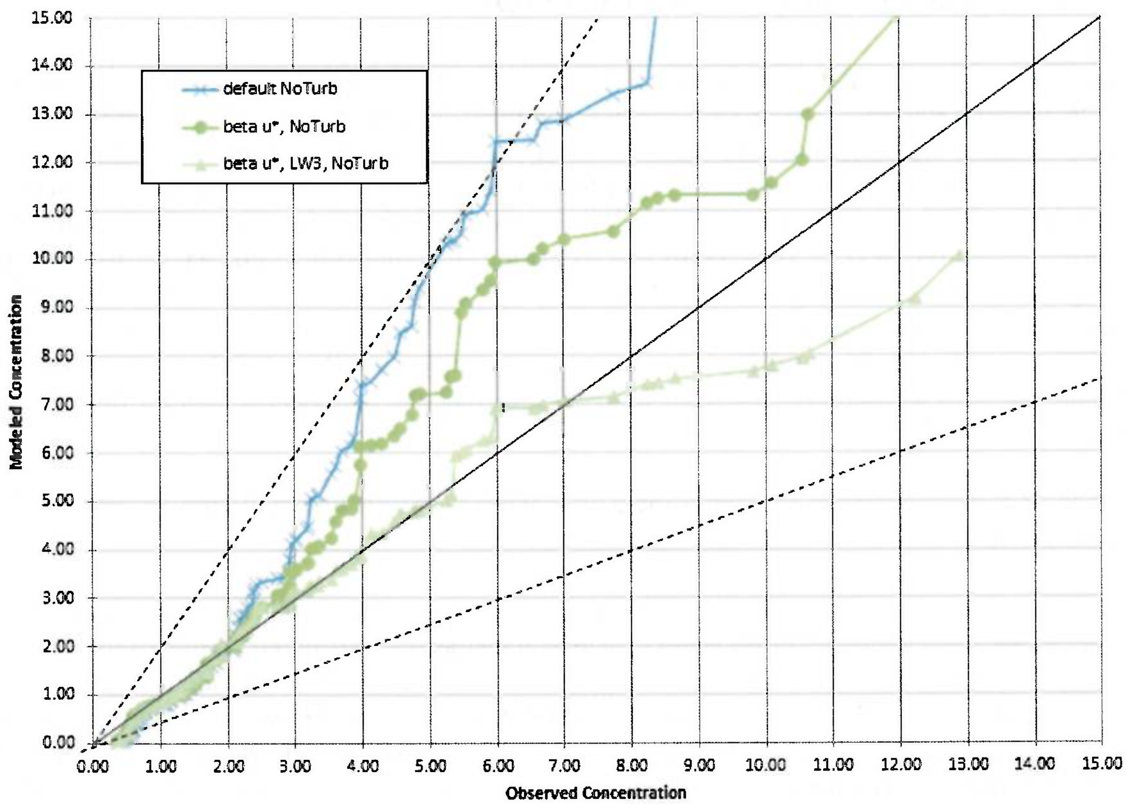
Due to the 60-minute averaging times for the Tracy turbulence data, we recommend for this database as used in AERMOD modeling that the turbulence data should not be used. We re-ran AERMOD with default and low wind options with the turbulence data removed from the model input; the results are shown in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

Review of AERMOD Low Wind Option Evaluation for the Tracy Power Plant Tracer Experiment

Review of AERMOD Low Wind Option Evaluation for the Tracy Power Plant Tracer Experiment

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April 18, 2016

Introduction

Some of the most restrictive dispersion conditions and the highest model predictions for AERMOD[1] (EPA's preferred dispersion model for short-range applications) occur under low wind speed conditions. Before 2010, there had been limited model evaluation for these conditions. After a 2010 API-sponsored study conducted by AECOM[2], the United States Environmental Protection Agency (EPA) proceeded to implement various improvements to the AERMET meteorological pre-processor (to address under-predictions 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[3] an updated set of options for AERMET ("ADJ_U*") and AERMOD ("LOWWIND3") for implementation as default options in the model. As part of the public comments to EPA's proposal, the Sierra Club provided[4] new evaluations for 5 databases, for which three of these led to questions as to whether these low wind options are sufficiently protective of air quality standards, especially the short-term SO_2 and NO_2 National Ambient Air Quality Standards (NAAQS).

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, 3 weeks (August 1984) with 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 Sierra Club evaluations for the Baldwin and Prairie Grass field studies led to a conclusion that the AERMOD low wind options were either overpredicting or nearly unbiased, but results for Lovett, Kincaid, and Tracy showed underpredictions for the peak concentration at each monitor (the "Robust Highest Concentration").

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[1] Available at https://www3.epa.gov/ttn/scram/dispersion_prefrec.htm#aermod.

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

[3] 80 FR 45340, July 29, 2016.

[4] EPA Docket Item, 2015. http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2015-0310-0114.

In follow-up work, AECOM reviewed the Sierra Club work and provided a rebuttal evaluation[5] for certain long-term (at least 1-year) databases: Lovett and Clifty Creek. The Kincaid SO_2 evaluation database was found in this study to be unusable due to local SO_2 sources that were not accounted for in the inventory. The basic conclusion from the AECOM rebuttal evaluation was that for the 99th percentile statistic associated with the SO_2 NAAQS, the use of the ADJ_U* LOWWIND3 options were sufficiently protective of the NAAQS.

Recent Sierra Club Comments on the Tracy Evaluation

The AECOM rebuttal evaluation did not address Tracy because of its short duration. However, the Sierra Club mentioned this database again in additional comments[6] made to the EPA Consent Decree docket on March 31, 2016. The Sierra Club comments can be summarized as follows.

- The proposed low wind options "undermine the reliability and credibility of the modeling".
- Applying these options to the original validation studies performed for AERMOD in some cases "quite significantly reduces modeled impacts as compared to real-world data, particularly so in the case of the Tracy validation study data."
- The Sierra Club provides quantile-quantile plots showing their model evaluation results, which are reproduced here in Figures 1 and 2. Figure 2 shows an underprediction tendency with the use of the low-wind options.
- The Sierra Club also criticizes the use of 1974 National Oceanic and Atmospheric Administration (NOAA) tracer databases (as being "severely flawed and outdated") and with a limited sample size.

Response to the Sierra Club Comments

It is important to realize that the AERMOD evaluations[7] referenced by the Sierra Club were conducted about 13 years ago. It must be understood that after these evaluations were conducted, there were several developments that increased the frequency of low wind input data used in AERMOD, and which "exposed" possible shortcomings in the model for these conditions:

- Observing stations at airports were converted in many cases to sonic anemometers ("ice free"), lowering the starting wind speed from 3 knots to virtually zero.
- The archival of 1-minute wind data made it possible for EPA to write a new pre-processor program to AERMET (AERMINUTE)that significantly increased the number of hours with wind speeds under 1 m/s, thus further testing the model in these conditions.
- The very nature of a steady-state model that assumes a 50-km distance coverage within 1 hour is invalidated for very low wind speeds.

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[5] Available at https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2014-0464-0326, Exhibit 7.

[6] Submittal to docket EPA-HQ-OAR-2014-0464 by Zachary Fabish, Sierra Club, on March 31, 2016.

[7] Available at https://www3.epa.gov/ttn/scram/7thconf/aermod/aermod_mep.pdf.

Figure 1: Tracy Evaluation Results with Default Options

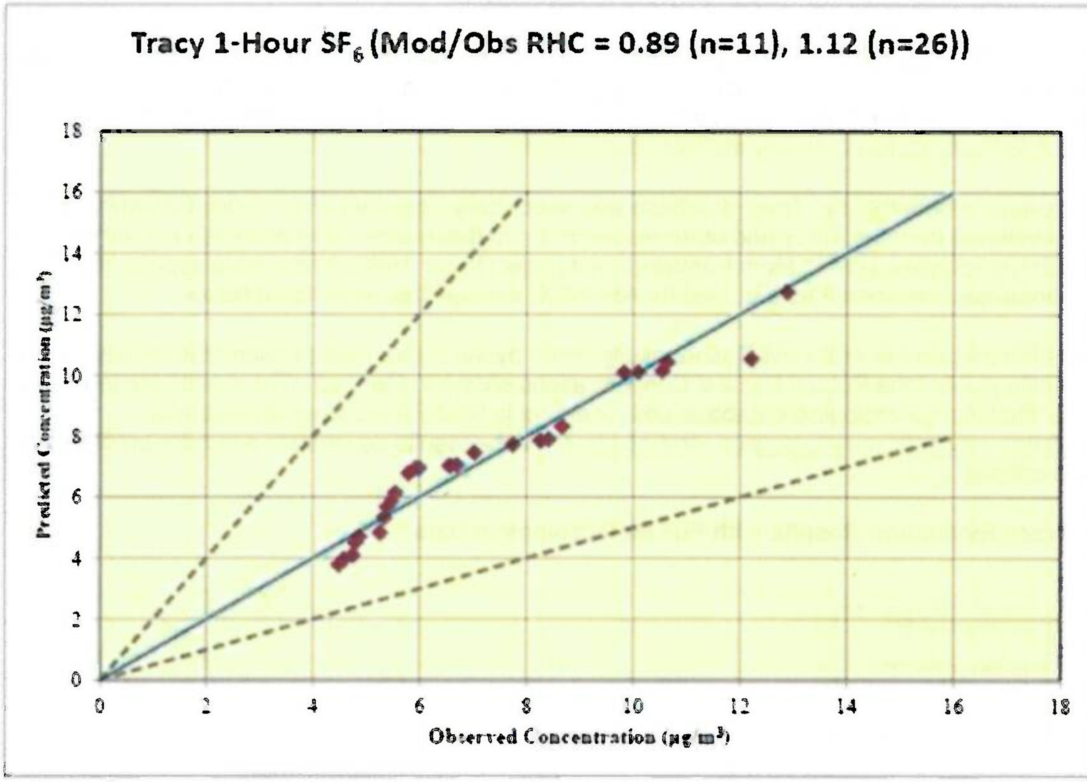
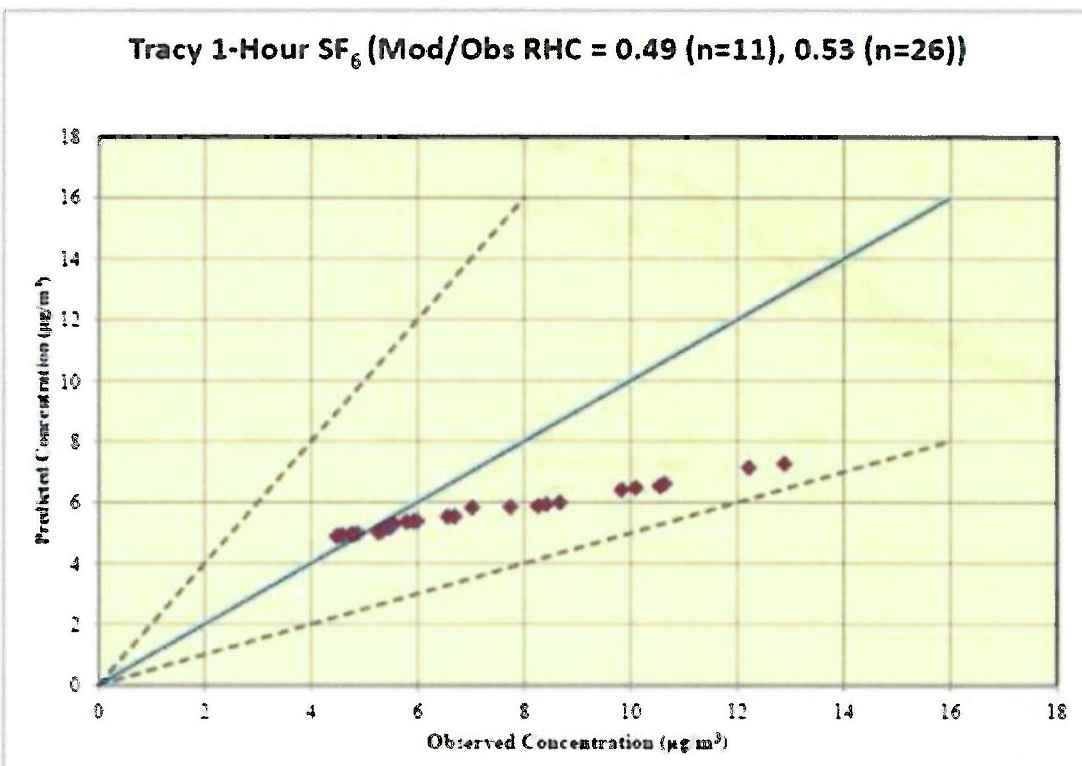


Figure 2: Tracy Evaluation Results with ADJ_U* and LOWWIND3 Used



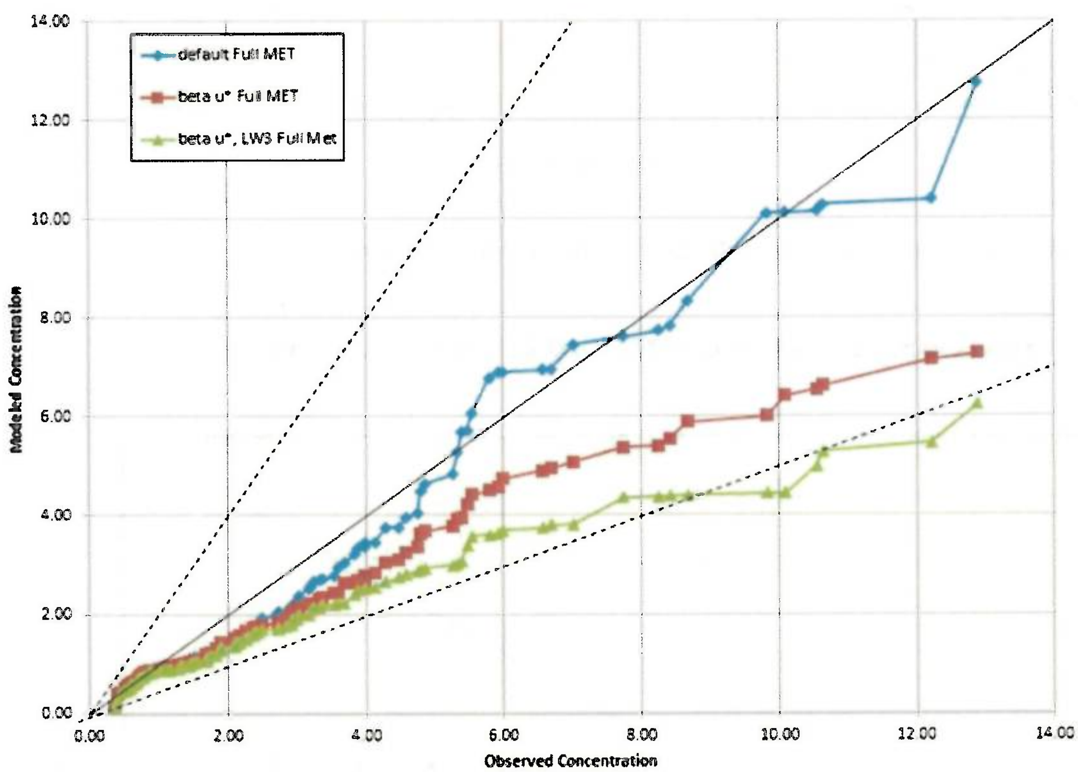
These issues led to the scientific investigations noted above that have resulted in the EPA proposals for these beta low wind options as part of the revisions to Appendix W.

In terms of the 1984 Tracy database, its age is not that much less than the 1974 NOAA databases. It also only spanned a 3-week duration which included only partial-day coverage (up to 11 hours at most on any given day). These aspects limit the Tracy database's usefulness for the SO_2 NAAQS, which is based upon a full year and full daily review of hourly monitor observations.

It is also important to note that the Tracy database was specifically designed for a model, CTDMPLUS[8], which was developed from the Tracy and other research-grade databases. This database and others involved in EPA's Complex Terrain Model Development project in the 1980s had unique aspects that require additional caution when they are used for AERMOD evaluations, as is noted below.

Our attempts to replicate the Tracy evaluation results noted by the Sierra Club provided the results for the quantile-quantile plots of the Robust Highest Concentrations shown in Figure 3. The results presented in Figure 3 use the full meteorological database and receptors in the EPA archives (available at https://www3.epa.gov/ttn/scram/dispersion_prefrec.htm). These results do indicate an under-prediction for the low wind options.

Figure 3: Tracy Evaluation Results with Full Meteorological Data



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[8] Available at https://www3.epa.gov/ttn/scram/dispersion_prefrec.htm#ctdmplus.

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[9]), 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 guidance document initially in 1987 and then updated in 2000[10] 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 rationale for this is based on the stability class calculations (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 under-prediction.
- 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 that the turbulence data not be used when evaluating AERMOD as it already accounts for plume meander. 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 4.

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 under-predictions for the peak concentrations and modest over-predictions for the mid-range of concentrations.

Conclusions

The Tracy AERMOD evaluations using the proposed low wind options need to be reviewed without the use of the full hourly-averaged turbulence data to avoid overestimating the turbulence input to AERMOD which occurs, in part, by double-counting the meander effect. Once this is done, it is evident that the default AERMOD options over-predict, and the low wind options show an improved and acceptable evaluation result.

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[10] 2000 version is available at https://www3.epa.gov/scram001/guidance/met/mmgrma.pdf.

Figure 4: Tracy Evaluation Results with Meteorological Data Omitting Turbulence Data